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16. ABSTRACT Highway maintenance operations often require a large truck equipped with a truck-mounted attenuator (TMA) to provide impact protection for workers from errant vehicles. Since the primary purpose of the TMA is to attenuate errant vehicle impacts, the driver of the TMA truck is inherently at continual risk of injury while protecting a highway work zone especially from high speed impacts by fully loaded semi-trucks. Recent advances in technology have provided the opportunity to considerably diminish TMA truck driver risk by relocating the driver to the relative safety of the protected work truck and have the TMA truck drive and follow the work truck autonomously. The objective of this research was to identify and procure a commercially available autonomous TMA system and conduct a thorough evaluation of the system's safety and performance characteristics.		13. TYPE OF REPORT AND PERIOD COVERED Final Report July 2018 – December 2021
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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Evaluation of Autonomous TMA Trucks for Use in Caltrans' Operations

Duane Bennett and
Principal Investigator: Ty A. Lasky

Report Number: CA22-3265
AHMCT Research Report: UCD-ARR-21-03-31-01
Final Report of Contract: 65A0560/65A0749 Task 3265

November 19, 2021

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

The California Department of Transportation (Caltrans) has begun a research effort seeking to deploy autonomously-driven truck-mounted attenuator (TMA) trucks primarily for moving closure highway maintenance tasks on mainline highways across the state. Reducing the risk of injury to TMA drivers is the main justification of autonomous TMA (ATMA) technology. The California Department of Motor Vehicles currently does not authorize autonomous operation of heavy trucks on highways. Therefore, it was also a goal of this research effort to demonstrate that safe autonomous TMA truck operation is attainable to potentially gain the approvals to begin deploying autonomous TMA trucks on the highway in Caltrans highway maintenance operations.

Caltrans regularly conducts highway maintenance and repair activities in or adjacent to live traffic lanes. To reduce the hazard of direct traffic exposure to maintenance workers in vehicles or on foot, a shadow (trailing) truck equipped with a TMA is deployed as a shield to block errant vehicle impacts to the work zone. The TMA truck driver is subject to much higher likelihood of errant vehicle impact than other maintenance vehicles. TMAs are designed to absorb a collision with cars and small trucks, but large truck collisions exceed design capacity and place TMA drivers in great danger of injury. Autonomous leader/follower driving technology provides a solution to mitigate TMA truck driver safety risk by removing the driver from the TMA truck during live traffic highway maintenance tasks.

The ATMA leader/follower autonomous driving technology, which is the subject of this research, was developed by Kratos, Inc., a leader in the emerging field of ATMA vehicle development. Kratos has significant experience in developing advanced automated target systems for the military. The prototype Kratos leader/follower ATMA system was developed and tested in connection with the University of Florida. The first Department of Transportation (DOT) version of the ATMA system was built by Royal Truck & Equipment for the Colorado DOT (CDOT) who demonstrated it on closed roadways. CDOT has subsequently purchased several more ATMA systems. Caltrans Division of Research, Innovation and System Information, Division of Equipment, and Division of Maintenance became interested in a research project wherein AHMCT would procure and evaluate a Caltrans-targeted version of the ATMA system. AHMCT purchased and began evaluation using the second-generation of the leader/follower autonomous controller. Kratos is continuously making technology advances to improve ATMA performance and reliability, which Kratos incorporated into the Caltrans ATMA while the AHMCT evaluation progressed.

AHMCT purchased a Caltrans-specified ATMA system from Royal/Kratos to conduct a performance evaluation to its suitability for Caltrans highway maintenance operational deployment. Caltrans elected to configure the research ATMA with a pick-up truck acting as the Leader Vehicle and a 19,000 lb Gross Vehicle Weight Rating flatbed TMA truck as the Follower Vehicle. AHMCT created an ATMA safety and performance test and evaluation plan that establishes the functionality and capabilities of the autonomous system related to the Caltrans deployment application. The most advantageous use of the ATMA system would be to support a Caltrans moving highway maintenance task such as paint striping or sweeping. These tasks are continuously moving so a driver must be in the standard TMA vehicle and stationary traffic management objects like traffic cones are not deployed.

Major Results and Recommendations

The ATMA will enable Caltrans to operate the TMA from the relative safety of the protected work truck. The ATMA leader/follower autonomous driving scheme was determined to be the simplest scheme by which to operate a shadow truck autonomously in a lane closure operation. Other popular competing autonomous driving schemes, such as remote control and self-driving autonomous schemes, are complicated, expensive, and less practical.

The ATMA successfully completed all safety and performance test scenarios. The next logical phase will be Caltrans deployment trials to determine how well the ATMA fits into maintenance operations in terms of functionality and operator training. Caltrans will need to obtain authorization to operate a heavy duty truck autonomously on the highway.

The key opportunity for Caltrans is with field operations on mainline highway moving closure maintenance operations in live high-speed traffic. These operations expose TMA drivers to the greatest risk of high-energy impacts. Once ATMA highway driving authorization is granted, AHMCT recommends that Caltrans Maintenance identify a suitable crew and actual, scheduled highway maintenance operations that AHMCT can partner with to support and participate in the initial field deployment trials. AHMCT recommends that initial ATMA field deployments be limited to highway sweeper operations. AHMCT views paint striping operations to be far more complex. Sweeping is simpler and involves fewer safety resources, which makes it ideal to conduct ATMA deployment trials. Upon successful conclusion of a brief AHMCT-supported field trial, AHMCT recommends that the ATMA be transferred to the Caltrans fleet and assigned to Division of Maintenance to continue agency-supported ATMA field trials and/or deployment.

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List of Acronyms and Abbreviations

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
ABS	Antilock Brake System
AD-IS	Air Dryer Integrated Solution
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
AIPV	Autonomous Impact Protection Vehicle
ATIRC	Advanced Transportation Infrastructure Research Center
ATMA	Autonomous Truck-Mounted Attenuator
CalSTA	California State Transportation Agency
Caltrans	California Department of Transportation
CARB	California Air Resources Board
CDOT	Colorado Department of Transportation
CHP	California Highway Patrol
COVID-19	Coronavirus disease 2019
DECT	Digital Enhanced Cordless Telecommunications
DMV	California Department of Motor Vehicles
DOE	Division of Equipment
DOT	Department of Transportation
DR	Dead Reckoning
DRISI	Division of Research, Innovation and System Information
DVR	Digital Video Recorder
E-Stop	Emergency Stop
FOG	Fiber Optic Gyro
FV	Follower Vehicle
GPS	Global Positioning System
GUI	Graphical User Interface
GVWR	Gross Vehicle Weight Rating
INS	Inertial navigation System
I/O	Input/Output
IPV	Impact Protection Vehicle

Acronym	Definition
Kratos	Kratos Unmanned Control Systems
LCD	Liquid Crystal Display
LED	Light-Emitting Diode
LiDAR	Light Detection and Ranging
LV	Leader Vehicle
MASH	AASHTO Manual for Accessing Safety Hardware
MAZEPP	Highway Maintenance Zone Enhanced Enforcement Program
META	Maintenance Equipment Training Academy
NCHRP	National Cooperative Highway Research Program
NextGen	Next Generation
OCU	Operator Control Unit
OEM	Original Equipment Manufacturer
PI	Principal Investigator
PO	Purchase Order
PTO	Power Take-Off
PTT	Push-to-Talk
PVC	Polyvinyl Chloride
RF	Radio Frequency
Royal	Royal Truck & Equipment
RTK	Real-Time Kinematic
SAE	Society of Automotive Engineers
SCU	System Control Unit
SD	Secure Digital card
SR	State Route
SSD	Solid-State Drive
TMA	Truck-Mounted Attenuator
UCD	University of California-Davis
V2V	Vehicle to Vehicle
VIN	Vehicle Identification Number
VMS	Vertical Message Sign

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Chapter 1: Introduction

Problem

California Department of Transportation (Caltrans) operations to conduct highway maintenance or repair activities often require a large truck equipped with a truck-mounted attenuator (TMA) referred to as “TMA trucks” to provide impact protection for workers from errant vehicles. The Caltrans safety manual term for using a TMA truck to protect a highway work zone is a “shadow vehicle.” Since the primary purpose of shadow vehicles is to take errant vehicle impacts on the highway, the driver of the shadow truck is inherently at continual risk of physical injury while protecting a highway work zone especially by high-speed impacts of fully-loaded semi-trucks, which can exceed the American Association of State Highway and Transportation Officials (AASHTO) Manual for Accessing Safety Hardware (MASH) attenuator impact standard limits. Recent advances in technology provide the opportunity to considerably diminish the shadow truck driver risk by relocating the driver to the relative safety of the protected work truck and have the shadow truck drive and follow the work truck autonomously.

Objectives

The objective of this research project was to identify a commercially available autonomous TMA (ATMA) system suitable for Caltrans use, procure a system, and conduct a thorough evaluation of the system’s specific safety and performance characteristics relative to Caltrans’ needs. The evaluation sought to determine if the procured ATMA technology fulfills the Caltrans need, and if not, document what is needed to reach that goal. If the research identified a suitable autonomous TMA system that satisfies all the essential Caltrans safety and performance requirements, Caltrans could endeavor to deploy the system for Division of Maintenance use.

Scope

This research project identified and procured an operational autonomous shadow truck system that was deemed to be appropriate for Caltrans use from an accomplished equipment manufacturer. The ATMA system was registered in the University of California-Davis (UCD) fleet, and may be transferred to the Caltrans fleet upon the successful conclusion of the research project. The Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) created an ATMA test plan designed to evaluate the ability of

the system to provide the same level of protection and functionality as a standard Caltrans shadow vehicle. To provide an additional level of safety, AHMCT operated the ATMA while executing the test plan on closed test tracks with a safety rider stationed in the autonomous vehicle. The full test results and recommendations of the ATMA evaluation are provided to Caltrans in this final report.

Background

Conventional shadow trucks with TMAs are an ordinary part of Caltrans highway work zone operations. Shadow trucks are utilized in a variety of ways in highway work zones, including as traffic control, maintenance support, and as a safety countermeasure for both workers and passing motorists. These shadow trucks can be positioned off the shoulder of the highway, operated within the lane closure, or utilized to block approaching traffic. A typical maintenance task being conducted in a temporary highway lane closure will position a shadow truck close to the work vehicle to shield workers from an errant vehicle entering the work zone. Often, the lead worker supervising the highway maintenance operation drives the shadow vehicle because it presents the best vantage point from which to monitor both the maintenance operation in front and the traffic control mitigation operations behind, including the Highway Maintenance Zone Enhanced Enforcement Program (MAZEED), and to actively monitor and respond to an imminent errant vehicle threat. The shadow vehicle is implicitly exposed to the greatest threat of impact on the highway. TMAs are designed to safely defuse the energy from impacts with standard-sized cars and trucks. TMA trucks and drivers are at the greatest risk from impact by fast moving heavy trucks, such as large commercial semi-trucks, which generate impact energy levels at highway speeds that far exceed conventional TMA design capabilities.



Figure 1.1: Caltrans TMA highway impact

ATMA vehicles were developed with the specific goal of eliminating the potential risk of shadow truck driver injury from errant vehicle impacts by removing the driver during highway operations. The manufacturing partnership of Royal Truck & Equipment (Royal) and Kratos Unmanned Control Systems

(Kratos) developed a leader-follower scheme that autonomously drives a TMA truck to follow a leader vehicle, shielding it from errant vehicle exposure. The follower TMA truck follows the exact path of the leader vehicle at a user-configurable gap distance. The ATMA vehicle follows automatically, and a wide arrangement of sensors monitor following accuracy and detect obstacles that may cross the following path between the vehicles. The shadow truck driver rides in the leader vehicle and is responsible for monitoring the motion of the shadow truck and providing an additional safety countermeasure to stop the follower truck instantly should it become necessary.

Since the shadow truck is unoccupied while autonomous driving, the only possible function for the vehicle during highway maintenance operations is as a barrier. This eliminates the possibility of any other additional capabilities or operational advantages available to conventional person-driven shadow trucks. Therefore, the additional expense and complication of deploying autonomous shadow trucks must be justified by an indeterminate safety benefit to at least one worker (driver) in a highway maintenance crew. In addition, autonomous vehicle control itself introduces new potential hazards that do not exist for conventional human driven vehicles. Consequently, many of the ATMA performance scenarios presented in this study seek to determine if the autonomous vehicle can deliver an overall net operational safety benefit. Reducing the risk of injury to shadow truck drivers is the main justification of ATMA technology.

The rules governing autonomous vehicle driving are relatively new and are adapting to keep pace with advances in technology development. For Caltrans to utilize the ATMA on California highways, an appropriate agency must provide approval based mainly on level of vehicle guidance automation and vehicle performance specifics. The Society of Automotive Engineers (SAE) levels of self-driving autonomy are based on a vehicle guidance automation model with a driver/passenger present that does not directly correlate with a leader-follower model without a driver/passenger residing in the autonomous vehicle. The ATMA leader-follower guidance autonomy technology fits somewhere between Levels 2 and 3 of the SAE self-driving autonomy model. Additionally the California Department of Motor Vehicles (DMV) autonomous driving regulations do not apply to heavy duty trucks such as the ATMA truck. The Caltrans Division of Research, Innovation and System Information (DRISI) is working with the California DMV, the California Highway Patrol (CHP), and Caltrans legal departments to attain a guideline, exception, or approval that would allow the ATMA system to be deployed with Caltrans Maintenance crews and operated on California highways.

Self-Driving Vehicle Autonomy Levels

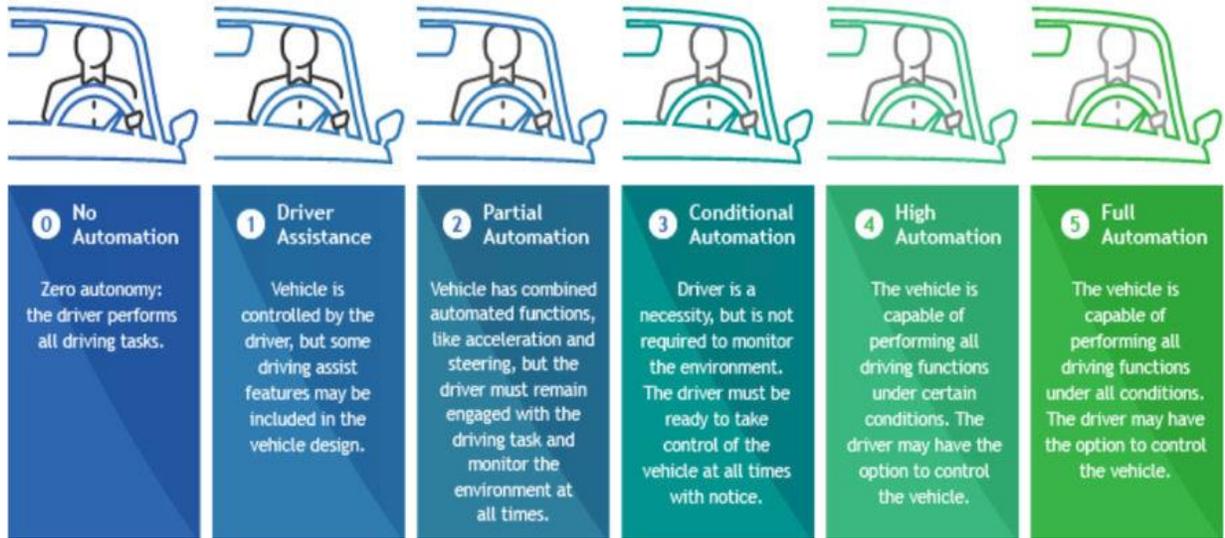


Figure 1.2: SAE autonomous driving levels¹

Research Methodology

The research methodology for the ATMA study involved purchasing a standard configuration ATMA system and executing a series of safety and performance scenarios with the equipment on closed test track facilities. The safety scenarios validated and further investigated various autonomous driving safety countermeasures integrated into the ATMA system to account for expected anomalies. In addition, test scenarios were created that explored how the ATMA system reacted to various unexpected system and operator errors that may logically be encountered in highway operations. The main objective of the safety scenarios is to verify that the ATMA is always under control regardless of the circumstances and if control is lost, that the ATMA always transitions into a safe state.

This study evaluated ATMA performance from the perspective of the most beneficial application of the technology to Caltrans operations. Logically, the greatest potential ATMA safety benefit would correlate with its application to the riskiest tasks. For Caltrans, highway maintenance operations on mainline highways represent the riskiest tasks needing to be conducted on a daily basis. These operations are exposed to the prospect of high-energy impacts that do not exist on low-speed roadways. In addition, since the ATMA technology singular benefit is autonomous driving, the study of ATMA performance utility was further narrowed to moving closure highway maintenance operations in live high-speed traffic. Stationary temporary lane closure operations were not

¹ [Society of Automotive Engineers \(https://www.sae.org/\)](https://www.sae.org/)

considered, because the autonomous driving feature would not be utilized and the shadow truck driver could simply exit the vehicle to reduce their impact exposure. Therefore, ATMA performance test scenarios were all developed to be representative of actions a shadow truck would normally encounter when conducting autonomous leader/follower operation in Caltrans moving closure mainline highway maintenance operations.

Overview of Research Results and Benefits

This research project succeeded in specifying and procuring an autonomously guided TMA vehicle suitable for Caltrans evaluation and potential future deployment. The ATMA system was studied and tested to determine both the safety and performance aspects of the equipment from the perspective of supporting appropriate highway maintenance operations. The study identified potential beneficial applications for Caltrans operations to improve worker safety. The results of ATMA system testing indicated that the leader/follower guidance system performance was well within the test measurement resolution, which should easily satisfy Caltrans highway operational accuracy requirements. The ATMA system operation proved to be simple to operate with a user interface that takes the operator through the necessary steps to engage the automated vehicle guidance system, which also simplifies operator training. Safety testing did reveal some safety deficiencies with this second-generation Royal/Kratos autonomous leader/follower system, but the severity of these issues will need to be evaluated by Caltrans and mitigated by the manufacturer should it be deemed necessary before Caltrans considers further deployment of the ATMA in highway maintenance operations. The most significant issues were resolved during the research by way of manufacturer system upgrades.

Chapter 2: Autonomous Leader/Follower TMA Technology Description

Kratos ATMA Basic Description

The leader/follower autonomous driving technology on the ATMA system was developed by Kratos, a company with significant experience in developing advanced automated target systems for the military. The company is also a leader in the emerging field of autonomously-driven shadow truck development. Royal Truck & Equipment, Inc. is a leader in manufacturing TMA vehicles. Together they developed the ATMA system that was the subject of this research project. The Royal/Kratos leader/follower autonomous guidance system is comprised of a conventionally-driven highway maintenance Leader Vehicle (LV), which contains a position tracking system that communicates the traveled vehicle path via Global Positioning System (GPS) waypoints (E-crumb) to a trailing traffic protection TMA vehicle. The TMA Follower Vehicle (FV) contains another position tracking system and a vehicle controller that receives the E-crumb path and autonomously drives the TMA FV along the path of the LV at a defined vehicle separation gap (Figure 2.1). Inertial Navigation Systems (INS) in both vehicles act as a reserve guidance system to follow the E-crumb path should a GPS signal be temporarily lost. Several safety systems are incorporated to ensure that the autonomously-driven FV is always safely under the control of the LV.

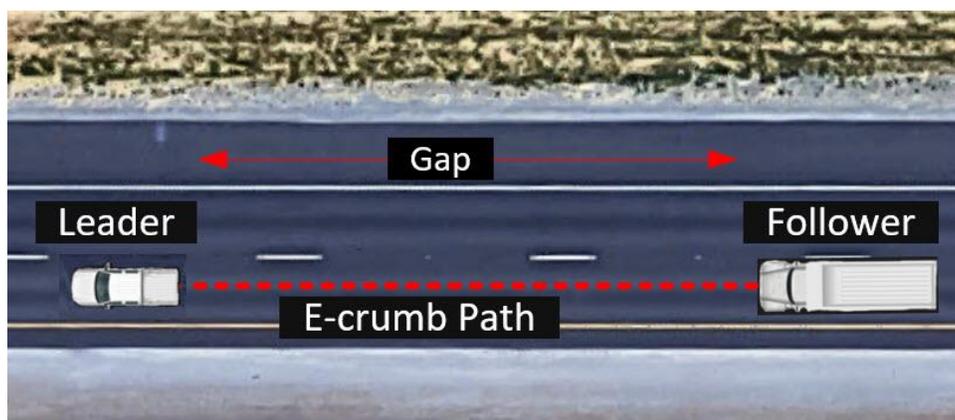


Figure 2.1: Autonomous E-crumb path guidance

Kratos ATMA Development

The prototype Kratos autonomous leader/follower TMA system was first developed and tested in connection with the University of Florida. The first DOT version of the ATMA system was built for the Colorado DOT (CDOT) and demonstrated on closed roadways. Caltrans DRISI, Division of Equipment (DOE), and Division of Maintenance became interested in a research project with AHMCT to procure and evaluate a Caltrans version of the ATMA system. AHMCT purchased the Kratos second-generation leader/follower autonomous controller as part of the integrated ATMA system provided by Royal. Meanwhile, Kratos is continuously making advances with this technology to improve ATMA performance and reliability. These refinements will be incorporated into future ATMA system builds and will be incorporated into the Caltrans ATMA vehicle as necessary. Several refinements were incorporated during this research.

Kratos Autonomous TMA Guidance System

The Kratos ATMA, as originally purchased, contained an independent GPS tracking systems for each vehicle, an INS for the FV, an Operator Control Unit (OCU) module for each vehicle, a Graphical User Interface (GUI) in the LV, and several sets of radio transmitters/receivers which form a line-of-sight communication bridge between the separate vehicles at up to a 1,500-ft gap. The FV is ringed with close range sonar detectors that function solely as an object detection warning system. A separate wireless Emergency Stop (E-Stop) system provides a segregated link that enables the LV operator to shut down the FV independent of OCU control. The FV is the platform where the guidance system is based, and the LV acts like a command/control platform remotely connected to the guidance system by radio signals. The LV sends a GPS trail of position data points (E-crumbs) via radio signal back to the FV. The guidance controller in the FV compares the current GPS position of the FV to the LV E-crumb path to autonomously drive the FV along the path of the LV.

Guidance System Specifications

The Kratos autonomous guidance system is designed to operate at speeds from 5 to 20 mph in non-GPS-denied environments with a high accuracy-following capability of ± 6 in or better relative to the LV path. The commanded FV following gap distance is user set in increments from 25 ft up to 1,500 ft. The FV lateral offset from the E-crumb path is differentially steered, and the combination of LV speed and desired gap distance dictates FV speed. A curved path of 100-ft radius is the system performance criteria, but the ATMA can reliably follow curved paths at lower speeds down to a 65-ft radius. The wireless link between the LV and FV has a 1,500 ft maximum line of sight constraint. Vehicle acceleration and braking is achieved by activating servo

motors mounted behind the driver seat which pull steel cables attached to the vehicle brake and accelerator pedals. A separate servo-driven ring gear is integrated into the steering wheel to provide automated steering control.

Primary GPS Navigation System

To achieve autonomous leader/follower driving control, Kratos primarily utilizes a GPS tracking system. Two GPS antennas are installed on each vehicle. One GPS signal is required to establish vehicle position and the second to determine vehicle heading. The accuracy of the ATMA GPS guidance system is inherently enhanced in a leader/follower arrangement because the FV positional accuracy is measured in relation to the LV path reference and not to the standard global reference, i.e., the FV uses relative sensing, which eliminates common errors.

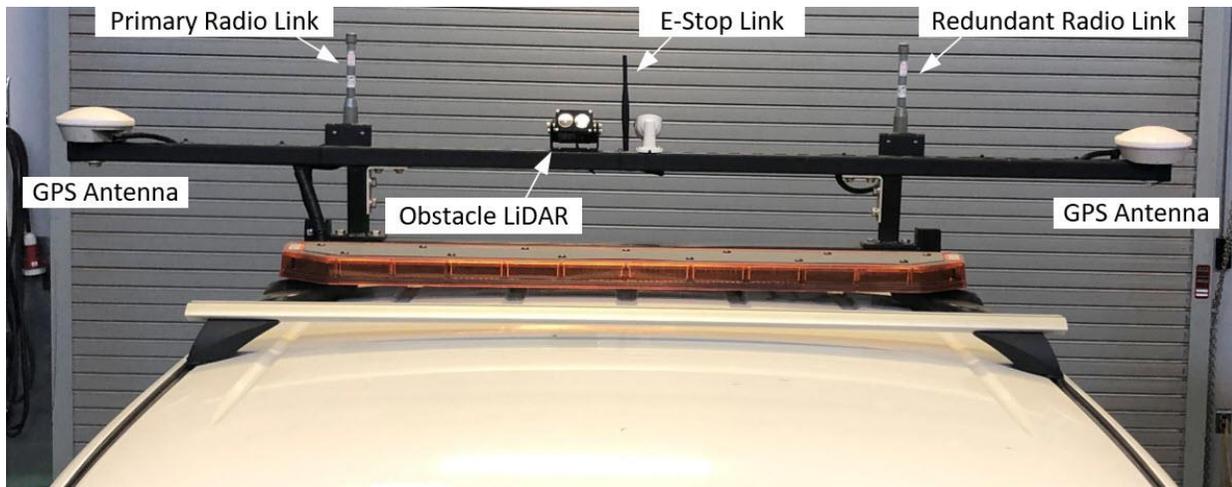


Figure 2.2: LV antenna rack

Reserve Inertial Navigation System

GPS signals can be blocked by overhead objects, leading to the loss of the GPS position data stream. With the loss of any of the GPS signals, the ATMA primary GPS guidance solution becomes indeterminate. In order to account for temporary GPS signal losses, Kratos incorporated a reserve INS in each vehicle. The ATMA system is designed to switch into this secondary guidance mode and continue autonomous driving should any of the primary GPS guidance system GPS signals be interrupted. Self-contained INS are installed in both vehicles to calculate vehicle position from a known starting point, orientation, and velocity by Dead Reckoning (DR) utilizing acceleration and rotation sensors. Inertial navigation systems are subject to integration drift errors that accumulate roughly proportionally to time. Therefore, the ATMA system can only accurately navigate for about a minute without reestablishing the primary GPS guidance mode.

Safety Systems

The ATMA features an array of safety systems to ensure that the FV remains under the control of the LV when operating in autonomous mode. Should a guidance abnormality occur, or an object be detected in the path of the FV while autonomously driving, FV motion can be stopped either automatically by the control system or manually by an observer.

Automated Safety Stops:

While in the autonomous driving mode, the guidance and control system monitors the motion of the FV to detect any deviations in the FV guidance path or if an object is detected on the path and automatically stops FV motion. Typically when the control system stops FV motion, it is in the form of an A-Stop, which can be immediately reset from the LV when safe and autonomous FV driving can be restored. If the guidance path is disrupted, a subsequent roll-out procedure would be required to return to autonomous driving mode. An example of automated safety stop that is not recoverable is when the LV steers too sharply and the FV cannot steer sharp enough to stay on the E-crumbs path.

Manual Safety Stops:

The ATMA leader/follower guidance scheme presumes a person in the LV is continuously monitoring the movements of the FV as a redundant safety countermeasure. The LV monitoring person has several options available to immediately stop the movement of the FV for any conceivable reason. In the LV, an A-Stop switch as well as a pause button on the UI screen will stop the FV motion in a recoverable state. An E-Stop button is also available in the LV for emergency situations. The LV E-Stop system maintains an independent wireless fail-safe mode link to the FV. Triggering any of these manual stops instantly overrides the autonomous control system and stops the FV motion by setting the FV brake. The E-Stop also turns off the FV engine and therefore, the autonomous mode is not immediately recoverable for this approach. Additionally, there are three E-Stop switches mounted on the FV: one E-Stop switch on the OCU in the cab and two external E-Stop switches. Triggering an E-Stop terminates the autonomous driving link and therefore requires a subsequent roll-out procedure to return to the autonomous driving mode.

Vehicle Driving Controls

The ATMA system controller utilizes a combination of mechanical and electrical controls to drive the FV TMA truck while in autonomous mode. The basic controls necessary to drive a vehicle include steering, brake, accelerator, and ignition. The ATMA controller employs the use of motor drives to physically actuate the vehicle brake pedal and to turn the steering wheel. There are two motors that actuate the brake pedal. One is a proportional servo motor driven by the autonomous speed control that provides analog brake actuation to

control vehicle speed. The other is a two-position motor actuator for the E-Stop system and only sets or releases the brake (Figure 2.3). The arrangement of the brake pedal cable pulls are such that a safety rider in the FV can press on the vehicle brake pedal at any instant to stop the FV motion while in the autonomous driving mode.

Steering is controlled with a proportional servo motor driving a gear ring nested with the vehicle steering wheel. When configured for autonomous driving, two aluminum “fingers” are attached to the ring gear housing ring that capture the vehicle steering wheel. The autonomous controller drives the steering servo, which directly turns the vehicle steering wheel. When out of autonomous driving mode, the steering motor is released and free-spinning so a driver can steer the FV with some resistance with the fingers installed, but for longer drives, the fingers should be removed to make steering easier.

The engine throttle for the fuel injected engine is controlled electronically by the autonomous controller. While in autonomous driving mode, a safety rider in the FV does not have a means to override engine acceleration. The safety rider can only apply the brake to stop the FV motion. The SCU will increase FV acceleration in an effort to attain the commanded FV speed, but brake application is far more prevalent and FV motion can be easily stopped. The safety rider may also switch the OCU to Idle to pause autonomous control. In emergency situations, the safety rider may also press the E-Stop switch, which releases an electrical relay wired into the ignition circuit that disables the vehicle ignition, turning off the engine.



Figure 2.3: Brake cable pulls



Figure 2.4: Steering motor

Kratos ATMA Operation

Autonomous Roll-Out

The ATMA FV is designed to be conventionally driven out to the highway work zone and stopped on a straight section of roadway near the beginning of the work zone off the right-of-way. To enter autonomous driving mode, the LV

and FV are aligned at 25 to 75 ft apart. The power to both SCU units are switched on, and a step-by-step pre-operational checklist is presented on the LV GUI. The LV driver reads-off the checklist communicating with the driver in the FV over radio headsets. Both drivers switch on controls in a choreographed procedure necessary to safely enter autonomous driving mode. Once the autonomous driving link is activated and the LV has control over the FV, the FV driver relocates from the FV to inside the LV. The FV will then follow the LV as it drives, following the LV's path at the commanded gap distance.

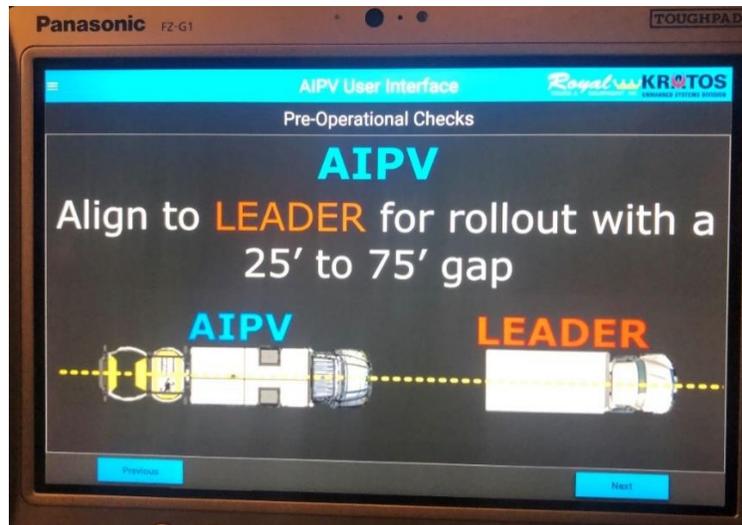


Figure 2.5: Pre-operational checklist

ATMA Autonomous Driving in Highway Work Zones

Utilizing the ATMA in a moving highway maintenance work zones provides the greatest opportunity for worker safety improvement. Moving closures are usually formed either on an entry ramp to the highway and drive onto the highway to take a traffic lane or are formed along the highway shoulder and move out onto the lane to close traffic. The ATMA is capable of supporting either of these taking the lane maneuvers. The ATMA vehicles are aligned either on the on-ramp or along the shoulder of the highway to conduct the roll-out procedure. With the checklist completed and autonomous driving mode established, the LV can start driving to take the traffic lane. Once autonomously driving in the closed traffic lane, the vehicle separation gap can be adjusted as necessary.



Figure 2.6: LV GUI offset and gap controls

Offset Path Feature

The ATMA leader/follower operational scheme simplifies FV operational control while autonomously driving in the moving lane closure and exiting the traffic lane, but presents a problem in regards to taking a traffic lane. DOT traffic safety practices normally have the shadow truck take live traffic lanes first to shield the LV and/or work truck as it enters the lane. Since the ATMA FV follows the exact path of the LV in autonomous mode, the LV must first drive out into the traffic lane and continue driving while being exposed to traffic until the point where the E-crumb path steers the FV out into the lane. This lane-taking operational discrepancy elevates the traffic exposure risk to the LV as compared to standard shadow truck highway operations.

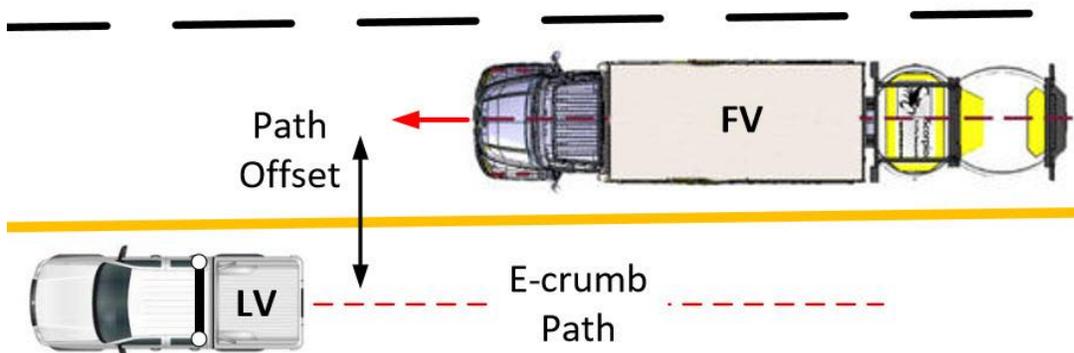


Figure 2.7: E-crumb offset functionality

AHMCT described the lane-taking safety discrepancy to Kratos. In response, Kratos created an altogether new ATMA operational feature for offset E-crumb

path following that was installed with an ATMA control program upgrade. The ATMA now has the additional functionality of commanding an E-crumbs path offset between the LV and FV paths. Utilizing this function, the LV can be driven slowly and the FV steered out into the adjacent lane by increasing the offset distance on the GUI. Once the FV has taken the lane, the LV can steer out into the lane while decreasing the offset distance on the GUI an equal amount. Using the offset function in this manner enables the ATMA to mimic the standard shadow truck safe moving lane closure lane-taking procedure.

Chapter 3:

ATMA Procurement and Commissioning

Caltrans ATMA System Specification

Caltrans conducted an initial investigation into acquiring an ATMA by requesting a specification and preliminary quote from the Royal/Kratos team (Appendix A). AHMCT subsequently collaborated with Caltrans to adopt a final ATMA specification and quote (Appendix B). The purchase specification included several line items that were a combination of items required to support the autonomous driving feature, Caltrans Maintenance vehicle standards, and optional items meant only to enhance the TMA vehicle operational capabilities, such as the Royal Technology package (Appendix C).

The Royal/Kratos ATMA system configured for Caltrans and AHMCT consists of an LV adapted from a legacy AHMCT pick-up truck and an FV consisting of an adapted TMA truck purchased from Royal. The autonomous driving system was installed by their partner Kratos on both vehicles. Royal based their specification on their Super TMA truck design with the Technology Package upgrade. The Royal Super TMA truck shares many common features with Caltrans TMA fleet vehicles, with the following exceptions:

- The Royal chassis dimensions were much longer than the standard TMA vehicle configuration that Caltrans DOE utilizes in their fleet. Royal prefers to incorporate a cement counterweight to add additional weight to the TMA truck to reduce rebounding when impacted. The cement is poured below the flatbed deck and between the chassis frame rails, so the length of the chassis dictates concrete volume and thereby weight. Counterweights are uncommon for Caltrans TMA fleet trucks, primarily because the added weight drastically reduces the payload capacity of the truck.
- Royal added a back-up generator to maintain the truck batteries when parked in a work zone while not idling the engine and a radar signboard.
- The Royal vertical message sign (VMS) telescopic mounting is designed to accommodate the Scorpion TMA unit by enabling the signboard to be hydraulically raised and lowered from the truck cab.
- The VMS includes the proprietary Royal radar speed sensor system designed specifically to support highway moving lane closure operations. The radar system utilizes a GPS system to determine the speed of the moving TMA vehicle and a radar sensor to determine approaching vehicle speed. A small processor in the signboard

calculates the absolute ground speed of the approaching vehicle and displays it on the VMS.

- Royal included their standard 8-channel TMA truck monitoring camera system and Digital Video Recorder (DVR), which displays and records the speed data sensed by the radar signboard.

Caltrans DOE reviewed the standard Royal ATMA vehicle configuration and made several changes. These changes were incorporated in the final AHMCT ATMA purchase specification (Appendix E). Some of the primary changes include:

- The radar signboard mounted on the rear of the vehicle is only visible when the attenuator is lowered and functions according to purchase specification as follows:
 - The ATMA vehicle shall be equipped with a radar message board with on-board GPS to determine truck speed allowing for proper driver feedback to approaching vehicle behind truck.
- The truck video monitoring system was upgraded to a 12-camera DVR system, which implicitly eliminated the utility of recording speed data on the DVR record.
- ATMA will be equipped with an arrow board and National Signal controller.
- Wireless headset communication system.

ATMA Project and Procurement Events Timeline

Procurement exceeded the proposed timeline by approximately nine months due to unforeseen complexities. In addition, procurement issues continued beyond the system commission as some items needed revision due to miscommunications. Overall, the vendor, Caltrans, and AHMCT worked cooperatively and successfully through the procurement and the needed system revisions. This led to a system well-suited to Caltrans needs and allowed Royal to incorporate some of the enhancements into its product line. Key ATMA project and procurement dates are provided in Appendix D.

Caltrans ATMA Configuration

Caltrans decided to configure their ATMA with a standard pick-up truck serving as the ATMA leader vehicle and a 26,000 Gross Vehicle Weight Rating (GVWR) cab-over flatbed truck as the TMA follower vehicle. Both vehicles were prepared for highway duty and delivered to Kratos for installation of the autonomous driving control system.

ATMA Leader Base Vehicle: Caltrans elected to prepare an AHMCT research vehicle to service as the LV. Caltrans DOE took the three-quarter-ton pick-up and installed the standard Caltrans markings and traffic advisor light bar

required to operate on the highway. The prepared pick-up truck was taken to a local Kratos facility to have the autonomous system installed. Kratos installed the System Control Unit (SCU), radios, and INS components under the rear seat. The autonomous controls are located under the front dashboard between the driver and passenger seats.



Figure 3.1: ATMA Leader Vehicle base vehicle

The current LV autonomous controls configuration is ideal for conducting ATMA testing trials. It allowed AHMCT to conduct ATMA testing scenarios with a safety rider always stationed in the FV and still operate with two people. The LV driver controls the autonomous settings and a safety rider in the FV monitors the safety of the FV motion. It remains unclear if the current LV configuration would be conducive to supporting ATMA highway deployment without a safety rider.

ATMA Follower Base Vehicle: AHMCT purchased a Royal Super TMA truck with the optional Technology package upgrade to serve as the ATMA FV. The Royal TMA truck was delivered to Caltrans DOE with all of the additional features installed with the exception of the Kratos autonomous driving systems. Caltrans DOE made a list of deficiencies (Appendix E). These deficiencies were either mitigated or accepted as-is by Caltrans DOE. The only exception was the radar signboard which was rejected and payment to the vendor reduced by the cost of the signboard. AHMCT worked with Caltrans DOE and the vendor to redesign and replace the signboard to meet Caltrans specifications. As of this report, Caltrans performance requirements have been met by the vendor. The signboard issue was not integral to the autonomous system operation and therefore, did not prevent ATMA testing and evaluation from continuing. Caltrans DOE then upgraded the base TMA truck with standard Caltrans markings and traffic advisor light bar required to operate on the highway.



Figure 3.2: Base ATMA Follower Vehicle

Autonomous System Installation

The prepared ATMA base vehicles were then delivered to a Kratos facility in the Sacramento area for the installation of the ATMA autonomous systems.

ATMA Leader Vehicle: Kratos engineers installed the majority of the autonomous driving control components under the rear extended cab seat of the LV pick-up truck. These components included the input/output (I/O) computer, SCU, Fiber Optic Gyro (FOG) module, data communication radios, and an Ethernet switch. An array of communication and monitoring components were attached to the light bar behind the cab. The mounted components included several radio and GPS antennas, a rear-facing camera, and a forward-facing Light Detection and Ranging (LiDAR) sensor. The radio antennas form a wireless line-of-sight data transfer link between the LV and FV. The GPS antennas provide position information for the LV. One GPS antenna provides a spot position and the second provides heading. The video camera provides a live video image of the trailing FV displayed on the GUI. The forward-facing LiDAR sensor is mounted on the LV light bar tilted slightly upward to sense an approaching overhead obstruction, such as a highway overcrossing, which will block GPS signals and enable the guidance system to switch from the primary GPS guidance scheme to the secondary INS guidance system.

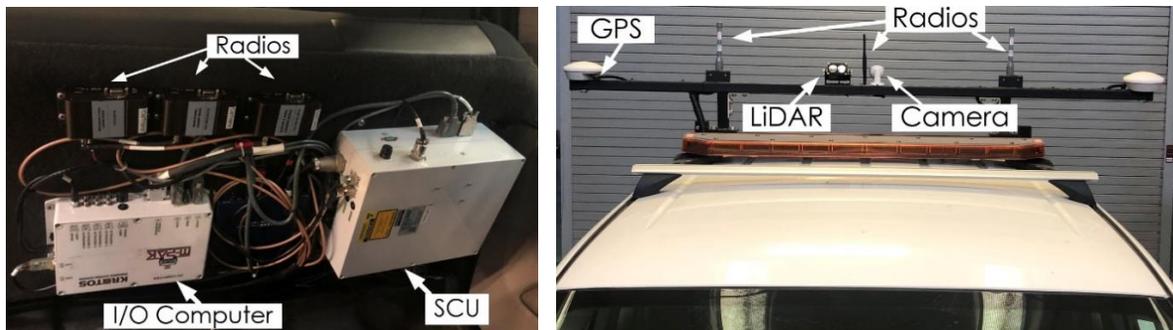


Figure 3.3: ATMA LV autonomous control components

The LV user interface components enable the operator to control the FV while in autonomous driving mode. The user interface controls are mounted

under the center and below the vehicle dashboard. This location provides direct access for either the LV driver or passenger. The LV user interface consists of a GUI, an OCU, and the E-Stop module. The primary user control for autonomous driving is the GUI program that runs on a Toughpad® computer. The GUI provides access to the roll-out procedure checklist and the status of FV autonomous control, displays error messages, provides a means to change autonomous operational parameters, and displays an LV rear-view video image of the FV. The OCU provides switches that power and engage the SCU along with indicator lights that display the status of important SCU inputs and outputs. The E-Stop module is paired wirelessly to an E-Stop module in the FV. If either of these modules' E-Stop switch is activated, or should the wireless link between the modules fail, the FV will go into E-Stop shutdown mode.



Figure 3.4: ATMA LV user interface controls

ATMA Follower TMA Vehicle: Kratos installed the majority of the autonomous driving control components inside a cabinet mounted between the driver and passenger seats of the FV TMA truck. The components included the I/O computer, SCU, data communication radios, FOG module, and Ethernet switch. An array of communication and monitoring components were attached to a mounting bar attached above the truck between the truck bed and cab. The components mounted on the bar included several radio antennas and a pair of GPS antennas. The radio data link provides a line-of-sight to communication link to transmit data back to the LV SCU. The GPS antennas tracks the position and orientation of the FV and transmits the position data back to the LV.



Figure 3.5: FV autonomous controller



Figure 3.6: FV antenna rack

The FV operator controls for the autonomous system are mounted under and in the center of the truck's dashboard. This location provides direct access for the FV driver. The FV operator controls simply consist of an OCU and E-Stop module. The OCU provides switches that powers and engages the SCU along with indicator lights that display the status of important SCU inputs and outputs. The E-Stop module is paired wirelessly to an E-Stop module in the LV. A radio communication system is mounted in the FV cab. There are six wireless headsets stored in a drawer under the passenger seat. There are power connections for each headset to keep them charged and ready to use. The use of headsets is critical for validation and testing, but only needed for the roll-out procedure in normal ATMA highway operations.



Figure 3.7: FV user controls



Figure 3.8: Communications headsets

The ATMA system features object detection sensors attached to the FV that automatically stop the vehicle should an obstacle be detected in the FV's path. The primary object detection sensor is a SICK® LiDAR sensor (Figure 3.9). This front-mounted LiDAR sensor has a 130-degree detection sweep, so it is capable

of detecting average-sized objects anywhere in front of the FV, but using dynamic software limits reaction only to objects that are within the E-crumb autonomous path. Below the LiDAR sensor is a radar sensor. Upgrade of the LiDAR sensor has relegated the radar sensor to a back-up object detection role.

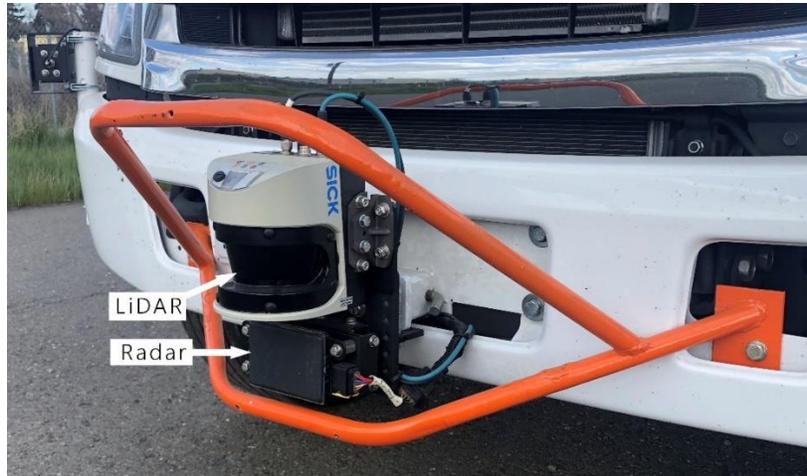


Figure 3.9: FV front LiDAR sensor with temporary bump guard

ATMA Initial Commissioning

Kratos installed the autonomous leader/follower system on the Royal TMA truck and then conducted a series of ATMA system calibration adjustments. Kratos then conducted a list of prescribed validation tests to confirm the ATMA was performing to specifications before commissioning the ATMA for Caltrans/AHMCT use in December 2019. Caltrans DOE conducted a final ATMA quality control inspection and issued an acceptance report in December 2019 (see Appendix E).

ATMA Operator Training

Kratos provided Caltrans with an ATMA Operator Training Manual (see Appendix F) and conducted ATMA autonomous system classroom operator training with a combination of Caltrans Maintenance Equipment Training Academy (META) staff, Caltrans maintenance crews, and AHMCT research personnel. The training presentation materials are presented in Appendix E. Following the classroom ATMA training, participants were given an ATMA operational quiz and certificates of successful completion were awarded. A Caltrans District 3 maintenance crew in attendance was also able to gain hours of ATMA hands-on training by operating the ATMA with Kratos engineers during many of the ATMA system commissioning trials. A Caltrans META instructor was also certified by Kratos to provide ATMA training using Kratos-supplied training materials and tests to officially train additional Caltrans operators in ATMA use.

Royal also provided Caltrans with an ATMA User Manual (see Appendix G), which focuses on the TMA truck and accessories operation.

AHMCT Temporary Testing Guards

The FV ATMA system radio link communication antenna height as provided by the manufacturer is nearly 13 ft. In the rural landscape surrounding AHMCT's Advanced Transportation Infrastructure Research Center (ATIRC) test facility, low-hanging tree limbs are common, so AHMCT installed temporary polyvinyl chloride (PVC) guards over the antennas for protection during transport (Figure 3.10). As an extra measure safety to protect against incidental contact, AHMCT fabricated a bump guard that surrounds the LiDAR and radar sensors mounted to the front of the FV (Figure 3.9). These guards were designed to attach to the ATMA without touching or disrupting the mounting of the sensors, adding holes, or making any other modifications to the FV. The sensor guard is comprised of steel tubing located out of the field of view of the sensors. The antenna guards are PVC plastic which is transparent to radio signals. Performance of the sensors and antennas was tested before and after attachment with no perceivable effect on system performance. These guards will be removed at the completion of testing at Caltrans' discretion.



Figure 3.10: Temporary radio antenna guards

Chapter 4:

ATMA Performance and Enhancement

AHMCT ATMA Evaluation Objective

The objective of this research study was for AHMCT to independently verify the safety and performance of the ATMA for Caltrans highway use to assist Caltrans with the next step of acquiring authorization to operate the ATMA on the highway.

AHMCT ATMA Test Plan and Enhancement

The ATMA as originally received from Kratos was not perfectly suited for Caltrans use. AHMCT worked with Kratos engineers throughout this research study to improve autonomous driving performance to be suitable for Caltrans use. Kratos engineered upgrades to the ATMA guidance system, vehicle safety systems, and system capabilities. These upgrades augmented autonomous driving reliability, vehicle safety, and functionality. The upgrades were a combination of software and hardware changes, and after each system upgrade, Kratos engineers conducted a prescribed series of ATMA system validation tests to ensure the ATMA was fully functional and safe to operate. AHMCT partnered with Kratos in conducting these validation tests, which served to broaden both user training and testing plan development. AHMCT utilized this experience to devise and refine a Caltrans-specific ATMA test plan.

The AHMCT test plan included many of the Kratos validation tests and created specific, new tests that evaluated the Caltrans highway moving lane closure operation application. The result was a series of ATMA test scenarios that were divided into safety and performance categories. The safety test scenario trials evaluated ATMA control in a variety of common system and operator functions, along with operational failure mode analysis, to ensure that the FV always remained safely under the control of the LV when in autonomous driving mode. The performance test trials evaluated the ATMA in autonomous driving mode in relation to guidance performance and how the ATMA would need to perform in a Caltrans highway moving closure maintenance operation, such as paint striping or sweeping.

The AHMCT ATMA safety and performance testing results described in the following sections of this report present only the current state of the ATMA after several Kratos system upgrades. A detailed description of the many steps of AHMCT ATMA testing and Kratos upgrades is presented in Appendix F.



Figure 4.1: The Caltrans ATMA performance testing system

Royal Technology Package

Royal built the TMA truck that served as the base for the autonomous guidance system. This TMA truck was purchased with an integrated Royal Technology Package which contains many innovative TMA safety features. None of these features are associated with the autonomous operation and therefore, were not within the scope of the AHMCT autonomous performance study. Consequently, Caltrans elected to transfer the evaluation and development of the Royal TMA Technology Package equipment features to a parallel but separate research project. Therefore, information related specifically to the performance of the Royal TMA Technology Package can be found in the separate Caltrans DRISI TMA Accessories research report.

AHMCT ATMA Testing Practices

AHMCT followed a strict set of testing safety practices while operating the ATMA in autonomous driving mode. The foremost of these practices was to always station a safety rider in the FV while driving in autonomous mode. Both the LV driver and the FV safety rider had to be in direct communication over the radio headset link while driving in autonomous mode. AHMCT performed ATMA testing away from traffic on a series of test sites.

AHMCT ATMA Test Sites

AHMCT identified an array of available test sites appropriate for conducting all of the ATMA test scenarios. A detailed description of each of the ATMA test sites can be found in Appendix F. Following an initial testing at the Old Davis Road test site, Caltrans requested that all subsequent AHMCT ATMA testing be restricted to closed test sites until the legal aspects of operating a heavy truck in autonomous mode could be resolved within the State of California. This policy change primarily affected the overcrossing test scenario, eliminating the Old

Davis overcrossing testing from further use. As a replacement, Caltrans twice closed a section of highway on State Route (SR) 905 that contained a suitable overcrossing for AHMCT to conduct the overcrossing validation test scenario.

AHMCT ATMA Operational Safety Test Results

The first series of ATMA test scenarios established that the safety rider in the ATMA can always regain control of the FV should it become necessary during performance trials and operation. The focus of the safety scenarios was to explore failure modes, errant hazards, and operator errors that could potentially occur during normal ATMA operation with Caltrans operators in highway operations. The test scenarios also sought to explore if any type of system failure while under autonomous driving control could ever result in the FV driving out of control or being set adrift.

Safety Test Scenario 1S – Recoverability of FV Control by a Safety Rider

While activated, the autonomous controller mechanically pulled on the FV accelerator pedal to maintain the commanded vehicle speed. Should the safety rider try to override autonomous control to stop the FV by pressing on the air brake pedal, the FV brakes, but the autonomous controller responds by increasing engine speed in an attempt to keep the vehicle moving. Therefore, ideally, the safety rider should exit autonomous driving mode before engaging the vehicle brake. An operational mode switch on the FV OCU toggles between [Idle] for manual mode and [Go] for autonomous driving mode. While driving under autonomous control, the safety rider, whenever possible, should first switch to idle mode before taking control of the vehicle driving controls. This scenario sought to quantify the time delay necessary for the FV safety rider to engage the Idle switch to and stop the FV vehicle in a simulated emergency event. Additionally, the test appraised the accessibility to the relatively small Idle switch on the OCU, which is the first task the safety driver must perform to take control the FV.

Procedure

The ATMA vehicles were placed in follower mode driving at a safe speed in a straight line. The LV driver randomly announced a “stop” command to the safety driver over the radio intercom and began a timer. The safety rider in the FV upon receiving the signal took control of the FV by switching the OCU to idle mode and pressing the brake to stop the vehicle as quickly as was reasonably possible. When the FV came to a complete stop, the safety rider announced “stopped” over the radio intercom and the time interval was recorded. Then the FV OCU was switched back to Go mode, and the FV should continue driving

autonomously. A subsequent roll-out procedure should not be required. This scenario was repeated five times for statistical accuracy.

Result

These trials were conducted with the FV safety driver deliberately, mentally distracting themselves to replicate an actual emergency situation. The reacting time between issuing a random “stop” command and the FV coming to a complete stop was measured to be 3.8 sec, 2.5 sec, 3.3 sec, 1.9 sec, and 2.5 sec, which averages to a 2.8-sec reaction time. The FV safety driver commented that the size and location of the Idle switch is not easily accessible for a quick response, but this is not necessarily a problem that needs to be mitigated because for normal ATMA operations a safety rider would not be in the FV. This test was only performed for the benefit of confirming ATMA safety during scenario testing.

Safety Test Scenario 2S – Pause Mode Operation

There is a Pause button on the LV GUI that suspends autonomous driving and applies the FV air brake when pressed. The autonomous driving mode link remains active in a similar manner as an A-Stop. While the FV is paused, the LV can continue driving and creating an E-crumbs trail. When the “Clear A-Stop” button is pressed on the LV GUI, the FV brake is released and the LV resumes driving along the E-crumbs path. The FV will then travel at a speed slightly faster than that of the LV to slowly return to the specified gap distance. This scenario assessed the performance of the pause mode and quantified the time delay necessary to stop the FV.

Procedure

The ATMA vehicles were placed in follower mode driving at a safe speed. The safety rider in the FV randomly announced “pause” over the radio intercom to the LV driver and began a timer. The LV driver responded by pressing the Pause button on the GUI to pause the motion of the FV. When the FV came to a complete stop, the safety rider announced “stopped” over the radio intercom and the time delay was recorded. The LV driver then released the A-Stop switch and pressed the Clear A-Stop button on the GUI to resume lead/follower driving. The LV continued driving to verify that autonomous driving mode resumed. The scenario was repeated two times each with the LV stopped during the pause while vehicles were in a line, in a curve with the LV stopped during the pause, and in a curve with the LV increasing the vehicle gap distance.

Result

Pressing the Pause button on the GUI consistently brought the FV to a complete stop in about one second. The LV could continue driving during the pause without any effect other than increasing the gap distance. The

autonomous driving mode link remained active and pressing the “Clear A-Stop” button on the GUI enabled autonomous driving to resume in about a second irrespective of the gap distance or straightness of the path. The FV only moved while the LV was moving regardless of the gap distance. The size and placement of the Pause button on the GUI makes it far more difficult to locate and press during operation than the A-Stop mushroom switch which produces the same result. Therefore, the usefulness of this feature during normal operation is unclear.

Safety Test Scenario 3S – A-Stop Operation

The ATMA A-Stop functions in the same manner as the Pause state described in detail in the 2S scenario. The A-Stop switch is maintained when pressed. The LV can continue driving forward during a maintained A-Stop state, increasing the gap distance. To clear an A-Stop state and return to autonomous driving, the A-Stop switch must be physically reset and the “Clear A-Stop” button pressed on the GUI. The LV must continue driving for the FV to begin moving to follow. This scenario evaluated the time delay required to stop the FV.

Procedure

The ATMA vehicles were placed in follower mode driving at a safe speed. The FV safety rider randomly announced “A-Stop” over the radio intercom to the LV driver and began a timer. The LV driver responded by pressing the A-Stop switch on the OCU to stop the FV motion. When the FV came to a complete stop, the safety rider announced “stopped” over the radio intercom and the time delay was recorded. The LV driver then released the A-Stop switch and pressed the “Clear A-Stop” button on the GUI. The LV continued driving to verify that the autonomous driving link was maintained. The scenario was repeated two times each with the LV stopping when the A-Stop was initiated, two times with the vehicle gap increased during an A-Stop in a straight line, and two times with the vehicle gap distance increased in a curve during the A-Stop.

Result

Pressing the A-Stop button on the GUI while driving in autonomous mode at a safe speed consistently brought the FV to a complete stop in about 2 seconds regardless of vehicle orientation or gap distance. The LV can continue driving during the A-Stop state, increasing the gap distance with no noticeable effect on resuming autonomous driving. Upon resetting the A-Stop switch and pressing the “Clear A-Stop” button on the GUI, autonomous driving resumed in about a second irrespective of the gap distance. The A-Stop switch is easy to see and access quickly, so it is the preferred method of pausing autonomous driving when necessary.

Safety Test Scenario 4S – Emergency Stop Operation

This test scenario evaluated the effectiveness of the E-Stop switch in the LV. Since the ATMA system is designed to only operate at speeds below 15 mph, vehicle dynamics are not as important a factor as the speed of the servo motor to pull on the brake cable. The braking servo speed is constant and not proportional to actual vehicle speed. Consequently, the measure of E-Stop FV stopping distance can be measured by time delay at a single vehicle speed, which is safe for the FV safety rider to be repeatedly subjected to during trials.

Procedure

Safety test Scenario 4S was conducted on the ATIRC closed test track. The ATMA vehicles were placed in follower mode driving at a safe speed. The FV safety rider announced “stop” over the intercom and began a timer. The LV driver upon hearing the “stop” message instantly pressed the E-Stop switch. When the FV came to a complete stop, the safety rider responded with a “stopped” message over the intercom, and the LV driver recorded the time delay between the messages. This scenario was repeated three times at both 5 mph and 10 mph while driving in straight line and around a curve and at different gap distances.

Result

The time delay results of the E-Stop trials at 5 mph were 2.5 sec, 2.5 sec, and 2.4 sec for an average of 2.5 sec. The results at the 10 mph vehicle speed were almost identical at 2.8 sec, 2.5 sec, and 2.6 sec, with an average time of 2.6 sec. The vehicle response to an E-Stop action did not perceptibly change with differences in vehicle orientation, gap distance, or vehicle speed.

AHMCT explored the recovery procedure from an E-Stop from the perspective of a Caltrans ATMA highway operation. Recovering from an E-Stop while in autonomous driving mode will require a driver to walk back to the FV to restart the engine. When the E-Stop switch is reset, the FV engine is off and the transmission is in Drive, but the parking brake is released. It is an AHMCT safety recommendation that Caltrans require the FV safety driver to take control of the FV and manually set the brake before resetting the E-Stop in the LV.

Safety Test Scenario 5S – External Vehicle Emergency Stopping

The FV also has external E-Stop switches mounted on both sides of the FV flatbed body just aft of the cab doors. In the unlikely event that a person was on foot next to the FV and needed to E-Stop the FV, they could physically trigger an E-Stop. These E-Stop switches operate in the same manner as the LV E-Stop switch explained in Scenario 4S. This safety scenario sought to verify the FV

external E-Stop switches would indeed completely stop and disable the FV while in autonomous driving mode.

Procedure

Safety test Scenario 5S was conducted on the ATIRC closed test track. The ATMA vehicles were placed in follower mode driving at a safe, slow speed in a straight line. A researcher on foot pushed the external E-Stop button on the side of the FV as it was moving past while simultaneously announcing "E-Stop" over the radio headset. The driver in the LV started a timer. When the FV came to a complete stop, the observer on foot announced "stop" over the radio and FV stopping delay time was recorded. The test was repeated twice on both the left and right sides of the FV.

Result

The pressing the E-Stop switches on the FV had the same effect of stopping the FV as was measured in safety test Scenario 4S.

Safety Test Scenario 6S – Communications Loss/Radio Link

The GPS positional data of the LV is continuously transmitted to the FV where it is combined with the FV GPS data to provide autonomous guidance control of the FV. A line-of-sight radio link establishes the communication link between the LV and FV to exchange position data and system information. There is a primary and redundant radio link between the vehicles. The ATMA controller is designed to operate with the primary radio link and if that signal is lost, to switch immediately to the secondary redundant radio link. If both are lost, the controller triggers an A-Stop, which stops the FV.

Procedure

The radio link test was conducted by covering the primary radio communication antenna and observing if the controller immediately switches to the redundant radio link and continues driving. If the radio link is lost in both radio antennas, the controller automatically triggers an A-Stop.

Result

The radio communication test scenario was tested as part of the Kratos post-upgrade validation testing with AHMCT assistance. To simulate the loss of radio communication, Kratos engineers physically disconnected the radio transmitters in the LV. First the Kratos engineer disconnected the primary radio transmitter and the ATMA controller switched immediately to the secondary radio link and continued autonomous driving without interruption. Then the secondary radio transmitter was disconnected, which triggered a communication loss error that A-Stopped the ATMA. Reconnecting either of the radio transmitters and resetting the A-Stop enabled autonomous driving mode.

AHMCT subsequently attempted to conduct the radio link loss test by simply blocking the antenna with a steel container. Simply covering the radio link antenna with an open bottom container could not cause either of the radio links to fail. This failed attempt demonstrated just how strong and robust the radio signals are. The Kratos results validated the successful completion of this test scenario.

Safety Test Scenario 7S – Obstacle Detection Mapping

The FV has a LiDAR/radar sensor mounted on the front bumper to identify obstacles in the E-crumb path. The data input of these two sensors is software-filtered to ignore detected obstacles out of the E-crumb path in front of the FV. When an obstacle is detected in the FV path, an A-Stop is triggered. The FV stops and a servo motor pulls the vehicle brake pedal. An obstacle detection message is displayed on the LV GUI tablet. The autonomous mode link remains active, so the LV driver can press the “Clear A-Stop” button on the GUI to return to autonomous driving mode. This scenario determined the size of the active object detection window in front of the FV for the case of a straight-line E-crumb path and at the Kratos recommended system minimum E-crumb curve path of a 65-ft radius. For purposes of mapping this active sensing region, a person moving around was the most practical target. The subsequent 1P test scenario tested a moving vehicle incursion between the LV and FV while under autonomous driving and was the more authentic dynamic test for actual ATMA highway operation.

Straight-line detection procedure

The ATMA vehicles were engaged in autonomous driving mode in a straight line. After roll-out was complete and a straight-line E-crumb following path was created, the LV was stopped, which caused the FV to stop with autonomous driving mode remaining active. With both vehicles stationary and brakes set, a researcher on foot moved around in front of the FV to trigger object detection that registered on the GUI in the LV as either a radar or LiDAR detection. An object detection along the E-crumb path activated a system A-Stop. The driver in the LV watched the GUI and announced to the researcher on foot when an object detection appeared. The researcher on foot then marked with chalk on the pavement where the detection occurred. The driver in the LV then pressed the Clear-A-Stop button on the GUI and the researcher was free to continue to move around and trigger additional detection locations. The collection of many object detection locations was used to create a map of the active FV object detection zone.

Straight-line detection result

The SICK LiDAR sensor has a 190-degree field of view so the FV object detection range that can detect objects from directly in front of the vehicle

bumper out to 150 ft away. Within this field of view, the ATMA is programmed with an activation region approximately 10-ft-wide centered on the FV and 100-ft-long measured from the FV front bumper (Figure 4.2). Only objects detected within the activation region will trigger an A-Stop. Neither Kratos nor AHMCT could get the radar sensor to trigger an object detection. Apparently the LiDAR detection technology has advanced far enough that the radar sensor is no longer relevant.

The Kratos ATMA controller upgrade included a dynamic maximum activation region distance that is linked to the actual gap distance between FV and LV up to 100 ft. So, for gap below 100 ft, the activation region maximum distance ends 15 ft from the back of the LV. For gaps above 100 ft, an object can be detected up to 150 ft, but these detections just trigger warning messages on the GUI similar to the side object detection warnings. Only when the object gets to within 100 ft does the object trigger an A-Stop.

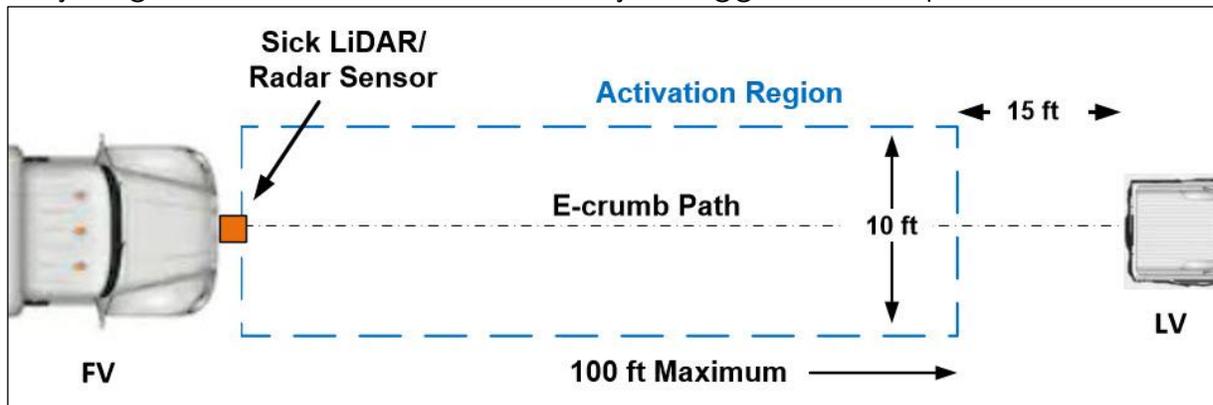


Figure 4.2: Upgraded object detection map - Straight E-crumbs path

Curved-path detection procedure

This scenario sought to engage ATMA vehicles in autonomous mode and drive the LV in a 90-degree turn with a 65-ft inside radius or an approximately 70-ft vehicle centerline turn radius. As the FV reaches the halfway point of the 90-degree turn, the LV was stopped, which also stopped the FV. With the vehicles stationary, an object detection map was created with the same procedure as the straight-line mapping.

Curved-path detection result

The ATMA object detection algorithm accounts for a curved E-crumbs path. The SICK LiDAR unit detects objects directly in front of the vehicle bumper in an 11-ft wide detection zone. The detection zone is centered on the vehicle/E-crumbs path and bends to follow the E-crumbs curved path. The maximum distance along the curve an object can be detected is approximately 50 ft along an 11-ft wide detection zone arc (Figure 4.3).

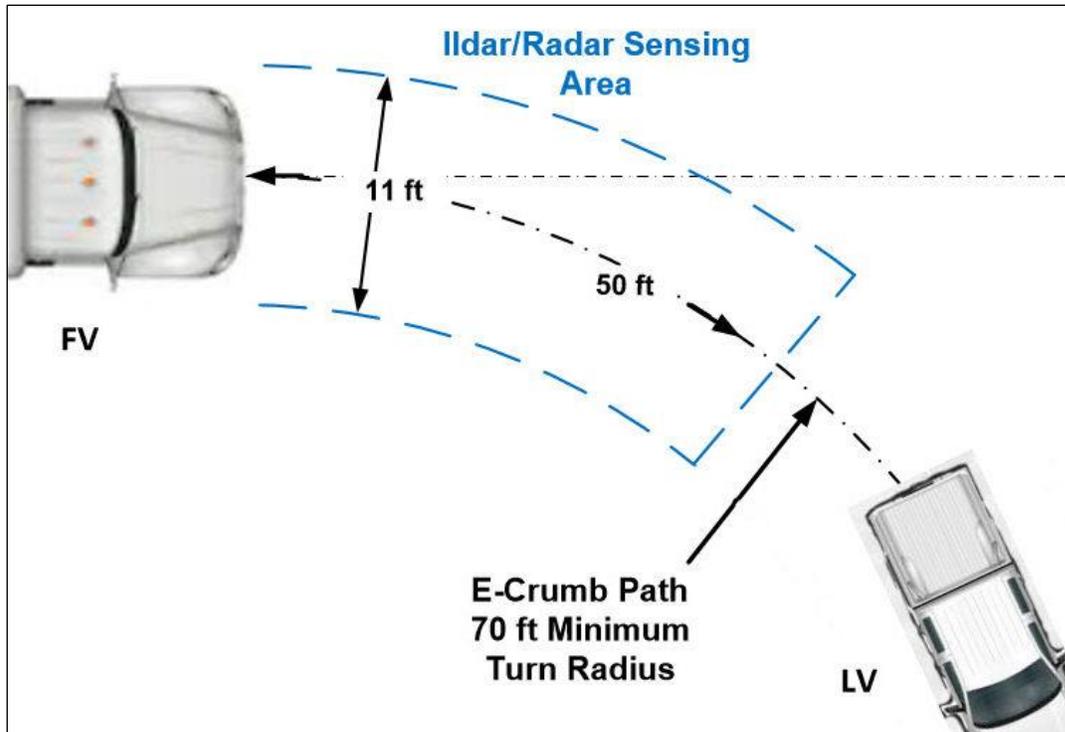


Figure 4.3: Upgraded object detection map - Curved E-crumb path

Safety Test Scenario 8S – Loss of Primary GPS Navigation Mode

GPS guidance is the primary ATMA autonomous driving mode. Two GPS antennas are mounted on the outboard sides of each vehicle to provide position and heading data. One GPS antenna provides position to the guidance controller while the second is necessary to determine vehicle heading. Should either of the GPS signals on either vehicle drop out, the guidance system is designed to switch to secondary INS guidance utilizing DR to continue driving autonomously. DR mode is intended only to provide temporary guidance. As the distance driven increases so does the navigation error, so if the GPS signal is not regained in a certain distance and time, the guidance system will automatically trigger an E-crumb error, stopping the FV. This trial sought to observe the effects of loss of GPS signal(s) while under autonomous driving and detail the recovery procedure.

Procedure

This safety test scenario was conducted with the assistance of Kratos engineers on the ATIRC closed test track. Shielding the GPS antennas while driving proved insufficient to produce a GPS signal loss. As such, AHMCT enlisted the assistance of Kratos engineers to disengage the GPS signal(s). While the ATMA vehicles were driving in autonomous mode, a Kratos engineer turned off

the GPS signal(s) using software to simulate the GPS antenna(s) being obstructed.

Result

Immediately upon terminating either of the GPS antenna signals, the ATMA guidance system switched to DR mode and continued driving. While driving in DR guidance mode, a bar graph on the GUI tracked the distance interval until an E-crumb error occurred. If the GPS signals were regained during this interval, the FV would continue driving autonomously. When the GPS signal was not regained and the DR interval ran out, an E-crumb error was triggered and the FV stopped. To recover from the E-crumb error, the OCU in the FV can be momentarily switched to Idle and back to Go to return the FV to autonomous driving mode.

Safety Test Scenario 9S – Follow Distance under LV Hard Braking

While the ATMA is in autonomous driving mode, the FV will only move while the LV is moving regardless of the gap distance. The speed of the FV will approximate that of the LV speed. Consequently, when the LV driver wants to stop FV motion in an emergency situation, the driver need only stop the LV. AHMCT named this action “hard braking” and created a test scenario to evaluate hard braking times for comparison to the ATMA A-Stop and Pause FV braking methods.

Procedure

The ATMA vehicles were engaged in autonomous driving mode in a straight line at a safe speed. The LV driver announced a “stop” command over the intercom while braking hard to stop LV motion. As the FV safety rider received the “stop” message, a timer was started. When the FV came to a complete stop, the time delay was recorded. This scenario was repeated three times for statistical accuracy.

Result

While in autonomous driving mode, the delay between when the LV brakes to when the FV fully stops was measured in four trials to be 3.8 sec, 3.3 sec, 2.6 sec, and 2.5 sec, which averaged to a 3-sec reaction delay. Therefore, braking the LV is an acceptable method of stopping the FV for the Caltrans single LV driver/operator ATMA configuration.

Safety Test Scenario 10S – Parking Brake Set Error

When engaging autonomous driving mode, the ATMA operator (safety rider) releases the FV truck air parking brake and shifts the transmission to drive before

leaving the vehicle. This scenario evaluated how the ATMA system reacts when the ATMA operator (safety rider) fails to release the FV parking brake after shifting the transmission to drive during the roll-out procedure. The autonomous controller in the LV cannot remotely release the parking brake, so the result of this potential operator error should be investigated.

Procedure

The procedure began by setting the ATMA parking brake and beginning the roll-out procedure by shifting the FV transmission to drive, but leaving the FV parking air brake set. The LV was then driven forward at a safe speed. The effect on the FV movement was observed. If a system error occurred, then a safe operator recovery procedure was established.

Result

When roll-out began with the FV parking brake set, the ATMA controller sensed the FV was not traveling at the commanded speed and increased the engine speed in an effort to accelerate the FV. Initially, the FV engine raced, but the vehicle did not move, and a system error was not triggered. In subsequent test trials, the LV was driven for a bit longer before ending the test. The FV engine raced to overcome the brake as before, but eventually the FV engine power did start to overcome the parking brake and the FV did move forward slowly. A system error was never triggered. This was not thought to be a safety concern because the FV would be moving along the E-crumb path under system control until a time when the ATMA operator would notice and stop the FV.

Safety Test Scenario 11S – Identify FV Adrift State(s)

This safety test scenario determined if any control states exist that may leave the FV free to move while not under the control of the LV. These potential adrift states could occur within and/or outside of normal operational guidelines, potential equipment faults, and actual highway impairments.

Procedure

While driving in autonomous mode with a safety rider in the FV, various autonomous mode control state changes, system faults, highway impairments, operation procedure violations, and operator errors were tried or simulated to discover any potential loss of control state of the FV during autonomous driving.

Result

None of the equipment faults, physical impairments, or operator faults AHMCT tried resulted in the FV entering an adrift state while driving in autonomous mode.

Note: A common operator mistake is not installing the FV steering fingers when going into autonomous driving mode. When this occurs, the FV will continue driving until it deviates off the E-crumb path and an E-crumb error will occur triggering an A-Stop. This lack of FV steering control while driving was not judged to be an adrift state because the FV position was under control of the ATMA guidance system and safely under control.

AHMCT ATMA Performance Test Results

The following ATMA performance test scenarios were specifically developed to evaluate how the ATMA might perform in Caltrans highway maintenance operations. Since the anticipated benefit of the ATMA is in supporting moving highway work zones, these performance test scenarios were intended to be representative of common Caltrans moving closure highway maintenance applications and maneuvers. These performance test scenarios evaluated various types of ATMA system operational error states while under autonomous driving control and describe the necessary procedures to re-establish autonomous control.

Performance Test Scenario 1P – Straight-Line Errant Vehicle Detection

Caltrans will primarily utilize the ATMA in autonomous mode in moving lane closure highway maintenance operations. For this application, the logical obstacles to be encountered are errant vehicles that unlawfully drive between the LV and FV. This scenario seeks to verify that an overtaking vehicle that cuts into the following gap between the LV and FV will be identified by the radar/LiDAR sensor package on the FV and an A-Stop is triggered, bringing the FV to a safe stop. The autonomous mode link remains active, so the LV driver can press the “Clear A-Stop” button on the GUI when the object is clear to continue autonomous driving. This scenario verified whether a moving errant vehicle is detected and the FV safely stopped.

Procedure

Autonomous driving mode was engaged at normal operating speeds between 10 and 15 mph with a 100-ft gap in a straight line. A vehicle was driven to overtake the FV and steer in into the active object detection window between the LV and FV for both parallel and crossing cases. It was observed whether the errant target vehicle was detected and if an A-Stop was triggered, stopping the FV. Multiple trials were conducted using large and small target vehicles and both parallel and crossing incursion cases.

Result

This scenario was tested at multiple test sites at different times during the project. The ATMA detected both large and small target vehicles regardless of speeds in every trial run. Once the errant vehicle was detected, an A-Stop was immediately triggered and the FV motion stopped. Once the target vehicle was clear, the A-Stop was cleared and autonomous driving mode resumed.

Performance Test Scenario 2P – Errant Vehicle Detection in a Curve

The 2P scenario was the same as the 1P scenario except the vehicle incursion occurred in a curve. The curve was at the Kratos-recommended ATMA minimum autonomous E-crumb curve radius of 65 ft.

Procedure

Autonomous driving mode was engaged at normal operating speeds between 10 and 15 mph with a 100-ft gap in a curve leaving a curved E-crumb path. Target vehicles were driven to overtake the FV and steer in into the active object detection window between the LV and FV. It was observed whether the errant target vehicle was detected and if an A-Stop was triggered, stopping the FV. Multiple trials were conducted using large and small target vehicles and both parallel and crossing incursion cases.

Result

This scenario was tested at multiple test sites at different times during the project. The ATMA detected both large and small target vehicles regardless of speeds in every trial run. Once the errant vehicle was detected, an A-Stop was immediately triggered and the FV motion stopped. Once the target vehicle was clear, the A-Stop was cleared and autonomous driving mode resumed.

Performance Test Scenario 3P – Straight-Line Guidance Accuracy

This test scenario assessed the accuracy of the ATMA system to autonomously guide the FV along the path of the LV when traveling in a straight line. The ATMA system records both LV and FV GPS position and heading data, which can be utilized to plot vehicle position graphs. How this GPS data is filtered through algorithms and how accurately this data correlates to actual positions on the pavement surface was previously untested. Therefore, this test scenario made direct measurements on the pavement as the vehicles passed fixed position measurement checkpoints. The lateral position data of the LV and FV as they passed tangent to the checkpoints were used to determine a true lateral offset accuracy value.

The test set-up consisted of six 1-meter metal rulers nailed down to the pavement in a straight line at 50-ft increments. Adjacent to each ruler, a traffic cone was placed to aid the steering of the LV driver. Together the ruler and cone constituted a measurement checkpoint. Video cameras were temporarily mounted on both the LV and FV fenders directly over the front steering axles to record the vehicle position as the measurement checkpoints were passed. Calculating the difference between the LV and FV lateral offset measurements at each checkpoint established path guidance data. The different LV and FV widths needed to be factored into each of the offset calculations. This video measurement scheme performed well within an absolute ± 5.5 -in resolution range, which is an appropriate accuracy range for Caltrans highway maintenance applications.



Figure 4.4: LV checkpoint video measurement



Figure 4.5: FV checkpoint video measurement

Procedure

A straight line of measurement checkpoints was installed on a section of the ATIRC closed test track. The ATMA vehicles began the roll-out procedure and engaged autonomous driving mode before reaching the first checkpoint. The LV driver steered the LV tangent to the line of cones without hitting them. Video cameras mounted on both vehicles recorded the lateral offset of the steer wheel of each vehicle as it passed over the measurement checkpoints. Subsequent review of the video record established the differential LV and FV lateral offset position data points utilized to quantify the ATMA system following accuracy. Upon completing the course, the ATMA vehicles switched to Idle mode to circle around to the beginning of the test course and repeat the roll-out procedure. The course was driven in the same direction for each trial. The trials were repeated three times each at 5, 10, and 15 mph to characterize how following accuracy is affected by increased vehicle speeds. The results are presented in Table 4.1.

Table 4.1: Scenario 3P data, straight-line guidance accuracy (all values in inches)

5 mph				10 mph				15 mph			
Run	LV	FV	Offset	Run	LV	FV	Offset	Run	LV	FV	Offset
Run 1				Run 1				Run 1			
CP1	32	25.5	6.5	CP1	35.5	32.5	3	CP1	25	23.5	1.5
CP2	25.5	18.5	7	CP2	23.5	20	3.5	CP2	18.5	24	-5.5
CP3	22.5	16	6.5	CP3	23	20	3	CP3	27.5	27	0.5
CP4	19.5	12	7.5	CP4	17	11.5	5.5	CP4	22	17	5
CP5	26	18.5	7.5	CP5	20	15	5	CP5	24	22	2
CP6	26.5	20	6.5	CP6	21.5	17	4.5	CP6	25	22	3
Average Offset			6.9	Average Offset			4.1	Average Offset			1.1
Run 2				Run 2				Run 2			
CP1	30	26	4	CP1	20	19	1	CP1	28	23	5
CP2	24.5	17.5	7	CP2	21	15	6	CP2	26.5	26	0.5
CP3	25	18.5	6.5	CP3	21	18	3	CP3	28	25	3
CP4	21	13.5	7.5	CP4	15	9	6	CP4	22	18.5	3.5
CP5	26	18.5	7.5	CP5	20	15	5	CP5	24.5	23.5	1
CP6	27.5	21	6.5	CP6	26.5	22	4.5	CP6	27	22.5	4.5
Average Offset			6.5	Average Offset			4.3	Average Offset			2.9
Run 3				Run 3				Run 3			
CP1	34	28.5	5.5	CP1	20.5	20.5	0	CP1	30.5	27	3.5
CP2	26	19	7	CP2	18	13.5	4.5	CP2	31.5	25	6.5
CP3	25	20	5	CP3	23	16.5	6.5	CP3	28	27	1
CP4	18	11	7	CP4	21.5	17	4.5	CP4	18.5	16	2.5
CP5	24	17.5	6.5	CP5	28	23	5	CP5	21	17	4
CP6	31	25	6	CP6	29.5	25.5	4	CP6	29.5	26	3.5
Average Offset			6.2	Average Offset			4.1	Average Offset			3.5
Combined Average Offset			6.5	Combined Average Offset			4.1	Combined Average Offset			2.5
Actual Offset			0.7	Actual Offset			1.4	Actual Offset			2.0

Taking into account that the width of the LV measured at the outside of the steering wheels, which served as the data reference point, is approximately 79 in and the width of the FV is approximately 90 in, the expected offset for perfect tracking between the LV and FV was approximately half of 11 in or 5.5 in. The average offset of the three 5 mph trials yielded 6.53 in. Therefore, the ATMA FV

steering error was consistently less than the resolution of the testing procedure and certainly within the required operational accuracy range.

Performance Test Scenario 4P – Lane Accuracy while Cornering

This test scenario appraised the accuracy of the ATMA system to autonomously guide the FV along the LV path while cornering. The minimum manufacturer recommended turn the ATMA can reliably navigate has a 65-ft radius. For the Caltrans highway work zone operational use, the ATMA will only logically need to navigate up to a 90-degree turn while in autonomous mode. Therefore, in this test scenario the ATMA vehicles were driven around a 90-degree curve at the minimum recommended turn radius while lateral position data was collected. The difference between the LV and FV lateral positional data for each measurement checkpoint was utilized to establish the ATMA following accuracy in a curve. The trials were repeated three times each at 5, 10, and 15 mph to characterize how following accuracy is affected by increased vehicle speeds.

Procedure

The procedure was similar to the 3P test scenario, but with the measurement checkpoints placed in a 90-degree sweep curve with a 65-ft radius on the ATIRC closed test track. The 90-degree curve sweep was bisected at 22.5-degree increments beginning at the start of the curve and ending with an added 50-ft straight section measurement checkpoint to observe if any curve recovery abnormalities occurred. Once again, video cameras were mounted on both vehicles to record the lateral offset of the steer wheel as it passed over the measurement checkpoints. Subsequent review of the video record established the LV and FV lateral position data points.

The ATMA vehicles were driven at a safe speed well beyond roll-out. The LV driver reached the first measurement checkpoint while driving in a straight line at the designated vehicle speed. Upon reaching the first curve measurement checkpoint, the driver began the 90-degree LV turn. During and after the turn, the designated vehicle speed was maintained. The ATMA vehicles switched to Idle mode to circle around to the beginning of the test course, repeat the roll-out procedure, and the drive the course in the same direction.

Result

Three trials each were recorded at 5, 10, and 15 mph. The lateral position data of where the LV and FV passed the measurement checkpoints is presented in Table 4.2.

Table 4.2: Scenario 4P data, lane accuracy while cornering (all values in inches)

5 mph				10 mph				15 mph			
Run	LV	FV	Offset	Run	LV	FV	Offset	Run	LV	FV	Offset
CP1	24	17.5	6.5	CP1	21	16	5	CP1	24	20.5	3.5
CP2	24	23	1	CP2	23	24	-1	CP2	19.5	25	-5.5
CP3	26	28	-2	CP3	32	35.5	-3.5	CP3	26.5	28.5	-2
CP4	23	25	-2	CP4	37	40.5	-3.5	CP4	28	31	-3
CP5	10.5	16	-5.5	CP5	24	30	-6	CP5	17	21	-4
CP6	26	21	5	CP6	26	24.5	1.5	CP6	16	16.5	-0.5
Average Offset	0.5			Average Offset	-1.3			Average Offset	-1.9		
Run	LV	FV	Offset	Run	LV	FV	Offset	Run	LV	FV	Offset
CP1	24	19	5	CP1	27	23	4	CP1	23.5	21.5	2
CP2	24	23	1	CP2	25	27.5	-2.5	CP2	15	20	-5
CP3	29	32	-3	CP3	32.5	36	-3.5	CP3	26	28	-2
CP4	24.5	28	-3.5	CP4	30.5	34.5	-4	CP4	30.5	33	-2.5
CP5	13	18	-5	CP5	28	23	5	CP5	17	21	-4
CP6	25	20	5	CP6	27.5	24.5	3	CP6	22	22	0
Average Offset	-0.1			Average Offset	0.3			Average Offset	-1.9		
Run	LV	FV	Offset	Run	LV	FV	Offset	Run	LV	FV	Offset
CP1	32.5	27	5.5	CP1	27	22.5	4.5	CP1	27.5	25	2.5
CP2	24	24	0	CP2	20	22	-2	CP2	20	24	-4
CP3	27	28.5	-1.5	CP3	23.5	26	-2.5	CP3	26	27.5	-1.5
CP4	27.5	29.5	-2	CP4	27	29.5	-2.5	CP4	30	29.5	0.5
CP5	17.5	23	-5.5	CP5	20	23.5	-3.5	CP5	23	25	-2
CP6	27	22	5	CP6	22	22	0	CP6	23.5	19.5	4
Average Offset	0.3			Average Offset	-1.0			Average Offset	-0.1		
Combined Average Offset	0.2			Combined Average Offset	-0.6			Combined Average Offset	-1.3		
Std. Deviation	4.2			Std. Deviation	3.6			Std. Deviation	2.9		

To evaluate the actual lateral offset distance of the FV in a curve, corrections for lateral vehicle off-tracking and the geometric relationship between the GPS mounting and the steering axle must be included. The off-tracking offset in a 65-ft curve is approximately 20 in for the LV and 36 in for the FV.² The vehicle off-

² Off-tracking Calculations for Trailer Combinations, Public Roads Vol. 34, No. 4, Hoy Stevens, Samuel Tignor, Pg. 93, 1966

tracking offsets combined with vehicle geometries, including the location of the GPS bar in relationship to the steering axles and the difference in vehicle widths, calculates to an approximate 1 in being added to the FV offset value to equal the lateral position of the LV.

Performance Test Scenario 5P – Slalom Course Accuracy

This scenario is similar to 3P but followed a slalom course. The slalom course measurement checkpoints were arranged longitudinally 80 ft apart and offset laterally at 12-ft spacing. The 12-ft lateral offset distance was selected to mimic a highway lane change and constrained the 80-ft longitudinal spacing in order to comply with the 65-ft minimum turn radius limitation. The trials were repeated three times each at 5 mph, 10 mph, and 15 mph to characterize how following accuracy is affected by increased vehicle speeds.

Procedure

A slalom course of five measurement checkpoints was installed on a straight section of the ATIRC closed test track. Video cameras were attached to the front driver side fenders directly over the steering axles. With the cameras recording, the aligned ATMA vehicles drove straight to complete the roll-out procedure before reaching the first measurement checkpoint. The LV driver executed the 38-degree turn necessary to navigate the slalom course, ensuring the front wheel of the LV tracked over the meter scale at each measuring checkpoint while maintaining the designated vehicle speed. Upon completing the course, both ATMA vehicles were switched to Idle mode and circled around to the beginning of the test course. The roll-out procedure was repeated for each trial and the course was driven in the same direction. The lane-following accuracy of the ATMA system was determined from the differential lateral measurements of the vehicles as they passed each of the checkpoints derived from the video logs of each trail.

Result

Three trials each were video recorded at 5, 10, and 15 mph. The lateral positional data of where the LV and FV passed the measurement checkpoints is presented in Table 4.3.

Table 4.3: Scenario 5P data, slalom course accuracy (all values in inches)

5 mph				10 mph				15 mph			
Run	LV	FV	Offset	Run	LV	FV	Offset	Run	LV	FV	Offset
Run 1				Run 1				Run 1			
CP1	17	12	5	CP1	22	21.5	0.5	CP1	18.5	20.5	-2
CP2	26.5	20	6.5	CP2	18	17	1	CP2	18	24.5	-6.5
CP3	20.5	12.5	8	CP3	22	17	5	CP3	19	16.5	2.5
CP4	27	21.5	5.5	CP4	23	22	1	CP4	17	19.5	-2.5
CP5	31.5	21.5	10	CP5	25	17	8	CP5	22.5	20.5	2
Average Offset	7.0			Average Offset	3.1			Average Offset	-1.3		
Run 2				Run 2				Run 2			
CP1	16.5	21	-4.5	CP1	22.5	23.5	-1	CP1	16	18	-2
CP2	26.5	19.5	7	CP2	21.5	22	-0.5	CP2	11	17.5	-6.5
CP3	24	15.5	8.5	CP3	20	16.5	3.5	CP3	17	17.5	-0.5
CP4	32.5	26	6.5	CP4	22.5	21	1.5	CP4	17.5	20.5	-3
CP5	32.5	24	8.5	CP5	26	22	4	CP5	18.5	16	2.5
Average Offset	5.2			Average Offset	1.5			Average Offset	1.9		
Run 3				Run 3				Run 3			
CP1	24	20	4	CP1	14	24	-10	CP1	24	27.5	-3.5
CP2	21	14.5	6.5	CP2	21	24	-3	CP2	9	18	-9
CP3	24.5	16.5	8	CP3	16.5	14	2.5	CP3	17.5	18	-0.5
CP4	24	18	6	CP4	22	22	0	CP4	18	27.5	-9.5
CP5	29	21.5	7.5	CP5	24.5	21	3.5	CP5	17.5	20	-2.5
Average Offset	6.4			Average Offset	-1.4			Average Offset	5.0		
Combined Average Offset =	5.2			Combined Average Offset =	0.9			Combined Average Offset =	-2.3		
Actual Offset =	0.3			Actual Offset =	4.6			Actual Offset =	7.78		
Std. Deviation	3.3			Std. Deviation	4.1			Std. Deviation	3.8		

Retest after Kratos Upgrade

The Kratos upgrade did not alter the ATMA guidance accuracy test results.

Performance Test Scenario 6P – Following Gap Distance Performance

The ATMA GUI displays the commanded following gap distance next to the actual gap distance. The commanded following gap distance can be selected from a list of discrete values. The ATMA following gap distance control algorithm is tuned to balance between smooth, steady, and safe FV motion, which vaguely maintains gap distance and aggressively controlling FV motion to precisely maintain gap distance. The first part of this test scenario evaluated the balance between following gap distance accuracy and FV smooth motion while driving autonomously. The second part of the following gap distance performance test evaluated the rate the ATMA can close a large gap that occurs when the following gap distance setting is reduced while autonomously driving, recovering from an A-Stop, or recovering from a Pause when the LV kept driving while the FV following motion was stopped.

Procedure

For both parts of the test scenario, the ATMA was driven around the Kratos test site in autonomous mode. The driven path was a combination of straight and curved sections, creating a large closed route. To evaluate the following gap distance capability, the ATMA was driven around the test track route with gap settings of 50, 100, and 150 ft, and observations were made of both the actual gap following distance and the smoothness of the FV motion.

To evaluate the gap closing capability, the ATMA was set at a 50-ft gap, and while driving autonomously the FV motion was paused. The LV kept driving to open up a 150-ft actual gap distance. FV motion was then resumed while the LV kept driving around the test site. The distance required to bring the FV back to the commanded following gap distance was observed.

Results

The test results for maintaining the commanded following gap distance while driving normally in autonomously produced a reasonably smooth FV motion on flat surfaces with the following gap distance deviation being maintained between approximately 0 ft and 10 ft. If the FV inertia caused the following gap distance to drop below the commanded distance, the FV brakes engaged. Holding the following gap distance on a slightly declined surface caused the FV motion to be more abrupt and jerkier. In future highway testing on steeper, declined highways, the following gap distance control parameter settings may need to be revisited.

For evaluation of closing the large gap, it took approximately 2,000 ft to close the 150-ft gap to the recommended 50-ft following gap distance. While autonomously driving, the act of selecting a shorter following gap distance in order to expedite the closing of the actual vehicle gap distance does not result in the FV speed increasing further to close the gap quicker. Kratos has limited

catch-up speed to 5 mph faster than LV speed due to associated operational safety concerns.

Performance Test Scenario 7P- Roll-Out Alignment and Gap Distance Sensitivity

The LV and FV must be in alignment to initiate a successful roll-out procedure, which is necessary to enter autonomous mode. This scenario quantified the alignment accuracy necessary to successfully enter autonomous mode. The scenario also determined if gap distance affects alignment accuracy.

Procedure

The centerline of the FV was chalked on the pavement as a reference. The LV was aligned with the chalk reference line and roll-out procedures were conducted at varying lateral offsets. The roll-out procedure began by driving the LV in a straight line. It was observed if the roll-out procedure was successful and the FV followed or failed with an E-crumb error. This scenario was repeated until the limits of roll-out misalignment could be fully evaluated.

Results

Several roll-out procedures were conducted with the LV offset from the FV chalked centerline with the vehicles remaining parallel. The largest misalignment that resulted in a successful roll-out procedure was an approximately 4-ft lateral offset (Figure 4.6). Trials with the vehicles parallel at larger gap distances and with the vehicle at an angle did not seem to change the offset result. At roll-out, the vehicles were separated. As the LV began roll-out, it started an E-crumb path. When the gap distance was exceeded, the FV began driving in a straight DR path. When the FV reached the E-crumb path, the guidance switched from DR to E-crumb path. If the offset to guide the FV onto the E-crumb path was too big for the FV to safely maneuver, an E-crumb error was triggered.

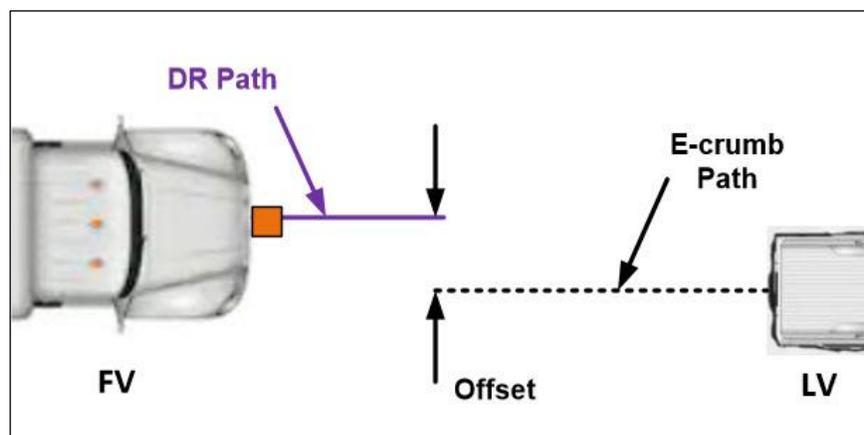


Figure 4.6: Roll-out alignment sensitivity

Performance Test Scenario 8P – E-Crumb Error and Recovery Operation

The ATMA leader/follower guidance scheme relies on a trail of E-crumb to autonomously guide the FV along the path taken by the LV. Occasionally the E-crumb trail is lost or disrupted, which triggers an E-crumb system error. The ATMA system responds to the E-crumb error by stopping the FV and terminating the autonomous driving link. This error usually occurs when there is a misalignment between the E-crumb path and the FV position such that FV steering cannot reasonably correct for the misalignment. The misalignment could have resulted from driving the LV in a very tight curve or conducting a roll-out procedure when the vehicles are not aligned. Under normal operating conditions, it would be unusual for an E-crumb error to occur in Caltrans ATMA work zone operations when conducting normal steering maneuvers. This scenario sought to establish a steering guideline and determine a safe E-crumb error recovery procedure should it occur on the highway from the shoulder. Ideally, the ATMA controller power would be cycled and restarted after an E-crumb error, but the time to accomplish a complete ATMA controller reset would translate into an additional five to ten minutes of delay on the side of the highway adjacent to high-speed traffic. Therefore, the ability to recover from an E-crumb error and resume autonomous driving without restarting the ATMA controller was evaluated for reliability.

Procedure

To cause an E-crumb error for the purposes of this test scenario, the LV and FV were purposely misaligned during the roll-out procedure. Once an E-crumb error was triggered, the procedure to clear the error and return to autonomous driving was observed.

Result

The ATMA recovery/reset procedure from an E-crumb error was as simple as toggling the operational mode switch on the LV OCU from Go to Idle and back to Go again. This procedure reset the error and made the ATMA ready for a roll-out procedure to start a new E-crumb path and enter autonomous driving mode.

Performance Test Scenario 9P – Autonomous Driving Acceleration/Deceleration

This scenario was intended to verify that the ATMA autonomous driving mode is not adversely affected by higher acceleration or deceleration of the LV. Once autonomous driving mode was activated, the LV was accelerated as quickly as possible to a constant speed of 20 mph in a straight line. It was observed if any adverse behaviors occurred.

Procedure

The ATMA was engaged in autonomous driving mode in a straight line. The LV driver accelerated to 20 mph as quickly as possible driving in a straight line and observing the response of the FV. Then, while driving at 20 mph, the LV was decelerated to a stop as quickly as safely possible, and the response of the FV was observed. The trials were conducted with a 75-ft gap and were repeated three times for consistency.

Result

This test scenario was conducted three times, and the autonomous driving performance was not noticeably affected by excessive acceleration or decelerations. It was observed that the FV's greater truck weight and momentum caused abrupt, but safe, FV response motions.

Performance Test Scenario 10P – Back-Up Error Evaluation

While the FV is driven in autonomous mode, the manufacturer recommends that the LV not travel in reverse. When operating in traffic on the highway, sometimes chaotic events occur and the ATMA LV may be driven in reverse for short distances either by accident, deliberately to negotiate traffic, and/or to mitigate a work-related issue. Given the likelihood that a reverse incident could occur on the highway during ATMA autonomous operation, this scenario sought to determine the operational repercussions of driving the LV in reverse while in autonomous driving mode.

Procedure

The ATMA was engaged in autonomous driving mode. The LV was stopped, which in turn stopped the FV. The LV transmission was switched into reverse and the LV was driven in reverse. ATMA controller response was observed, and the safe procedure to recover from an ATMA reverse error state and resume autonomous driving mode was determined. This scenario was repeated three times to establish consistency.

Result

As the LV began to reverse direction while in autonomous mode, the gap distance displayed on the GUI continued to increase for a few feet while the FV continued driving forward. After a few feet of travel, an E-crumb error was triggered and the FV stopped. The LV stopped, and the E-crumb error was cleared by switching the LV OCU switch from Go to Idle and back to Go to clear the error and continue autonomous driving with the incorrect, larger gap distance. As autonomous driving continued, the gap distance seemed to slowly converge back to the correct value. Based on these trials, it appears that, should the LV be driven in reverse while in autonomous driving mode, the ATMA

system does not result in a FV drift state. An indirect danger may occur should the reverse motion trigger a system error that cancels the autonomous driving link while operating in a highway moving lane closure in live traffic. The vacant FV would be stopped and require a driver to access the FV to conduct a subsequent roll-out procedure to continue driving.

Results

The ATMA autonomous controller identified each time the LV was driven in reverse and immediately triggered an E-crumb error stopping the FV. To recover the ATMA from a reverse error, the operational mode switch on the LV OCU was toggled from Go to Idle and back to Go again. This procedure reset the error and made the ATMA ready for a roll out procedure to start a new E-crumb path and enter autonomous driving mode.

Performance Test Scenario 11P – ATMA Driving under a Highway Overcrossing

Kratos designed the ATMA to account for interruptions in their primary GPS guidance scheme such as would occur when passing under a highway overcrossing, structure, or other obstruction. When GPS signal loss occurs, the ATMA controller automatically switches to a secondary INS guidance scheme that utilizes a combination of accelerometers and gyros to continuously calculate vehicle motion by DR. Autonomous driving continues in DR mode until GPS guidance can be re-established.

Autonomous driving under a highway overcrossing is a common occurrence for the ATMA, so a special procedure has been developed by Kratos to mitigate these incidents. A LiDAR sensor has been attached to the roof of the LV to specifically identify when the LV is about to pass under an overcrossing (overhead obstruction) to switch to DR guidance. Small innate errors in DR vehicle guidance increase over time and distance traveled, so Kratos placed a reasonable safety limit on the time and distance the ATMA can travel in DR mode before triggering an E-crumb error. As the LV clears the overcrossing and re-acquires a stable GPS signal, it begins to create an E-crumb path. When the FV reaches the beginning of this E-crumb path, the FV guidance control switches from the current DR position to the starting point of the E-crumb path and continues following the LV autonomously. This scenario evaluated the guidance when passing under a highway overcrossing by driving the ATMA under an actual highway overcrossing structure.

Procedure

Caltrans identified a suitable overcrossing test site on SR 905 in the Otay Mesa area. The ATMA was driven autonomously under the Caliente Avenue overcrossing repeatedly in both directions and in different traffic lanes. The ATMA was observed as the navigation GPS antennas were obstructed by the

overcrossing structure and ATMA guidance switched into DR mode. Once clear of the overpass and GPS lock was re-established, the ATMA guidance switched back to GPS guidance mode. Twelve trial passes were conducted at speeds of 10 to 15 mph. Half of the trials were conducted with the vehicle gap set at 150 ft and the other half at 100 ft. Video was captured of all the trials.

Result

The ATMA was driven autonomously under Caliente Avenue highway overcrossing a dozen times in both directions and in multiple lanes. In all of the test runs, the FV continued to smoothly follow the E-crumb path at the commanded gap distance as the guidance system switched to DR guidance mode and back to GPS mode once clear of the structure. The FV motion can be paused while under the overcrossing in DR mode and resumed, but the FV cannot stay under the overcrossing for a prolonged period, because the INS error continues to increase even while the FV is stopped and eventually an E-crumb error will be automatically triggered. An E-crumb error cannot be cleared from under the overcrossing. Both ATMA vehicles must be clear of the overcrossing or any other GPS obstructions in order to perform a roll-out procedure and restart autonomous driving mode.



Figure 4.7: Caltrans Otoy Mesa SR 905 overcrossing test site

Performance Test Scenario 12P – Shoulder Autonomous Driving

Caltrans will operate the ATMA on the highway, which is often initiated and ended on the highway shoulder. This scenario determined if a sloped dirt shoulder affects the roll-out procedure and stable steering of the FV.

Procedure

A roll-out procedure was conducted with both the LV and FV aligned on a sloped shoulder with their right-side wheels on dirt. The LV accelerated at the

fastest, safest rate while jogging the steering to bring the vehicle fully onto the pavement, simulating taking a traffic lane on the highway. Whether the FV could successfully complete the roll-out procedure, stay in stable control while driving up on the flat roadway, and continue autonomous driving was observed. This scenario was repeated three times for statistical accuracy at a 10 to 15 mph LV driving speed.

Result

This test scenario was conducted on the shoulder of the ATIRC test track, which has a 10- to 15-degree down slope consisting of dirt and loose gravel similar to a typical highway shoulder. The test was conducted three times, and each time the FV accelerated smoothly and steered up on the roadway while maintaining autonomous driving mode. The FV appeared to follow the E-crumb path without deviation or hesitation in every trial run.

Performance Test Scenario 13P – High-Speed ATMA Operation

As a safety precaution, Kratos limited the ATMA FV maximum driving speed to 20 mph while in autonomous driving mode. This test scenario was intended to determine if the ATMA operates safely when the LV is driven faster than 20 mph as might occur in a highway operation.

Procedure

The ATMA was engaged in autonomous driving mode in a straight line. The LV speed was increased to 30 mph, and the reaction of the FV was observed. The 30-mph test was repeated three times followed by two trial runs at a speed of 40 mph.

Result

The FV drove following the E-crumb path at the maximum speed of 20 mph. The speed difference resulted in increasing the vehicle gap but did not appear to otherwise interfere with the autonomous performance.

Performance Test Scenario 14P – Taking-the-Lane Maneuver

The Kratos upgrade package included the new functionality of FV offset. This scenario sought to mimic a typical Caltrans taking-the-lane maneuver where the vehicles comprising the maintenance operation line up on the highway shoulder and then successively steer out into the traffic lane. TMA trucks are specifically designed to act as a shield for less protected maintenance vehicles. Therefore, the TMA truck is always the first vehicle to steer out into the live traffic to establish the work zone. This is called “taking the lane.” Since the original ATMA system could only directly follow the LV E-crumb path, the unprotected LV

had to take the lane first and remain unshielded for the length of the current gap distance. The new offset function could enable the LV to drive down the shoulder and by selecting an offset value on the LV OCU, subsequently steer the FV with its TMA out into the lane first. This test scenario experimented with the offset function and determined if a safe taking-the-lane procedure can be established.

Procedure

Both vehicles were aligned in a straight line simulating a highway shoulder. A roll-out procedure was conducted. Upon completing the roll-out procedure, but before the LV started moving, the lateral offset function became active. A full lane offset was selected on the LV OCU, then the LV started driving straight down the shoulder. The FV followed and began to steer out into the adjacent lane at the selected lateral offset distance. Once the FV was established in the adjacent traffic lane, the LV was steered out into the adjacent lane while simultaneously reducing the commanded lateral offset distance. The goal was to maintain the FV in the traffic lane providing TMA protection for the LV while the LV was steered into the traffic lane. The trial was conducted three times while observing the steering of the FV during the taking-the-lane maneuver.

The scenario was then repeated three times in reverse, simulating leaving the traffic lane and returning to the shoulder.

Result after Kratos upgrade

In three trials, the LV driver was able to steer straight along the edge of the test track and gradually increase the FV lateral offset to simulate the FV taking an adjacent lane first. The LV driver then steered out into the lane while simultaneously decreasing the FV commanded offset distance to keep the FV centered in the lane as the LV came into line. Additional testing would need to be conducted on a larger test track or highway to further evaluate the full performance potential of this feature.

Performance Test Scenario 15P – ATMA FV Impact Safety Shutdown

The ATMA FV contains an accelerometer sensor system capable of detecting vehicle impacts. When an FV impact occurs, the SCU is programmed to set the FV brake and turn off the engine. A sensor input from the FV truck camera monitoring system is also set to store a video clip of the impact event.

Procedure

The ATMA vehicles were engaged in autonomous driving mode in a straight line. After roll-out was complete, the LV was stopped, which caused the FV to stop while the autonomous driving mode remained active. With both vehicles stationary, a chain was connected to the rear of the FV and to a separate pull

truck. Starting with slack in the chain, the pull truck drove at a safe speed, and when the slack was taken-up, the chain created a high-impulse tug on the FV. The reaction of the ATMA system to the impact was observed.

Result after Kratos upgrade

The test was conducted three times with a magnitude of impulse great enough to jerk the safety rider's head safely, but the ATMA did not trigger a system shut-down. The ATMA remained in active autonomous driving mode following all impact testing. When Kratos was consulted, they said that the magnitude of impact was set at approximately 20 g to avoid system false triggering such as hitting large potholes. Simulating a 20 g magnitude impact for testing purposes alone was deemed too dangerous to attempt to replicate.

Chapter 5:

Conclusions and Recommendations

ATMA Evaluation Conclusions

The Caltrans DRISI ATMA evaluation project was initially intended to focus primarily on autonomous vehicle operating and testing scenarios. However, the Royal/Kratos ATMA as originally delivered was found not to be suitable for Caltrans use due to safety and performance issues revealed early in testing. Consequently, the AHMCT evaluation project scope was amended to include promoting ATMA development and expanding autonomous system capabilities. AHMCT worked with Kratos on a series of ATMA enhancements that increased reliability and operational safety and tailored the original generic use ATMA to be compatible with Caltrans highway maintenance procedures and safety practices. The result of the ATMA enhancement process and collaboration is an autonomous shadow truck system that is robust, practical, easy to use, and establishes a remarkable new level of TMA driver safety protection.

AHMCT created an ATMA safety and performance test plan that ensured that the final enhanced Caltrans ATMA could be safely and effectively operated by Caltrans Maintenance crews in actual moving lane closure highway maintenance operations, such as paint striping or sweeping. The ATMA will enable the Caltrans shadow truck driver in these moving closure operations to operate the TMA from the relative safety of the protected work truck and not be left exposed to physical harm should the TMA be impacted by another vehicle on the highway. The ATMA leader/follower autonomous driving scheme was determined to be the simplest scheme to operate a shadow truck autonomously in a moving lane closure operation. In a leader/follower scheme while in autonomous driving mode, the FV operator serves only a passive supervisory role. Other popular competing autonomous driving schemes, such as remote control and self-driving autonomous schemes, are complicated, expensive, and generally less practical for a shadow truck application.

The Caltrans ATMA, after several Kratos upgrades and enhancements, successfully completed all of the safety and performance test scenarios AHMCT could envision while limited to closed test track evaluation. The next logical phase in ATMA evaluation is Caltrans deployment trials to determine how well the ATMA fits into a Caltrans maintenance operations from the perspectives of both functionality and operator training.

Issues that May Affect Full Implementation

The Caltrans ATMA was configured with the leader vehicle autonomous controller installed in a standard pick-up truck. Standard pick-up truck seating is designed to have the driver and front passengers seated facing forward. So, while operating autonomously, the person in charge of monitoring the FV is facing forward in the front passenger seat and does not have a direct line of sight view of the motion of the FV. The FV monitor must either view the FV in the small video window on the GUI (Figure 5.1) or twist their body almost 180 degrees while seated to look backwards (Figure 5.2). Neither method provides a clear view or is conducive to the continuous monitoring of the FV while in motion. For AHMCT testing purposes, the current LV configuration was ideal. It enabled AHMCT to operate the ATMA safely with the LV driver also acting as the ATMA operator due to the fact that a safety rider was always stationed in the FV to monitor motion safety. But in a few instances where AHMCT was conducting ATMA demonstrations with the FV operator in the LV and there was no safety rider in the FV, the visibility problem became a major concern. AHMCT views this LV seating and visibility problem to be the only major safety issue that could hinder the Caltrans effort to deploy the ATMA in moving closure highway maintenance operations in the near future.



Figure 5.1: GUI Rear view image



Figure 5.2: ATMA operator in LV

Therefore, AHMCT recommends that a different LV passenger/monitor configuration that provides better visibility be considered for the purpose of Caltrans deployment. The simplest reconfiguration may be to change the seating in the LV to add a 180-degree swivel passenger bucket seat (Figure 5.3) and keep the rear seat in the LV cab folded up. Switching to a swivel LV passenger seat will enable the passenger to face forward during normal driving and the FV operator to face towards the rear during autonomous operation, providing a direct line of sight of the FV movements. The ATMA autonomous

controls would also need to be relocated to the rear or made to swivel with the passenger seat.



Figure 5.3: ATMA LV seating modification

ATMA Evaluation Recommendations

AHMCT has spent hundreds of hours operating the ATMA autonomously on closed test tracks and is confident that the current state of the Caltrans ATMA is ready to begin highway deployment trials. Caltrans will need to obtain special authorization to operate a heavy duty truck autonomously on the highway. The Caltrans ATMA operational authorization effort may benefit from a two-stage approach similar to the standard research equipment deployment process that AHMCT has been utilizing for many years. In this process, a first round of field trials are conducted with AHMCT operational and training participation in partnership with Caltrans maintenance crews in regularly scheduled Caltrans maintenance operations. This is followed by full Caltrans deployment with AHMCT support if needed. The ATMA authorization process can follow a similar process where the first phase of autonomous highway driving authorization is limited to a safety rider stationed in the FV with AHMCT operational and training support as needed. ATMA highway deployment may reveal new autonomous driving challenges not exposed by the AHMCT test plan and also reduces the Caltrans pioneering risk of gaining heavy truck autonomous authorization. Only after successfully completing the initial field testing trials and proving that the ATMA can be operated safely and effectively in a Caltrans highway maintenance operation should Caltrans seek authorization to operate the ATMA without an FV safety rider. This two-step autonomous vehicle authorization and deployment process provides the dual benefit of lower risks for all involved and enhanced prospects for a successful deployment outcome.

The key opportunity for Caltrans to demonstrate the full safety benefit of the ATMA is with field operations on mainline highway moving closure maintenance operations in live high-speed traffic. These operations expose Caltrans TMA

drivers to the greatest risk of high-energy impacts. Once autonomous ATMA highway driving authorization is granted, with or without a safety rider restriction, AHMCT recommends Caltrans Maintenance identify a suitable crew and actual scheduled highway maintenance operations that AHMCT can partner with to support and participate in the initial field deployment trials. AHMCT recommends that the initial ATMA field deployments be limited to highway sweeper operations. AHMCT views paint striping operations to be more complex based on the striping process itself and the added safety resources involved. In comparison, sweeping is a simpler task and involves fewer safety resources, making it the best first choice to conduct ATMA deployment trials. Upon the successful conclusion of a brief AHMCT-supported field trial period, AHMCT recommends that the ATMA be transferred to the Caltrans fleet and assigned to Caltrans Division of Maintenance to continue agency-supported ATMA field trials and/or deployment.

Appendix A: Original Specification and Quote for Caltrans Assessment of Autonomous Truck-Mounted Attenuator System

Quotation

Phone: 610-282-4090 Fax: 610-282-8986

AAAQ34951

Quotation Prepared For:



Sacramento, CA 95816

California Department of
Transportation 12/08/17
Thai Van Nguyen Division of
Equipment
3400 R Street, PO Box 160D48

Fred

Vehicle Information

Stock #
Year:
Make:

Model:
VIN:

Invoice #

Date

Sales Rep.

Phone: 916-227-9610

Qty Description

Caltrans ATMA Turnkey System with Leader Vehicle Kit and training -----
----- \$ 350,800.00

1 All autonomous components for both the leader and follower vehicles including installation, and one week's training as stated below.

A brand new 2019 Hino TMA vehicle (Specs attached) will be delivered by Royal to Caltrans. Royal will transport the newly built ATMA to customer test facility to support 1 week (on-site Monday departing Saturday) on-site; general ATMA operator training and test/demonstration of ATMA following customer provided traffic control vehicle (Leader) on closed test road/track. Additionally, a brand new Leader kit will provided and installed on a customer provided vehicle at the customer facility. Two MSI engineers will be onsite supporting the effort during the 1 week duration.

1- week of on-site operation of the new ATMA with MSI support will include:

- Demonstration preparation coordinated with customer
- Operation at speeds from 5 to 15 mph in non-GPS denied environment
- Several miles of Leader-Follower operation with Safety Rider onboard Follower Vehicle who can take over manual control at any time.
- Demonstration of E-Stop Capability
- Wireless from Leader Vehicle
 - From inside Follower Vehicle
 - From Follower Vehicle External Switches
- Demonstration of Obstacle Detection
- Demonstration of high accuracy Following to +/- 6in or better relative to Leader vehicle using cones
- Vehicle Gap: customer defined in range of 50ft - 150ft (fixed)
- Turn Radius: 100ft
- Hand's-On training of customer operators ensuring flawless system deployment -Additional demonstrations desires can be negotiated

The brand new Follower Kit installed creating the new ATMA includes:

- Actuators for Steering, Braking, Acceleration, and E-Stop - Vehicle Control Module w/ integrated precision RTK GPS
- Operator Control Panel
- 3 vehicle -external E-Stops
- Obstacle Detection Radar
- Transmission Controller
- Impact Detection Capability
- Antenna Kit (datalink, GPS, RF Cables)

The brand new Leader Kit will include:

- Vehicle Control Module w/ integrated precision RTK GPS
- Operator Control Panel
- Independent wireless E-Stop System
- Antenna Kit (datalink, GPS, RF Cables)

NOTE: This is dependent upon using the same version of Hino truck as used in CDOT (no mounting bracketry changes are included).

ATMA (FOLLOWER VEHICLE) CAB AND CHASSIS

2019 Hino 338, Hino Diesel Engine, 260 HP, Allison Automatic Transmission, Spring Suspension, Air Brake, GVWR De-Rate 25,950, CAB COLOR WHITE, A/C, Power Locks, Power Steering, Power Windows, Radio See Attached Hino 338 Specifications (2019).

WARRANTY 7 YEAR 150,000 MILE WARRANTY OR 5 YEAR 250,000 (Customer Choice) See Hinowatch/Warranty Documentation

3 Year 24/7 Unlimited Mileage Hinowatch Roadside Assistance - See Hinowatch/Warranty Documentation

DPF Extended After treatment System - See Hinowatch/Warranty Documentation

NOTE - Variation of chassis not approved by Royal and partners may incur significant additional cost to modify autonomous mechanical components.

Provide fire extinguisher, reflector kit, and federal inspection.

1 Royal TMA Package includes:

Body

- Engineer Designed HD Custom Built Steel Flatbed Body (15' or 18') with 54" Bulkhead and LED Marker Lights

- Royal Custom Engineered Center Compartments with Concrete Ballast Installed to achieve a minimum 20,000 lb GVWR of Completed Truck and Properly Balance Axles (Meeting Attenuator Manufacturer's Recommendations and Requirements of NCHRP Report 350).
- Painted Black with Non-Skid on Deck.
- Install Flatbed Body and Lighting Connections
- Install Weathertight Electrical Junction Box & Backup Safety Alarm

Lighting

- Install Two (2) Low-Profile (Amber) Strobes to Corners of Bulkhead & (2) Rear-Mounted (Amber) Strobe Lights- Install Eight (8) LED Work Lights. Two (2) mounted to bulkhead facing body. Six (6) Mounted along underside of body to illuminate work area around body. - Wire all lights to OEM Switch on Dashboard.

Attenuator

- Install New Scorpion 100kph (62 mph) Truck Mounted Attenuator, hydraulic motor cylinders & supports, and in-cab controls
- Scorpion Unit is compliant with new MASH requirements
- TMA Unit Installation includes Mounting Plate, and Hard Wiring Unit From Battery with Fuse & Power Switch.

Variable Message Board

- Install New Variable Message Board (VMS) on Vertical Telescopic Mount (Hydraulically Raised & Lowered), Solar Panel Charging System with dedicated Battery, and Cab-Mounted Control.

Body Components

- Man-Buckets - Install Two (2) 60" Wide Body-Mounted Cone/Man Buckets with Steps, Lids, Props & Sliding Safety Rails
- Racks - Install Custom Fabricated 36" High Removable Racks, Powder coated Yellow

Safety Components

- 7" LCD monitor with audio and 3 video inputs, 600TVL Sony camera with audio and 18 IR illumination IP69K rated, 600TVL Hi-Res Sony camera with audio 28IR illumination, with cables - 1 year warranty. Install Rear-Facing Camera, and Monitor to TMA Truck. ** Sign Holder w/Posts

Certification

Professional Engineer Certificate

- Engineering Certification of minimum requirements for operation in the State of New Jersey

- Certification of compliance with strictest standards within continental United States (New Jersey) 1 Royal's Technology Package (Generation 2)

**Royal's Mobile Safety System (UPGRADE from standard backup camera system - already included) - 4 Channel "Black Box" Recording System, Includes "Customized And Proprietary" DVR Recording System with SSD Storage, (3) Additional 600TVL Hi-Res Sony cameras with audio and 28IR illumination, cables, and installation - 2 year warranty.

Camera Placement:

- (Backup Camera) - Non Recorded
- (Top of Arrow Board Facing Body)
- Top of Arrow Board facing rear
- In-Cab - Forward Facing
- In-Cab - Driver Facing

**Royal's Radar & Messaging System - 36" x 60" Full Matrix Dynamic Message System (.8 ppi)

- Equipped with Radar and Driver Feedback
- Radar System provides input for speed overlay on DVR recording
- Full programmable dynamic messages with alpha numeric characters and graphics (arrows, chevrons, etc.) customizable with BitMap editor.
- Onboard GPS to determine truck speed allowing for proper driver feedback to approaching vehicle behind truck.- Sealed electronic assemblies designed to withstand truck and road vibration, along with protection against deicer and other harsh road chemicals and contaminants.
- Comes housed in powder coated enclosure with clear polycarbonate face
- Mounting to truck directly below rear VMS Board when raised- 3 Year Warranty

SIGN CAGE

4' x 8' Secured storage sign cage, made to drop into existing rack pockets of TMA body - powder-coated - BLACK & YELLOW.

- Sign cage equipped with shelving.
- Mounted directly next to bulkhead.

TMA shall be equipped with enclosed sign cage; designed to restrain any contents from becoming projectiles in the event of an impact. Cage will be

equipped with lockable double doors to be mounted on both street and curb side of truck. Cage will be bolted to the rear body deck and stake pockets, covering the full width of the body and fit under folded attenuator and be capable of storing standard 4' x 8' highway construction signs. Doors will be powder coated Yellow for enhanced durability and visibility, with the remainder of the cage powder coated black.

COMMUNICATIONS SYSTEM

Royal's Headset Communications System - Specifications provided - (5) Sonetics APX377 headsets and charging accessories.

- (1) Sonetics SON150 base station - Installed and tied to black box recording system.
- (1) Extended range antenna.

Audio from Comms tied into DVR Black Box and recorded on customer selected channel.

System can be linked to a cell network, radio, or other communications system via variable channel selection.

1 RIG MASTER SMART DIESEL GENERATOR

Kohler Diesel Engine, 2 Cylinder, Tier 4 Final 10.5 hp @ 2400 RPM, Fuel Consumption (avg.) 0.13 gallons/hour, Alternator 12V DC, 170 AMP, Total System Weight 300 lb, Dimensions: 20" W x 25" H, 26" D, Auto Start Feature for Low Battery, Stretch Fit Flex Serpentine 6 Rib Belt, Glow Plugs for Cold Weather Starting, Electric Start, Installation Hardware (frame grabbers/fuel hose/battery cables/bolts), Diamond Plate Aluminum APU Cover, RigMaster Unit Warranty is 1 year/2,000 hours, which covers all the RigMaster Components. Kohler Engine Warranty 3 years/2,000 hours.

- 1 Transportation of ATMA: Royal will provide transportation from the point of installation of Autonomous components to Caltrans location at a rate of \$2.75 per mile. This will support the cost of drivers, fuel, airfare, hotel and meal costs to deliver the ATMA vehicle to the California DOT location.

All Components will comply with California State Approved Product List.

Customer: Royal Truck and Equipment Quote Name: 2019 Hino 338 Derate
 Dealership: TransEdge Truck Center - Quote Id: 86426
 Allentown 83720
 Prepared By: Jonathan Hausman



Quotation Details

Quote Information	
Quote Name	2019 Hino 338 Derate
Expiration Date	12/20/2017
Model	2019 Hino 338
Transmission	Auto - Allison 2500RDS w/Syn Fluids (PTO). w/ FuelSense
Wheelbase	271.0

Standard Options

Qty	Order Code	Description
1	ENGINE	Engine - HINO J08E-VB Turbo charged and intercooled with glow plugs, 6 cylinder, In-line water-cooled; Max Output 260hp @2500rpm; Max Torque 660lb.ft. @ 1500rpm; 7.68L displacement, EPA10 Emissions Certified.
1	INSIGHTSTD	INSIGHT hardware. 1 year telematics. 5 years remote diagnostics.
1	BLHZASTD	Engine block heater (1000W / 120ACV)
1	OIL	Oil Capacity - 16.15 quarts
1	EXHBRAKE	Exhaust Brake - Driver controlled w/steering column Stalk Switch
1	FUELFILT	Fuel Filter - Davco 243 Diesel Pro Heated fuel/water separator. (Diesel Pro 243)
1	ALT	Alternator - Delco 12 volt 130 amp Brush Type
1	BATTERY	Battery - Two 12 volt parallel connection, 600 CCA x 2. GR31
1	STARTER	Starter - Denso 12 volt 4.8 kW / 6.4 HP rating
1	RADIO	Radio - AM/FM with single CD, bluetooth, two speakers.
1	AIRCOND	Air Conditioning - Denso Cab AC System designed specifically for Hino - Refrigerant 134A
1	DISPLAY	Meter Cluster - Information display: Instant and trip fuel consumption, Diesel Particulate Reduction System performance/status, maintenance intervals, engine and vehicle diagnostics.
1	GAUGES	Gauges - Speedometer mph (km/h), odometer, fuel/DEF gauges, coolant temp gauge, engine tachometer, air pressure gauge.
1	FTGRILL	Grille - Chrome plated
1	HORN	Horn - Electric Dual Horn
1	HEAT/DEF	Heater/Defroster - 18,357 BTU/h
1	LAMPS	Lighting - Marker lamps, stop/tail lights, back-up lights, side-flasher lights.
1	MISC	Cab Features - Standard: Cruise control, power steering with tilt and telescopic steering column, cup holders, cigarette lighter, coat hook, bag hook, two overhead compartments, two door pockets, sun visors, side mirrors (1 flat, 1 convex) each side.

11/20/17

1

Customer: Royal Truck and Equipment Quote Name: 2019 Hino 338 Derate
 Dealership: TransEdge Truck Center - Quote Id: 86426
 Allentown 83720
 Prepared By: Jonathan Hausman



Standard Options

Qty	Order Code	Description
1	SEATS	Seats - Vinyl driver seat adjustable reclining, with AIR suspension and two person passenger bench seat. Three point seatbelt for driver and outer passenger, two point seatbelt for center position.
1	INDICATORS	Warning Indicators - Oil pressure, brake pressure, coolant level, battery charge, high beam, turn signal, parking brake, engine control system and ABS.
1	FREIGHT	Equalized Freight Charge
1	COOLSYS	Cooling Capacity - 7.075 gallon cooling system capacity
1	WARRANTY_05	Warranty - Basic Vehicle-24 months unlimited mileage; Engine-36 months unlimited mileage; Engine-60 month Extended Coverage, 250,000 miles (includes injectors, fuel supply pump and turbo); Emission-60 months 100,000 miles; Frame Rails & Cross Members-48 months unlimited mileage; Cab-48 months unlimited mileage; ABS-24-36 months 300,000 miles.
1	HWATCH_05	Hino Watch Roadside Assistance - 3-year unlimited roadside assistance including lockout, *out of fuel/DEF, battery jumpstart, information, and warranty towing (2 year coverage). *Fluids are customer pay responsibility. Tire Service - assist customer in arranging for roadside tire service if requested
1	GVWR	GVWR - Gross Vehicle Weight Rating - 25,950 lbs.
1	AIRTANK	Air Tank - Two 34 liter tanks (68L total),(15cfm@1250rpm)
1	BRAKES	Brakes - Full air dual circuit "S" cam type, leading and trailing shoes with automatic adjustment and Antilock Brake System (ABS). Front Brakes: 15.0" diameter x 4.0" x 0.73" thickness: Rear Brakes: 16.5" x 7.0" x 0.85".
1	AIRDRYER	Air Dryer - Bendix -AD-IS (Air Dryer Integrated Solution) heated air dryer.
1	FRAME	Frame - Straight C Channel frame, ladder type, powder coated, 34" wide, yield strength 80,000 PSI, resistance bending moment (RBM) 1,280,800 in./lbs. (one side no reinforcement).
1	WHEELS	Wheels - Accuride powder coated 22.5" x 8.25" 10-stud disc.
1	TIRES	Front tires - Bridgestone 11R 22.5 R268 Rib pattern; Rear tires - Bridgestone 11R 22.5 M726EL Lug pattern.
1	AXLES	Front Axle - Meritor MFS12, 12,000 lb. capacity, Reverse Elliot "I" beam with oil lubricated hubs. Rear Axle - Meritor MS21-14X, 21,000 lb. capacity, full-floating single reduction hypoid gearing.
1	SPRINGS	Front Spring: Tapered leaf springs with shock absorbers, 12,000 lb. rating; Rear Spring: Semi-elliptical main, 21,000 lb. rating.
1	AXLESTD	Rear Axle Ratio - Standard 5.57

Premium/Upgrade Options

Qty	Order Code	Description
1	338-19V	271" WB / 203.6" CA

Customer: Royal Truck and Equipment
 Dealership: TransEdge Truck Center - Allentown 83720

Quote Name: 2019 Hino 338 Derate
 Quote Id: 86426



Prepared By: Jonathan Hausman

Premium/Upgrade Options

Qty	Order Code	Description
1	HBGRDS25	Auto - Allison 2500RDS w/Syn Fluids (PTO). w/ FuelSense
1	Z01DIF	Differential Oil – Synthetic Oil for Rear Differential Road Ranger FE 75W-90
1	PWDL	Power Windows & Power Door Locks.
1	MRRH	Side mirrors - power heated mirrors.
1	PDI	PDI at Factory.
1	STD90X1	Single 90 gallon aluminum fuel tank
1	DRTVT	VIN Tag DeRate Rt 25,950, Axle10/21
1	PAINT CAB/HOOD/BUMPER TO MATCH PENNDOT	PAINT CAB/HOOD/BUMPER TO MATCH PENNDOT
1	HINO OPTIONAL EXTENDED ENG WARR 7 YEARS/150K MILES	HINO EXTENDED ENG WARR 7 YEARS/150K MILES
1	DELIVER TO SHOEMAKERSVILLE LOCATION	DELIVER TO SHOEMAKERSVILLE LOCATION
1	No_SalesTax	No Sales Tax
Sales Tax		
Unit Quantity		1

Appendix B: Final Specification and Quote for AHMCT Procurement of Autonomous Truck-Mounted Attenuator System



Phone: 610-282-4090
 Fax: 610-282-8986

Quotation

AAAQ38460 Quotation Prepared For:

University California, Davis 01/09/19
 Ty Lasky
 Dept. Mechanical & Aerospace Engineering One Shields Ave.
 Davis, CA 95616-5294

Phone: 530-752-6366

Model:
VIN:

Vehicle Information

Stock # 6720
Year: 2019
Make: Hino

338 Fred

5PVNV8JV6K4S59152 **672**

Date
Sales Rep.

0

Qty	Description	Unit Price	Ext. Price
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Caltrans Autonomous TMA Turn-key System with Leader Vehicle Kit and Training.
 \$205,000.00 \$205,000.00

Specification documents number ATMA-042-181T and ATMA-042-181A are incorporated into this quote by reference and are attached. Upgrade to the ATMA NextGen System as described in Appendix A, Performance Specification attached. All autonomous components for both the leader and follower vehicles including installation, and one week's training as stated below.

Royal Truck & Equipment will build an Autonomous Truck Mounted Attenuator (ATMA) truck on a Hino 338 and will install a ATMA Leader Kit on a similar Caltrans vehicle to complete the leader/follower autonomous system. Royal/Kratos will support one week (onsite Monday departing Saturday) general operator training and test/demonstration of the ATMA following the customer provided traffic control vehicle (Leader) on a closed test road/track. Kratos will be on site supporting the effort during this one week of support. Kratos will install the leader kit in a partner's facility on Raley Blvd Sacramento during the one week time period. Caltrans may do a final inspection while the vehicles are at that facility. Royal requests that Caltrans provide a suitable test track or closed roadway for the demonstration of the ATMA system.

Prices in this quote are good for six months after delivery (acceptance).
 Royal will accept an "in-service" letter from Caltrans to begin the warranty period.

ATMA (FOLLOWER VEHICLE) CAB AND CHASSIS \$77,060.00
 \$77,060.00

2019 Hino 338, GVWR 25,999 (10,000 lb Front Axle, 21,000 lb Rear Axle), 260 HP, Diesel Engine, Allison Automatic Transmission, Spring Suspension, Mileage Not to Exceed 5,000, Cab Color - Hino WHITE, Air Conditioning, Power Locks, Power Steering, Power Windows, AM/FM Radio. Upgrade Alternator to 200 AMP, Add Third Battery (600 cca)
 WARRANTY - 7 Year/150,000 Mile Warranty Including 7 Year/150,000 Mile DPF
 Extended After treatment Warranty, 3 Year 24/7 Unlimited Mileage Hino watch Roadside Assistance
 Provide Fire Extinguisher, Reflector Kit and Federal Inspection

Royal TMA Package includes: \$42,700.00
 \$42,700.00

- Body
- Engineer Designed HD Custom Built Steel Flatbed Body 18' with Bulkhead and LED Marker Lights
 - Royal Custom Engineered Center Compartments with Concrete Ballast Installed to achieve a minimum 20,000 lb GVWR of Completed Truck and Properly Balance Axles (Meeting Attenuator Manufacturer's Recommendations and Requirements of NCHRP Report 350).
 - Painted WHITE with Non-Skid on Deck
 - Install Flatbed Body and Lighting Connections
 - Install Weathertight Electrical Junction Box & Backup Safety Alarm Lighting
 - Install Eight (8) LED Work Lights. Two (2) mounted to bulkhead facing body. Six (6) Mounted along underside of body to illuminate work area around body.
 - Wire all lights to OEM Switch on Dashboard.

- All Switches shall be clearly labeled and identified
- Attenuator (Traffix Part No. 100BC-041AD02611E2)
- Scorpion Unit is Compliant with New MASH Requirements
- 24" Fast Track
- MASH TL-3 Attenuator with Strobes that illuminate when in motion
- In Cab Controller
- Heavy Duty Jacks
- Longer Drop Jacks
- Made to Caltrans Specifications
- Installation of Scorpion Unit
- Install New Scorpion 100kph (62mph) Truck Mounted Attenuator, hydraulic motor cylinders & supports, and in-cab controls
- TMA Unit Installation includes Mounting Plate, and Hard Wiring Unit From Battery with Fuse & Power Switch (TMA Power Connector Cables Shall Be 1 AWG Wire
- Body Components
- Racks - Install Custom Fabricated 36" High Removable Racks, Powder coated - WHITE

** Sign Holder we/Posts

LED Warning Light Bar: A LED warning light bar (Ref. Whelen Engineering Company \$3,120.00 \$3,120.00

Part Number WAT8CUT or equivalent) shall be installed on a bracket, mounted on or behind the cab. The light bar shall be wired as recommended per manufacturer instructions; the controller shall be installed inside the cab, within reach of the driver seat and discussed with the purchase order contact.

(2) 1" D-Rings, 20 Ton Pintle Hook, (1) Ladder on Passenger's Side - Installation Included	\$561.92	\$561.92
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Royal's Technology Package (Generation 2)	\$16,200.00	
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**Royal's Mobile Safety System (UPGRADE from standard backup camera system already included) - 8 Channel "Black Box" Recording System, Includes "Customized And Proprietary" DVR Recording System with SSD Storage, (3) Additional 600TVL Hi-Res Sony cameras with audio and 28IR illumination, cables, and installation - 2 year warranty.

Camera Placement:

- Backup Camera - On Attenuator
- Top of Bulk Head Facing Body
- Top of Arrow Board facing rear (IP Camera)
- In-Cab - Forward Facing
- In-Cab - Driver Facing
- Left and Right Fender Bullet Cameras (2) Each Side

** (9) Total Cameras

**Royal's Radar & Messaging System - 36" x 60" Full Matrix Dynamic Message System

(.8 ppi)

- Equipped with Radar and Driver Feedback
- Full programmable dynamic messages with alpha numeric characters and graphics(arrows, chevrons, etc.) customizable with BitMap editor.
- Onboard GPS to determine truck speed allowing for proper driver feedback to approaching vehicle behind truck.
- Sealed electronic assemblies designed to withstand truck and road vibration, along with protection against deicer and other harsh road chemicals and contaminates.
- Comes housed in powder coated enclosure with clear polycarbonate face
- Mounting to truck directly below rear Arrow Board when raised
- 3 Year Warranty

Transportation of the ATMA by Truck (not driven) is estimated (firm quote not available \$16,975.00 \$16,975.00 until closer to shipment date) in two portions:

Transportation from Royal Truck and Equipment in Shoemakersville, PA to Kratos in Fort Walton Beach Florida.

Shoemakersville, PA to Ft Walton Beach, FL: \$5,130.00.

Transportation from Kratos in Fort Walton Beach FL to Kratos in Sacramento CA. Ft Walton Beach, FL to Sacramento, CA:

\$11,845.00.

Document Fee \$141.00, Dealer Fee \$38.00, Notary Fee \$5.00, 60-Day Temporary	
\$214.00	\$214.00

Registration & Tag \$30.00

SubTotal

\$361,830.92

OPTIONS:

Option 1: Additional 1-week of on-site operation of the new ATMA with Royal/Kratos \$26,553.60 \$26,553.60 support will include:

- Demonstration preparation coordinated with customer
- Operation at speeds from 5 to 15 mph in non-GPS denied environment

- Several miles of Leader-Follower operation with Safety Rider onboard Follower Vehicle wo can take over manual control at any time.
 - Demonstration of E-Stop Capability
 - Wireless from Leader Vehicle
 - From inside Follower Vehicle
 - From Follower Vehicle External Switches
 - Demonstration of Obstacle Detection
 - Demonstration of high accuracy Following to +/- 6in or better relative to Leader vehicle using cones
 - Vehicle Gap: customer defined in range of 50ft - 150fr (fixed)
 - Turn Radius: 100 ft
 - Hand's-On training of customer operators ensuring flawless system deployment
 - Additional demonstrations requests can be negotiated
- If two consecutive weeks are requested the cost would be reduced by \$5,156 for the two weeks.

Option 2: Spare Leader Kit for ATMA Leader/Follower System \$62,150.00
 \$62,150.00

Spare Leader Kit includes:

- Vehicle Control Module with integrated precision RTK GPS
- Operator Control Panel
- Independent wireless E-Stop System
- Antenna Kit (datalink, GPS, RF cables)
- Identical installation kit components (Brackets, fasteners, etc.) as initial Leader Kit.

Note: Does not include cost for engineering support or travel to install system in vehicle. Does not include installation. Installation, calibration and testing can be done during the one week of onsite support but that will cut into the time needed for training. This could be done in conjunction with Option 1 if Caltrans chooses the additional week of on-site support.

Baseline ATMA spare leader kit was priced at \$51,996 for kit only. Install not included. NextGen ATMA spare leader kit is priced at \$62,150 for kit only. Install not included.

Installation can be made by choosing Option 1 for additional week of onsite support in combination with this Option (2).

Option 3: The ATMA will be equipped with an arrow board and controller National Signal \$7,840.00
 \$7,840.00

Model Numbers: Combination of 2169872 and 2169907 on the rear of the vehicle on a driver-adjusted, vertical mount (Traffix devices 11160A or comparable) and is visible when the attenuator is lowered and the radar message board deployed.

Option 4: COMMUNICATIONS SYSTEM \$7,500.00 \$7,500.00
Royal's Headset Communications System -
Specifications Provided - (5) Sonetics APX377
headsets and charging accessories.

- (1) Sonetics SON150 base station - Installed and tied to black box recording system. - (1) Extended range antenna.
Audio from Comms tied into DVR Black Box and recorded on customer selected channel. System can be linked to a cell network, radio, or other communications system via variable channel selection.

Option 5: RIG MASTER SMART DIESEL GENERATOR \$7,400.00
\$7,400.00

Kohler Diesel Engine, 2 Cylinder, Tier 4 Final 10.5 hp @ 2400 RPM, Fuel Consumption (avg.) 0.13 gallons/hour, Alternator 12V DC, 170 AMP, Total System Weight 300 lb, Dimensions: 20" W x 25" H, 26" D, Auto Start Feature for Low Battery, Stretch Fit Flex Serpentine 6 Rib Belt, Glow Plugs for Cold Weather Starting, Electric Start, Installation Hardware (frame grabbers/fuel hose/battery cables/bolts), Diamond Plate Aluminum APU Cover, RigMaster Unit Warranty is 1 year/2,000 hours, which covers all the RigMaster Components. Kohler Engine Warranty 3 years/2,000 hours.

Option 6: Optional extension of installed Autonomous Equipment Warranty to add 2 \$12,075.00 \$12,075.00 years/30,000 miles to the existing 1 year/15,000 mile warranty _____

Job Total \$485,349.52
Sales Tax \$0.00
Total \$485,349.52

Customer Acceptance X _____ DATE _____

Appendix C:

ATMA System Procurement Line Items

#	Item
1	Caltrans Autonomous TMA turn-key system with leader vehicle kit and training
2	ATMA (FV) cab and chassis
3	Royal TMA package
4	LED warning light bar
5	1" D-rings, 20-ton pintle hook, ladder on passenger's side
6	Royal's Technology Package (Generation 2)
7	Transportation of the ATMA by truck
8	Document, Dealer, and notary fees, 60-day temp. registration & tag
9	Option 1: Additional 1-week of on-site operation of the new ATMA with Royal/Kratos support
10	Option 3: Arrow board and controller
11	Option 4: Royal's headset communications system
12	Option 5: Rig Master smart diesel generator

Appendix D

ATMA Procurement Timeline of Key Project and Procurement Events

Approximate Date	Event
12/08/17	Caltrans DOE Contacts Royal for a ATMA quote Appendix A
2/20/18	Pre-task planning meeting, including initial collaboration between DOE and AHMCT to update spec
5/1/18	Sent initial specs to Royal, requested updated quote
6/11/18	Filed ATMA truck purchase Fleet Services exemption request
7/1/18	Project work start
8/13/18	PO request submitted, including specification provided in
11/7/18	Original PO UCD496948 issued by UCD Purchasing
12/12/18	Specification revision teleconference
2/7/19	Amended PO for revised specification provided in Appendix B
6/13/19	Meeting with DMV and CHP, included Caltrans Legal
6/30/19	Royal provided memo indicating their assessment of ATMA automation is SAE Level 4
8/22/19	Met with Thai Nguyen, DOE, to inspect Chevy pickup truck, for use as LV in ATMA project
9/12/19	Delivered Chevy truck to DOE for striping, decals, and light bar, to be used as ATMA LV
9/18/19	Sent final of ATMA test plan
11/27/19	Royal provided invoice #1 (all but tech package). AHMCT approved payment for invoice #1
11/20-25/19	ATMA training and validation testing at META

11/27/19	Hino Dealer clears DOE punch list of ATMA repairs and Hino truck taken to DOE to finish installing Caltrans decals
12/2-6/19	While at DOE shop, antennas are damaged and replaced
1/10/19	Post antenna damage repair, validation testing encounter ATMA performance Issues
1/11-27/20	AHMCT, DOE and Kratos conduct testing and repair operations at META to troubleshoot operational issues
1/22/20	Radar speed sign telco
1/28/20	ATMA validation testing is successfully completed
2/5/20	Draft radar speed sign functionality needs defined
2/14/20	Demo by AHMCT to Caltrans, CHP, DMV, and California State Transportation Agency (CalSTA)
3/2/2020	Test plan updated and finalized based on Royal and Kratos demonstrations
3/16/20	UCD entered Coronavirus disease 2019 (COVID-19) shelter-in-place and remote work mode. This prohibits further testing of ATMA until further notice.
4/1/20	Revised radar speed sign functionality needs finalized. Royal and Caltrans agree on needs in teleconference. Royal proceeds work with TraffiCalm based on agreed needs.
4/15/20	Principal Investigator (PI) filed AHMCT COVID-19 Response Plan with Vice-Chancellor for Research, including request to continue ATMA testing. Request denied.
5/13/20	TMA technology package revision teleconference
5/21/20	PI filed AHMCT COVID-19 Phase 1.x proposal with Vice-Chancellor for Research, including request to continue ATMA testing
6/5/20	AHMCT COVID-19 Phase 1.x proposal approved
6/6/20	ATMA testing resumed
5/25/1	Royal delivered updated radar speed sign

10/6/21	Caltrans DOE and Maintenance approved updated radar speed sign
10/19/21	Royal provided invoice #2 (tech package)
10/19/21	Caltrans DOE approved Royal invoice #2 (tech package)
10/19/21	AHMCT PI initiated internal UCD process to pay Royal invoice #2 (tech package). Pending UCD payment for invoice #2 concludes project procurement.

Appendix E: Caltrans DOE ATMA Acceptance Inspection Report



SUPPLIER Royal Truck & Equipment, Inc.		MANUFACTURER Hino/Royal Truck
PO NUMBER UCD496948	PE NUMBER	MAINTENANCE CLASS - SPEC NUMBER ATMA - 042 – 131T
DESCRIPTION Autonomous Truck Mounted Attenuator Vehicle		
PURPOSE OF INSPECTION Pre-Delivery Follow-Up		LOCATION OF INSPECTION Headquarters Shop, Sacramento
EQUIPMENT INSPECTED BY Tom Keshishian		DATE 12/3/2019
INSPECTION REPORT E-MAILED TO CK Madeira		DATE 12/4/2019

A Pre-Delivery Follow-Up Inspection was performed on an Autonomous Vehicle, Hino VIN 5PVNV8JV6K4S59152. The following items were found to be either non-compliant, or in need of further resolution.

1. Specification Section 3 b, page 2 of 14, requires the engine comply with the CARB 5-minute Idle Rule. The vehicle provided does not comply with this rule. [This item is acceptable for the following reason: vehicle is legal to idle beyond the CARB 5-minute idle rule with Clean Idle Decal installed as is. ATMA's engine need to be running beyond the 5 minutes due to its operation. \(TVN, 12-05-2019\)](#)
2. Administrative Procedures, Section 16, page 8 of 9, requires a minimum of 3 sets of keys. Provided are 3 ignition keys, 2 accessory keys, and 1 square key. [Vendor must bring into](#)

compliance. Please deliver additional keys to: (TVN, 12-05-2019)

Caltrans, Division of Equipment
C/O: Thai Nguyen
3400 S street Sacramento, CA 95816

3. Spec. Sec. 29, page 10 of 14, requires a radar message board. The board is provided but does not work correctly. Vendor must bring into compliance. The radar speed sign turns on but it won't display the approach vehicle's speed when the ATMA is in motion. (TVN, 12-05-2019)
4. Administrative Procedures, Section 5, page 3 of 9, requires the equipment and any accessories be a product of good workmanship and be free from any defects that will affect their appearance or serviceability. The installed steering wheel controls interfere with the driver applying the accelerator and brake pedals. This item is acceptable for the following reason: Manufacturer's standard with no other manufacturer's alternative. (TVN, 12-05-2019)



Appendix F:

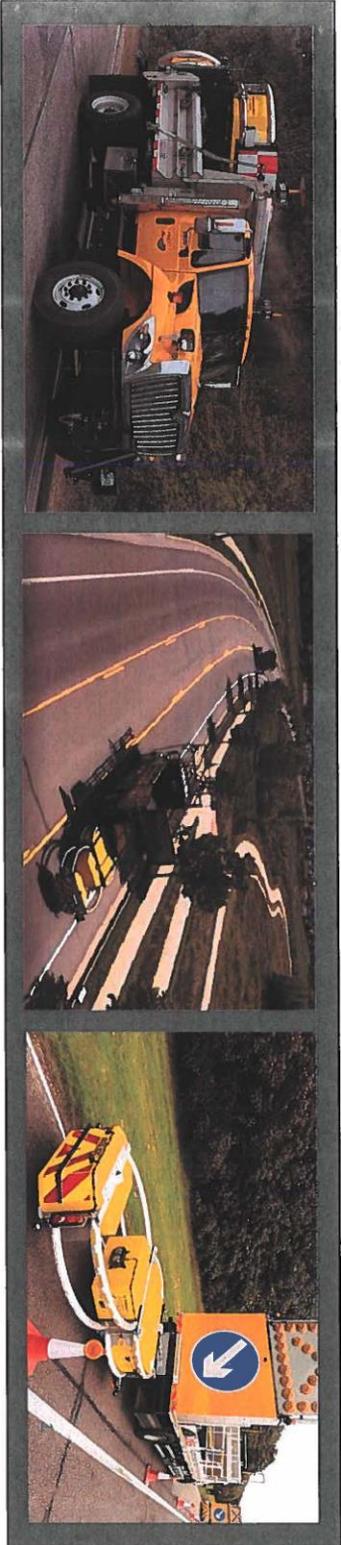
ATMA Operator Training Manual

KRYOTOS
UNMANNED SYSTEMS DIVISION

Royal
TRUCK & EQUIPMENT INC.



ATMA - AIPV Operator Training Course



Discussion Topics

- ALPV System Overview
- Leader Vehicle Component Familiarization
- ALPV Component Familiarization
- Key Operating Parameters
- ALPV Safety Information
- A-Stop and E-Stop Information
- Operating Procedure Familiarization

1



NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Hands-on Training

- Demonstration and Practice Sessions
 - Pre-Start Inspection
 - ALPV Manned Operations
 - A-Stop / E-Stop During ALPV operations
 - ALPV System Start-up and Shut-down
 - ALPV Basic Maneuvers
 - Straight line, bends, and curves
 - Cornering, U-turns, Rollout, and 360-degree turns
- ALPV Basic Troubleshooting

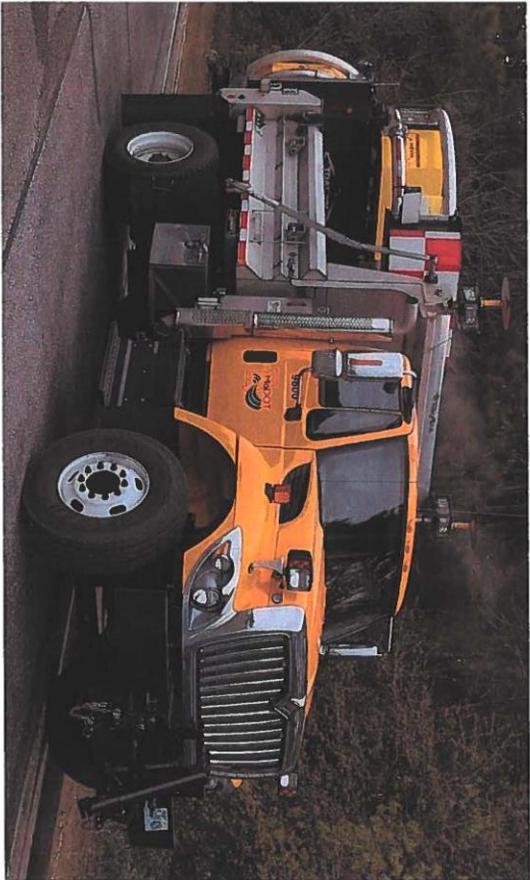


NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

System Overview

- The ALPV retrofit autonomous kit converts Impact Protection Vehicle (IPV) into a ALPV Leader / Follower system
 - ALPV system increases worker safety by eliminating the need for a human driver in an IPV
 - During operations, the ALPV follows the path of the Leader Vehicle while maintaining a user-defined, safe distance
 - Leader Vehicle and ALPV maintain constant communication with each other over two redundant Vehicle-to-Vehicle (V2V) communication links
 - **Safety Features**
 - Redundancy in object detection and V2V links
 - Rear looking camera
 - A-Stop, E-Stop, Independent E-Stop
 - Human in the Loop

Leader Vehicle Overview



4

KRATOS
UNMANNED SYSTEMS DIVISION

Royal
TRUCK & EQUIPMENT INC.

ATMA
AERIAL THERMAL IMAGING

IPV
INTEGRATED PAYMENT VEHICLE

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Leader Vehicle Components



Circled Components
are the only ones the
user has to touch



5



NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19



Leader Vehicle Components

- Battery Breaker – Powers and protects ALPV components and systems
 - Connected directly to vehicle's battery
 - Typically mounted near the battery
 - Leader Vehicle components are connected to the battery breaker
 - Design prevents accidental discharge of the vehicle's battery when not in use
 - Switch must be turned to ON position before operating ALPV system components
 - Turn switch to OFF when system is not in use
 - Do not switch to OFF while system is on GO





Leader Vehicle Components

Custom OCU Model Indicators / Controls

1 - ON Indicator	Red Light	When light is illuminated, indicates SCU is powered on.
2 - A-Stop Control	Automatic Stop	Depressing the A-Stop Control stops the AIPV. Turning the A-Stop Control clockwise causes the A-Stop Control to reset to its original position.
3 - Ready Indicator	Green Light	When light is on and not flashing, indicates SCU is completely initialized.
4 - GO Indicator	Green Light	When light is illuminated, indicates Leader Vehicle SCU is in the GO mode and starts transmitting GPS positioning and velocity data to AIPV SCU.
5 - ON / OFF Power	Toggle Switch	Used to power on or off the Leader system.
6 - GPS Lock Indicator	Green Light	When light is illuminated and not flashing, indicates that the GPS has acquired a signal to support AIPV operations.
7 - IDLE Indicator	Yellow Light	When light is illuminated, indicates Leader Vehicle SCU is in the IDLE mode; sends a status message to AIPV SCU that it is in the IDLE mode.
8 - GO / IDLE Control	Toggle Switch	Placing SCU in the GO mode transitions AIPV system into AIPV operations; placing AIPV SCU in IDLE position releases steering, brake, and accelerator controls to the operator.



7 **KRATOS**
UNMANNED SYSTEMS DIVISION

Royal
TRUCK & EQUIPMENT INC.

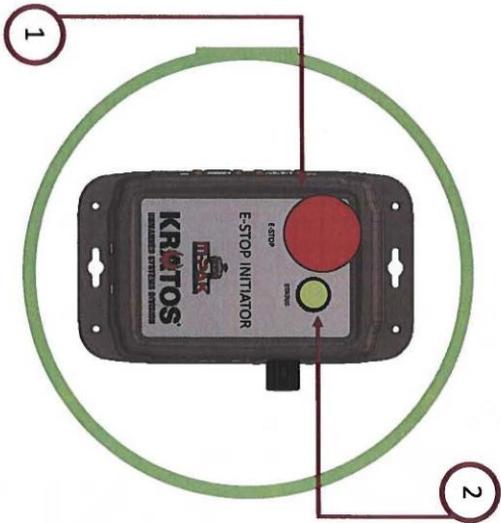
ATMA
AERIAL TARGETING SYSTEMS

AIPV
AUGMENTED INTELLIGENCE PLATFORM VEHICLE

NASDAQ: KTOS
DEFENSE & SECURITY SOLUTIONS
REVISION DATE: 26/9/19

Leader Vehicle Components

Independent E-Stop Indicators / Controls		
1 - E-Stop Control	Emergency Stop	Depressing the E-Stop Control stops the APV and kills the APV engine. Turning the E-Stop Control clockwise causes the E-Stop Control to reset to its original position.
2 - Status Light	Green / Red Light	When green light is illuminated, indicates that system is ON and operational. When red light is illuminated, that means an Emergency Stop was initiated and is active.



Hands On Section

- Break for On Truck review:
 - Battery Breaker location and operation
 - Leader OCU location and operation

9

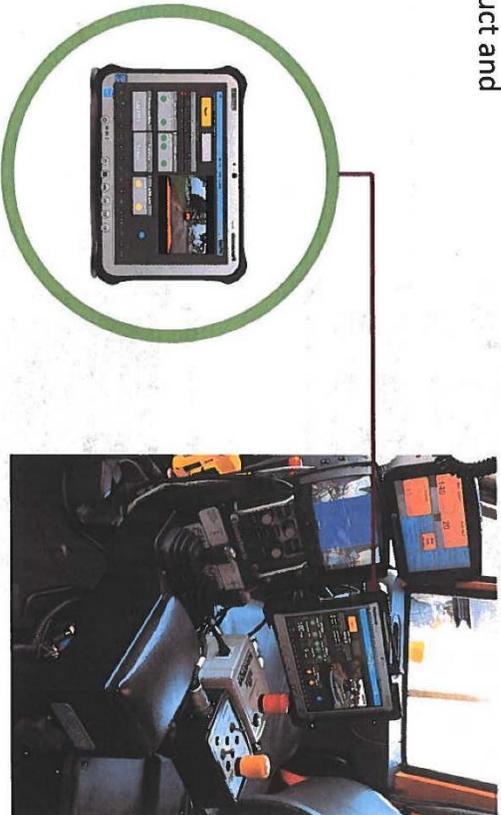


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Leader Vehicle Components

- User Interface – Enables user to conduct and monitor ALPV operations
- Must be installed / powered to start ALPV operations
- Enables Gap Control
- Displays system warnings and cautions
- Provides user with video feed for Leader rear looking camera



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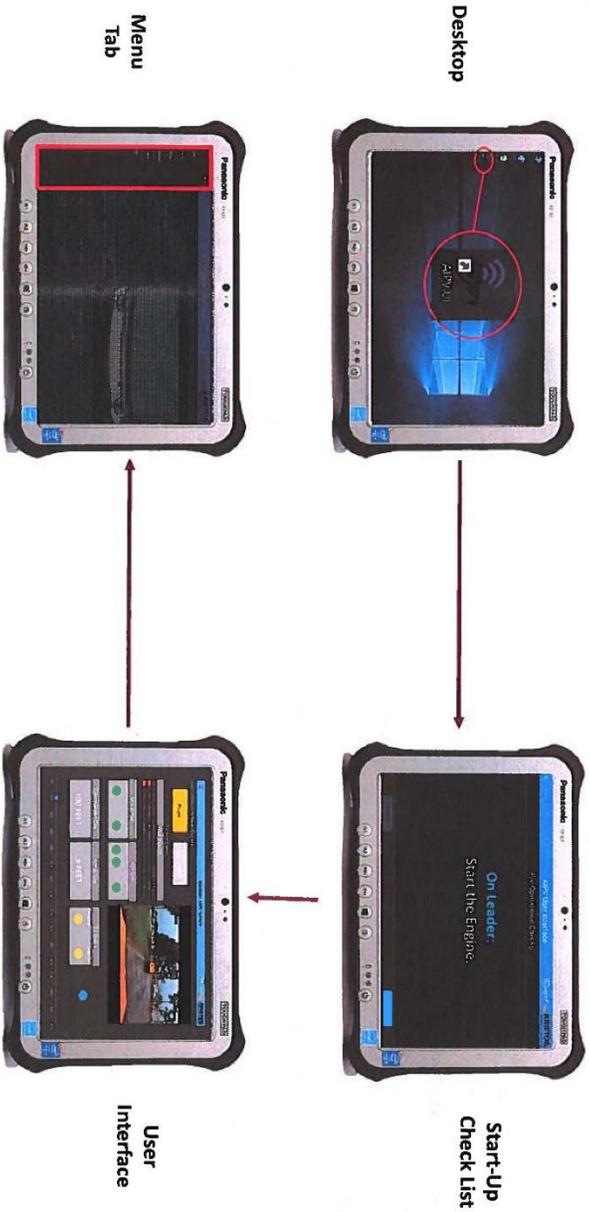
Royal
TRUCK & EQUIPMENT INC.

ATMA
AERIAL TARGETING AND MAPPING APPLICATIONS

ALPV
AERIAL LAUNCH AND RECOVERY SYSTEM

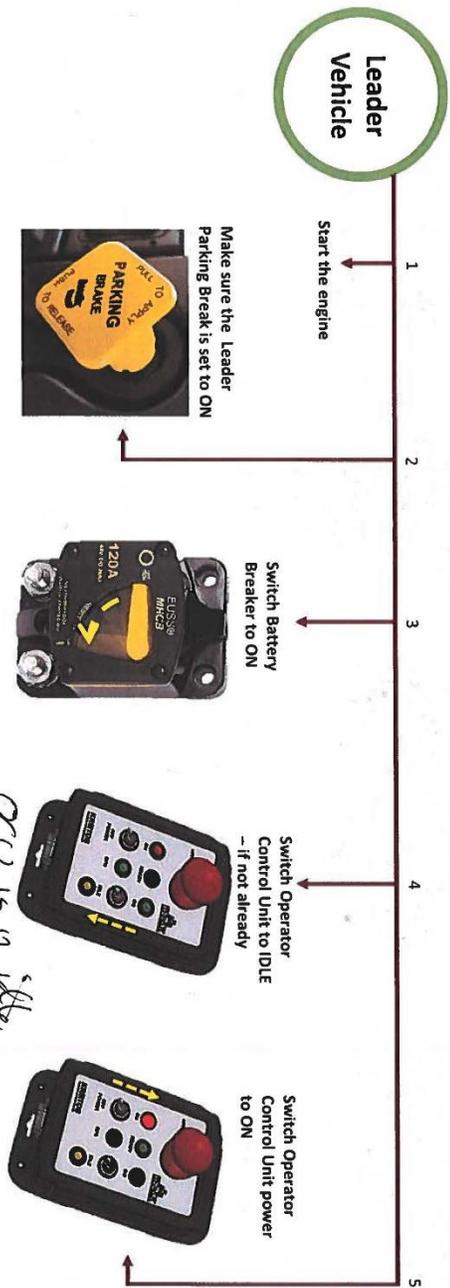
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User Interface



User Interface – Check List

- User Interface Checklist gives the user a detailed procedure of how to start ALPV operations
 - System will not be able to operate until the checklist is complete



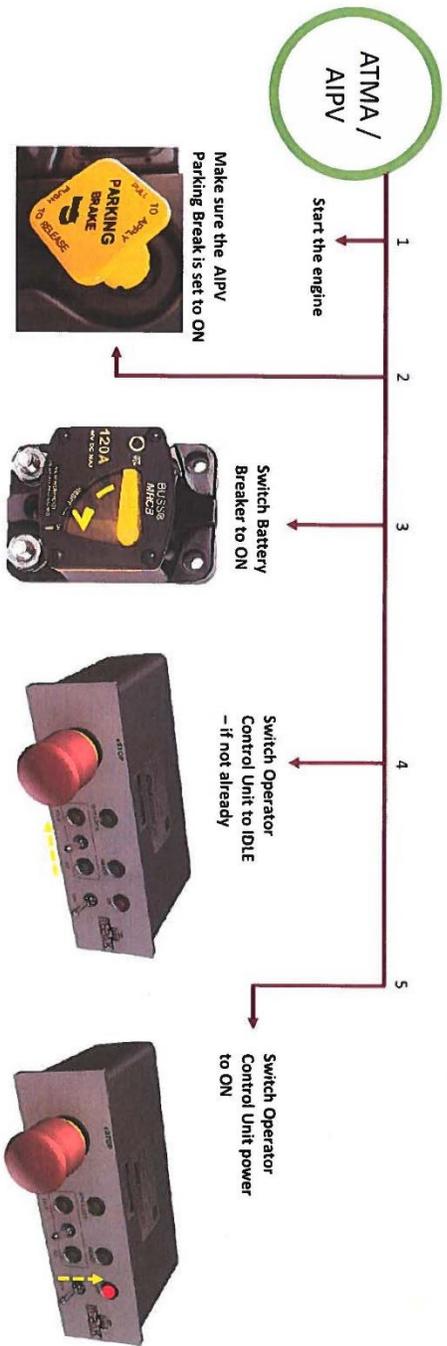
OCU is in the before starting

12



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User Interface – Check List

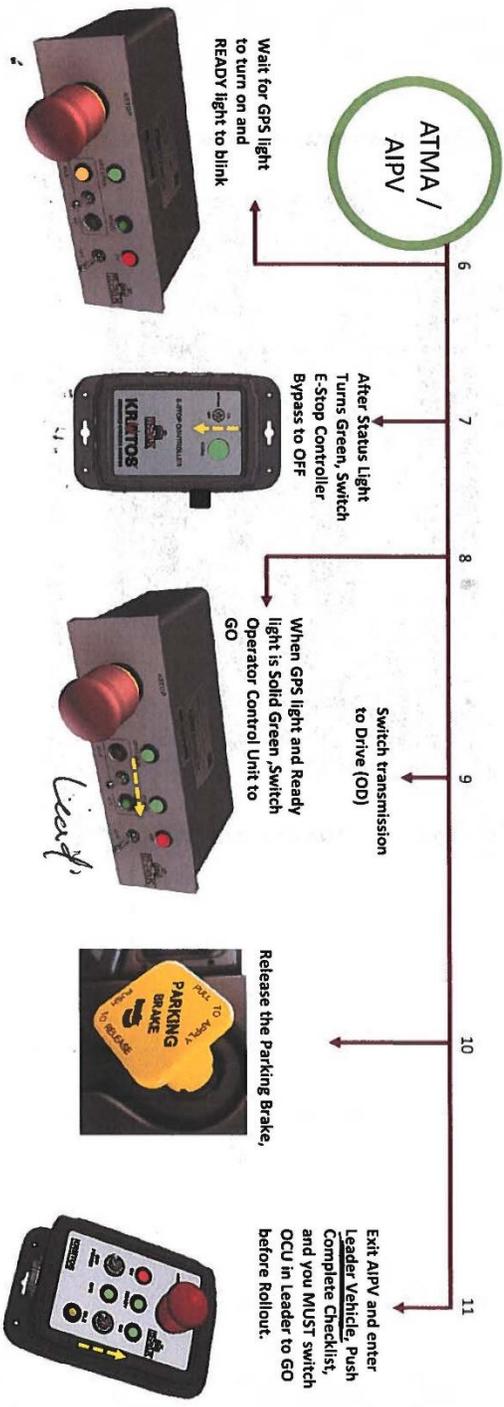


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User Interface – Check List



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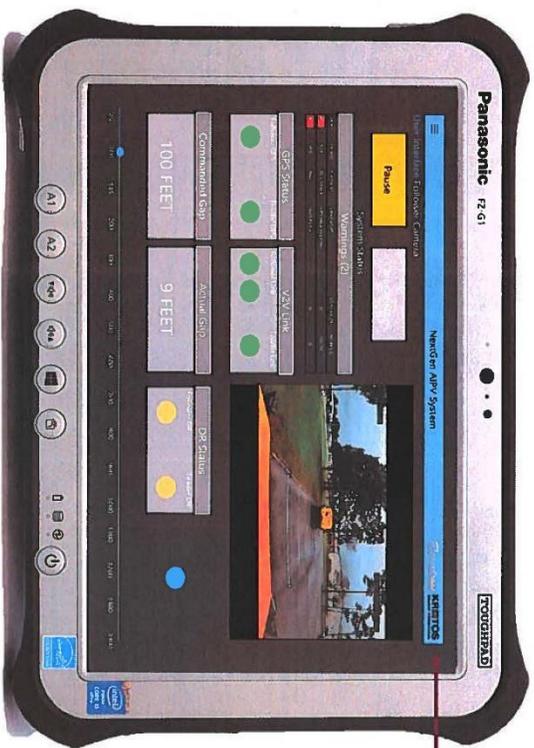
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ATMA
ATTENTION TO THE TAIL

AIPV
AUTONOMOUS INTEGRATED PLATFORM VEHICLE

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User Interface – Title Bar



Title Bar

User Interface – Title / Status Bar

- Give the user overall status of operations

☰	NextGen AIPV System	
	Normal operations will indicate a blue Status Bar with "NextGen AIPV System"	
☰	Follower Paused	
	When the system is Paused, you will see a yellow Status Bar with "Follower Paused"	
☰	Follower A-Stop	
	When the system initiates an A-Stop, you will see an orange Status Bar with "Follower A-Stop"	
☰	E-Stop	
	When the E-Stop button is pressed, you will see a red Status Bar with "E-Stop"	
☰	Collision Detected	
	In case of a collision to the AIPV, the G Sensor will trigger a stop to the vehicle, you will see a red Status Bar with "Collision Detected"	
☰	Error (Follower)	
	In case of a follower system error, you will see a red Status Bar with "Error (Follower)"	

User Interface – Pause Button

Pause Button



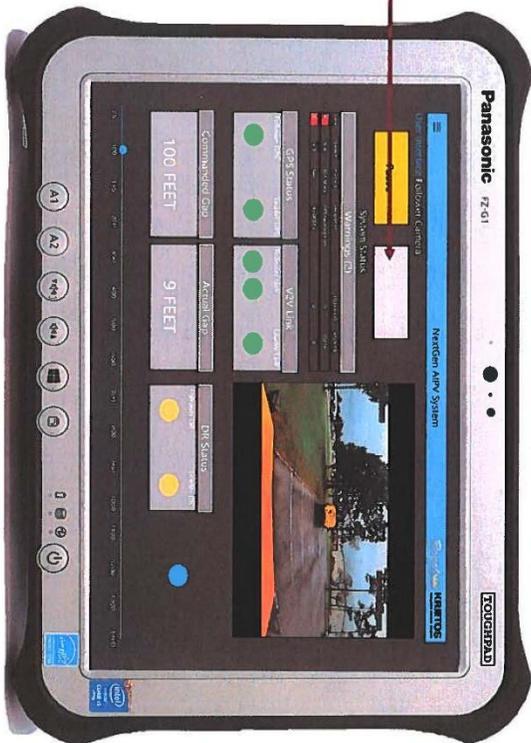
User Interface – Pause

- The Pause button is orange and displays “Pause” as the text under normal operations
- If the vehicle is paused, then the text changes to “Clear Pause”
- If the vehicle is in A-Stop or an error state, then the Pause button is disabled
- Pause will stop ALPV and will keep track of the E-Crumbs for up to 1,500 feet
- When the pause is cleared, ALPV will follow the E-Crumbs that it collected to catch up slowly to the commanded gap
- Not recommended to use the Pause function for more than 1,500 feet and / or for a very long time

User Interface – Clear A-Stop

This button is used to clear an A-Stop once the obstacle is no longer in the path of the ALPV. Once cleared, ALPV operations can resume.

Clear
A-Stop
Button



User Interface – A-Stop



Warning Dialog Box
 The warning dialog box will list all system warnings.

Follower A-Stop
 This status bar indicates if an A-Stop has occurred. The warning dialog box will tell you the cause of the A-Stop.

User Interface – GPS / Radio Status

GPS Status

When GPS status is green, GPS signal is good. A status turns red when it is bad.



Radio Status

When V2V links are green, links are good. A link turns red when it is bad.

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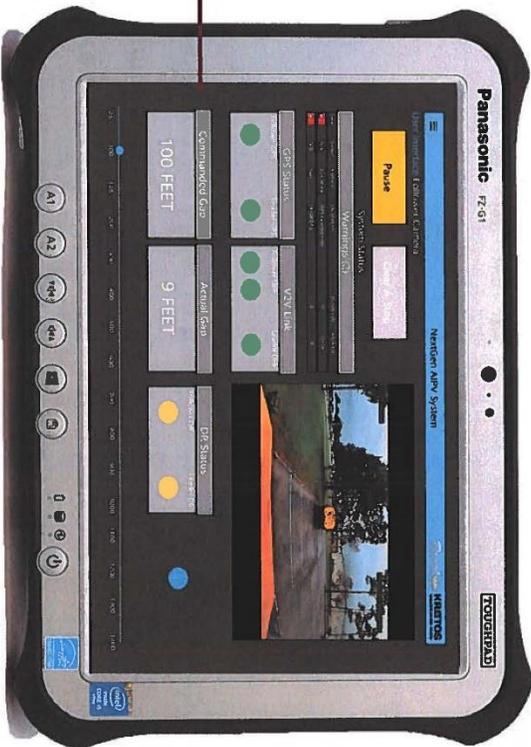
TMA
SYSTEMS

IPV
SYSTEMS

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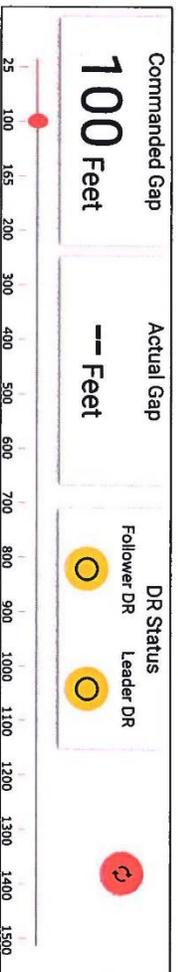
User Interface – Gap Control

GAP
Control Section
See next Slide
for details



User Interface – Gap Control

- Command Gap is the set distance between the Leader and ALPV as adjusted by the user
- Actual Gap is the current distance from the rear of the Leader Vehicle to front of ALPV
- Gap Slider allows the user to choose the Commanded Gap from 25 to 1,500 feet
- Slider also works like a repeat button. By tapping on the Slider to the right or left of the thumb selector, the Gap will increment or decrement respectively



User Interface – DR Status



DR Navigation

DR Status	
Follower DR	Leader DR

DR Status	
Follower DR	Leader DR

DR Status	
Follower DR	Leader DR

DR Status

- When yellow, GPS denied navigation not available
- When Green, GPS denied navigation available
- When Purple, GPS denied navigation taking place
- Note DR Status will turn green when system is on GO

User Interface – Video



Rear Looking Video

This displays the video looking backwards from the leader

Video Refresh

This restarts the video camera



Hands On Section

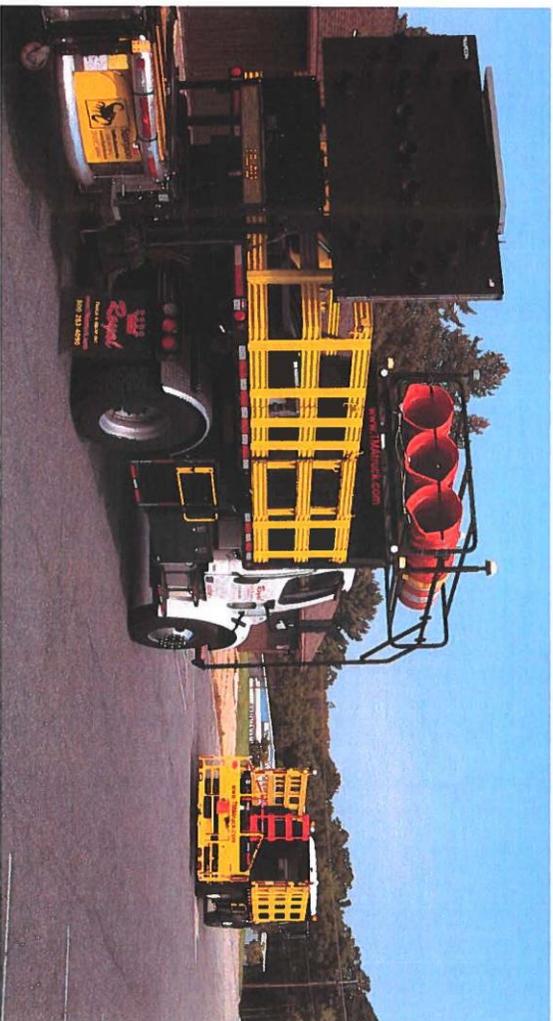
- Break for On Truck review:
 - Leader User Interface

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Follower / AIPV Overview



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TMA
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MANAGEMENT ASSOCIATES

AIPV
AUTONOMOUS
INTEGRATED
PLATFORM VEHICLE

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Follower/ALPV Vehicle Components



Circled Components
are the only ones the
user has to touch



x3

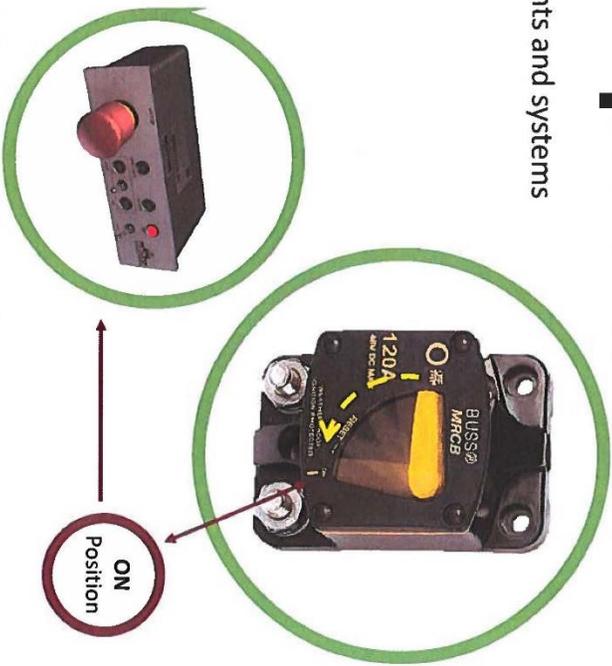
x6

x2



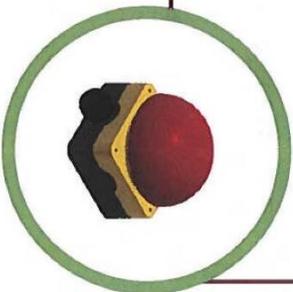
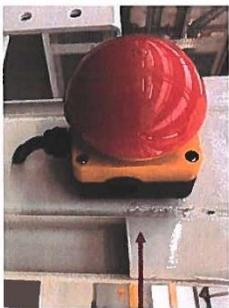
Follower Vehicle Components

- Battery Breaker – Powers and protects AIPV components and systems
 - Connected directly to vehicle's battery
 - Typically mounted near the battery
 - AIPV SCU connected to the battery breaker
 - Design prevents accidental discharge of the vehicle's battery when not in use
 - Switch must be turned to ON position before operating AIPV system components
 - Turn switch to OFF when system is not in use
 - Do not switch to OFF while system is on GO



Follower Vehicle Components

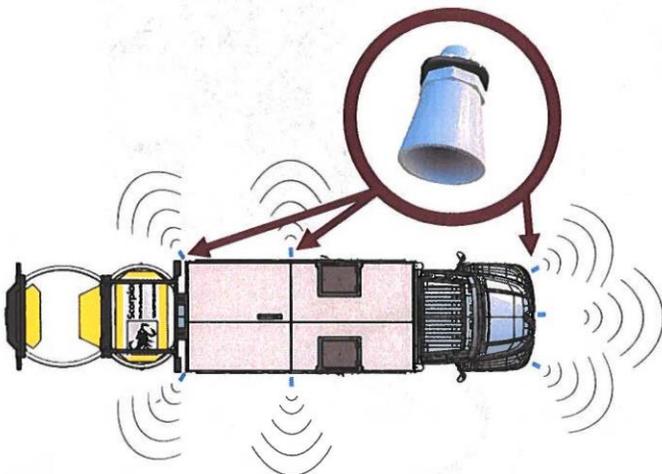
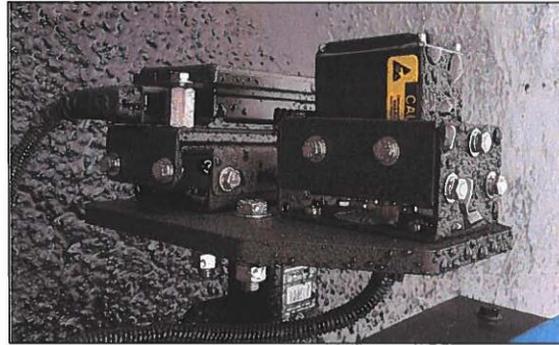
- External E-Stop Buttons – Allows workers to stop the vehicle in emergency situations
 - Installed outside of ALPV vehicle cab
 - Depressing an E-Stop button will bring ALPV to a controlled stop and shut down ALPV engine
 - Pulling the E-Stop button out resets the E-Stop button
 - Note, Rollout Process has to be repeated to start ALPV operations



Obstacle Detection

- Front View Obstacle Detection and Avoidance – Object detection and avoidance system
 - Radar – Detects objects in lane up to 150 feet, can cause A-Stops
 - LIDAR – Detects objects in lane up to 150 feet, can cause A-Stops
 - Ultrasonic Sensors – Detects and warns user of objects in front of vehicle up to 30 feet
- Side View Obstacle Detection Warnings – To detect and warn the user if there is an object on the side of AIPV
 - 4 Ultrasonic Sensors
 - If triggered, the system will warn the user of the Leader Vehicle

Obstacle Detection



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TMA
THERMAL IMAGING

IPV
INTEGRATED VIDEO

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Follower Vehicle Components

- Steering Actuator – Drives the steering wheel to make turns
- Serves as controlling mechanism for AIPV's steering wheel
- A pair of captive fastener thumbscrews are used to secure the fingers and allow easy removal to enable AIPV manned operations



- Cautionary Note**
- Fingers must be re-attached before conducting AIPV operations
 - Fingers must be off when not driving AIPV operations

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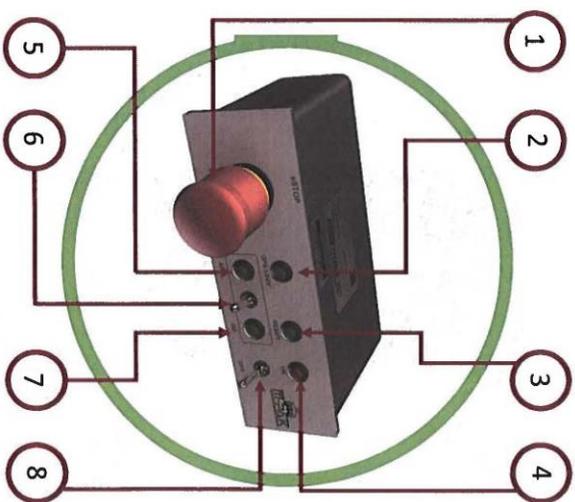


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Follower Vehicle Components

• OCU Indicators and Controls

In-Dash OCU Model Indicators / Controls		
1 - E-Stop Control	Emergency Stop	Depressing the E-Stop Control stops the APV. Turning the E-Stop Control clockwise causes the E-Stop Control to reset to its original position.
2 - GPS Lock Indicator	Green Light	When green light is illuminated, indicates that GPS has acquired a signal to support APV operations.
3 - Ready Indicator	Green Light	When green light is illuminated and not blinking, the APV is completely initialized.
4 - ON Indicator	Red Light	When red light is illuminated, the system is turned on.
5 - IDLE Indicator	Yellow Light	When yellow light is illuminated, the system is in the IDLE mode.
6 - GO / IDLE Control	Toggle Switch	Placing SCU in the GO mode transitions APV system into APV operations; placing APV SCU in IDLE position releases steering, brake, and accelerator controls to the operator.
7 - GO Indicator	Green Light	When green light is illuminated, indicates Leader Vehicle SCU is in the GO mode and starts transmitting GPS positioning and velocity data to APV.
8 - ON / OFF Power	Toggle Switch	Used to power on or off the system.



Follower Vehicle Components

- E-Stop Indicator and Controls

Indicators / Controls		
1. ON / OFF Bypass	Toggle Switch	Used to put the Independent E-Stop Controller in Bypass mode.
2. Status Indicator	Green / Red Light	When green light is illuminated, that means the system is ON and operational. When red light is illuminated, that means the system is a "no-go" due to E-Stop button engaged or no V2V communication.

*this table is contained in Section 5 of APV User Manual





Hands On Section

- Break for On Truck review:
- Follower Vehicle Components



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Operating Parameters

- GPS Navigation Functionality – Primary Navigation System
 - ALPV system uses electronic breadcrumbs (E-Crumbs) that enable Leader / Follower autonomous vehicle operations
- GPS Denied Navigation Functionality
 - Occurs when GPS satellite signals are blocked due to obstructions
 - ALPV system switches into GPS denied navigation when GPS is blocked
 - If GPS signal is not re-established in less than 45 seconds, safety software triggers an A-Stop

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 **ATMA**
AERIAL TARGETING AND MONITORING

 **ALPV**
AERIAL LAUNCH AND RECOVERY VEHICLE

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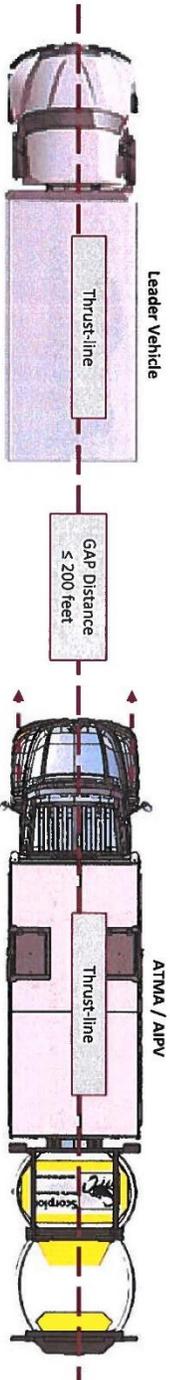


Operating Parameters

- ALPV Rollout
 - Rollout is the distance the ALPV travels at startup until it reaches the position the leader started from
 - Leader Vehicle must not roll out faster than 4 to 8 MPH
 - Rollout is a **critical** procedure for ALPV navigation
 - Rollout must be repeated after all E-Stop actions
- Do not go in REVERSE while in unmanned mode. System must be in OFF or IDLE for Leader Vehicle to go in reverse, if E-STOP is pressed and the ALPV is stopped and engine off then you may reverse
- Not recommended to stop in middle of rollout

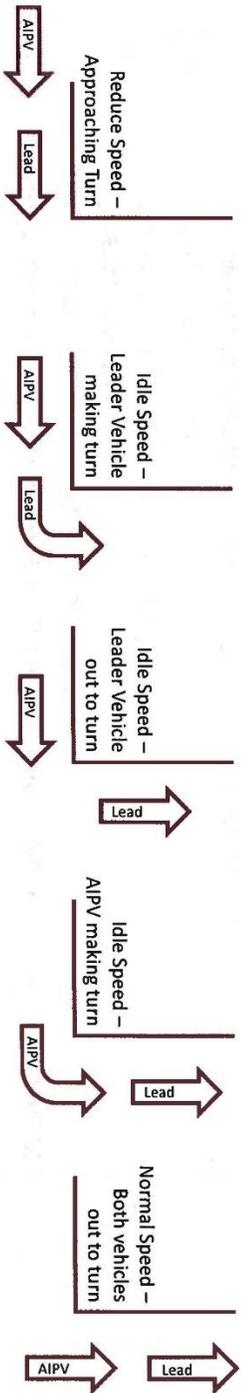
Operating Parameters

- Vehicle Alignment before Rollout
 - Vehicle alignment is a **critical** step in the Rollout process
 - Vehicle alignment must take place **before** powering on the Autonomous System
 - Vehicle alignment includes:
 - Align AIPV's front and rear axle in line to the Leader Vehicle's thrust-line
 - Ensuring the front tires on AIPV are pointed straight ahead



Operating Parameters

- Navigating Around Corners
 - Making safe turns require Leader Vehicle to reduce its speed
 - Best practice requires Leader Vehicle operator to maintain an idle speed (-5 MPH) after making the turn (may vary up or down hill)
 - Allows AIPV to make the turn at a safe speed
 - Visualize AIPV as a trailer with a long electronic hitch (E-Crumbs) on its rear bumper
 - Do not make sharp turns (65 foot minimum turn radius)



A-Stop and E-Stop Safety

- **ALPV system supports an emergency stop counter measure for unsafe conditions**
 - A-Stop functionality brings ALPV to a controlled stop
 - Releases Throttle
 - Applies Full Brake (operational brake actuator)
 - Leaves Engine Running
 - Can be cleared from the Leader Vehicle to resume operations
 - E-Stop functionality brings ALPV to a controlled stop
 - Releases Throttle
 - Applies Full Brake (emergency brake actuator)
 - Shuts Engine off
 - Cannot be cleared from the Leader Vehicle
 - Users will have to re-line up the vehicles for a new rollout



A-Stop and E-Stop Safety

- **ALPV system supports an emergency stop counter measure for unsafe conditions**
 - Independent E-Stop is a backup safety system
 - Capable of operating during a complete system failure if battery power is available
 - Overrides other system components in the event of an emergency
 - Releases Throttle
 - Applies Full Brake (emergency brake actuator)
 - Shuts Engine off
 - Cannot be cleared from the Leader Vehicle
 - Users will have to re-line up the vehicles for a new rollout

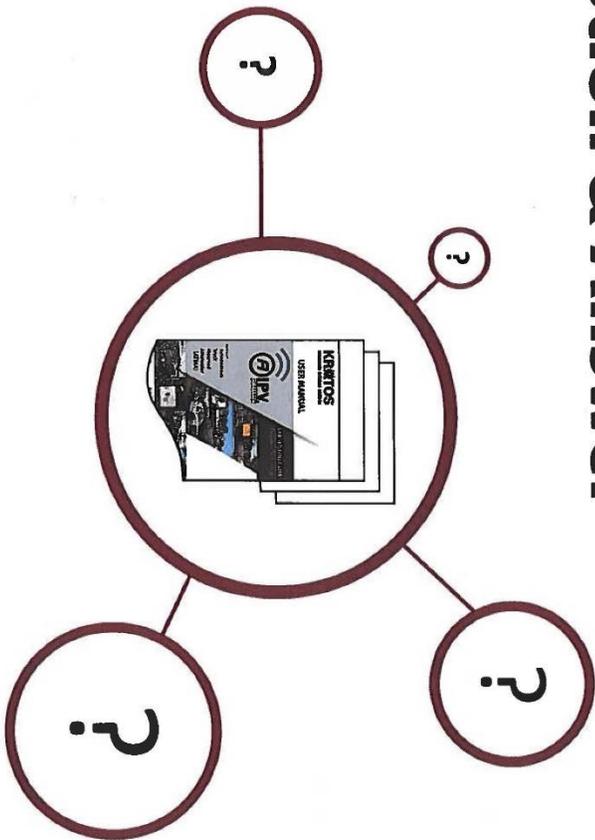
Safety Information

- It is important to follow all safety guidance in ALPV User Manual
 - ALPV operations require additional safety precautions to prevent consequences such as injury, loss of life, or damage to property
- KRATOS cannot anticipate every possible circumstance that might involve a potential hazard
 - Safety guidance in ALPV User Manual is not all inclusive
 - Be sure to review safety guidance in the vehicle's Operation and Maintenance Manual being used for ALPV operations



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Question & Answer



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ATMA
ATTENDING TOWER

ATIPV
ATTENDING TOWER

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Hands On Section

- Break for On Truck review:
 - Leader/Follower hands on operation



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Appendix G: ATMA User Manual

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SYSTEM CHECKLIST Autonomous TMA



November 2019

Contents

1. Attenuator	2
2. Arrow Board	10
3. Truck Lighting	12
4. DVR System	14
5. Generator	19
6. Sonetics.....	23

1. Attenuator



Figure 1: Scorpion Attenuator

1.1. Operation

- Master Disconnect
 - Ensure Master Disconnect is ON when operating the attenuator

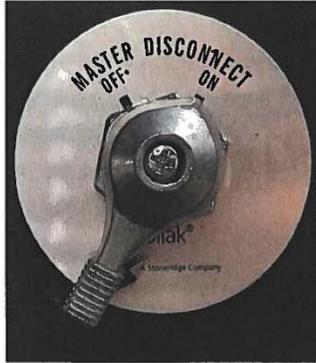


Figure 2: Attenuator Master Disconnect

- When "ON", two-button controller has power
- When "OFF", two-button controller has no power
- Deploying
 - Use the two-button controller to fully deploy the attenuator

- Press and hold the DOWN button to 1) lower the attenuator and 2) raise the arrow board
- Press and hold the UP button to 1) lower the arrow board and 2) raise the attenuator to the stow position
- Releasing the button will **immediately** stop the movement

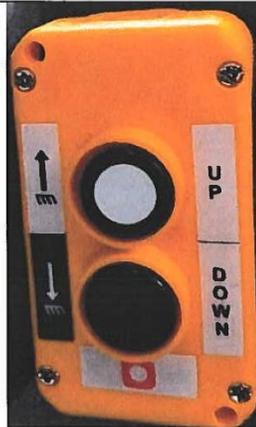


Figure 3: Two-Button Controller

- Ensure the area behind the attenuator is clear of all obstructions
- Check to see that there is enough room to deploy the attenuator behind the truck using mirrors and monitor
- Press and hold the button until the arrow board is fully deployed in the up position
- In the event of an emergency where the attenuator needs to be stopped immediately, release the up or down button (whichever is being used to set the attenuator in motion)
- Check ground clearance: From the ground to the bottom of the A-Module should rest 12 inches +/- 1 inch

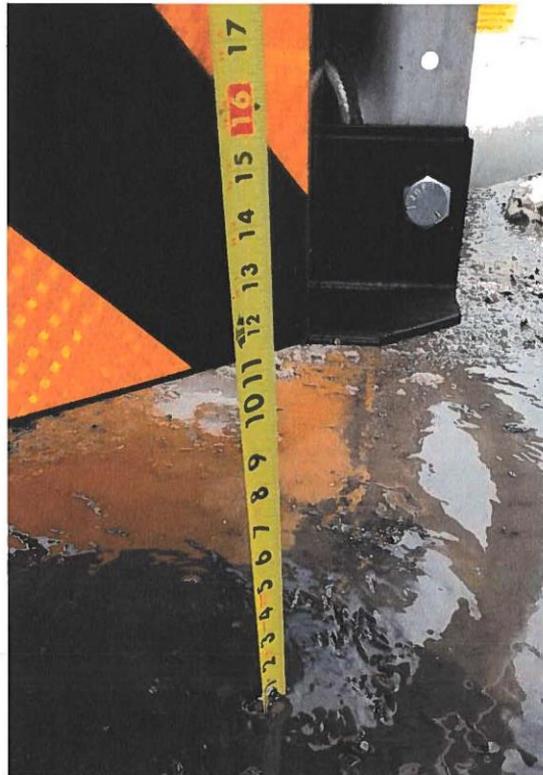


Figure 4: Ground Clearance

- Motion Alarm: Listen to make sure the alarm is sounding when in motion

- Check all electrical connections: Make sure they are all fully plugged in for both the truck side and the attenuator side



Figure 5: Electrical Connections

- Stowing
 - To fully stow the attenuator, press and hold the UP button
 - Continue to press and hold the UP button for 5 seconds **after** the attenuator has landed on the prop
 - Check to ensure the lock out arm has locked out fully



Figure 6: Lock-Out Arm

- Motion Alarm: Listen to make sure the alarm is sounding when in motion

1.2. Structure

- Strut and Cartridge Tubes
- Check the tubes between each section for damage to the tubes itself or the reflective tape



Figure 7: Strut & Cartridge Tubes

- Modules
 - Check all of the modules for punctures, dents or scrapes



Figure 8: Modules

- **Hydraulics**
 - Ensure reservoir is at a minimum 1/2" from the threads when the attenuator is fully lowered but before the arrow board begins to raise
 - Make sure there are no leaks by checking under the attenuator after complete deployment and stowing



Figure 9: Hydraulics

- **Service**
 - Change the oil once per year preferably with ATF. However if you are in extremely cold temperatures, ATF can be substituted with Aviation Low Temperature Hydraulic Fluid
 - It is not necessary to drain the hoses and the cylinders. Only the fluid in the reservoir tank needs to be changed
- **Lights**
 - Turn on the truck's marker lights and check the lights on the attenuator while both stowed and deployed
 - Check the brake lights
 - Check the reverse lights
 - Check all strobes on the attenuator
 - Ensure the back up beeper sounds when in reverse



Figure 10: Lights

- Auxiliary Two-Button Controller
- This controller can be plugged into the passenger side of the attenuator and will allow you to operate the attenuator outside of the cab controls

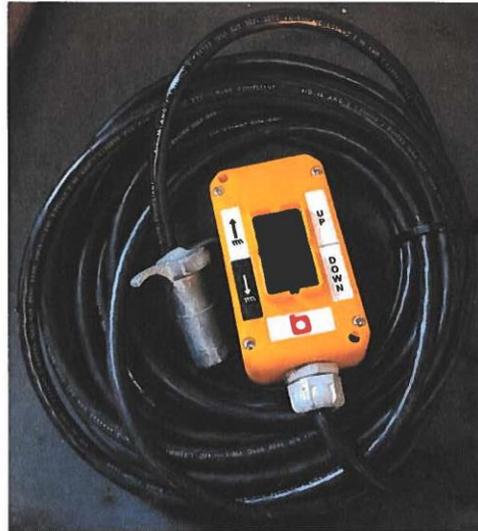


Figure 11: Auxiliary Two-Button Controller



Figure 12: Auxiliary Controller Plug

of 27

2. Arrow Board



Figure 13: Arrow Board

2.1. Operation

- The arrow board will raise and lower **together** with the attenuator using the two-button controller

- Press and hold the DOWN button to 1) lower the attenuator and 2) raise the arrow board
- Press and hold the UP button to 1) lower the arrow board and 2) raise the attenuator to the stow position
- Releasing the button will **immediately** stop the movement

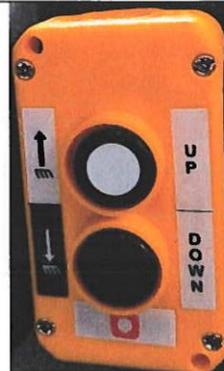


Figure 14: Two-Button Controller

- Always ensure the arrow board is fully raised and fully lowered
- The arrow board should be stowed fully to ensure the attenuator does not hit it up on raising



Figure 15: Stowing the Arrow Board

2.2. Arrow Board Lights & Patterns

- Check all of the lights on the arrow board to ensure they are all working properly
- Turn on the arrow board control with the switch on the dashboard and then on the controller
- Cycle to the double arrow and caution bar. These two patterns will operate all of the lights on the arrow board

3. Truck Lighting

3.1. Operation

- **Rocker Switches**
 - Turn all of the switches to the on position
 - Ensure the light on the rocker switch illuminates
 - From left to right in below figure: Strobes, Left Work Lights, Bulkhead, Right Work Lights

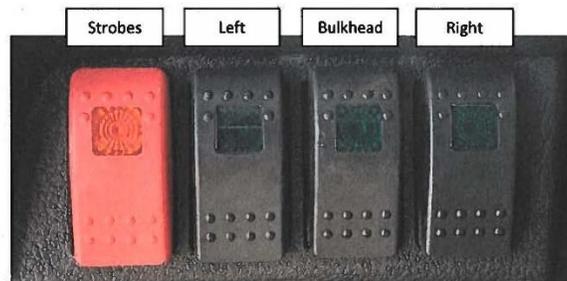


Figure 16: Rocker Switches

- **Work Lights**
 - Check all work lights for damage or debris
 - Make sure all LEDs are lit

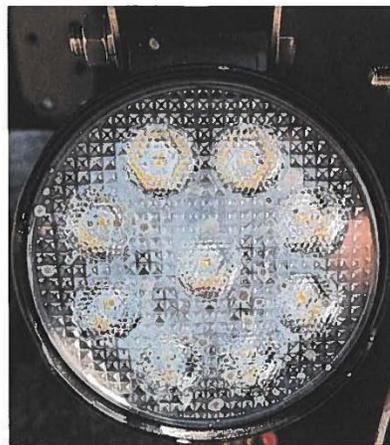


Figure 17: Work Lights

- Strobe Lights
 - Check all strobe lights for damage or debris
 - Rear facing strobes are located on the rear of the body facing away from the truck cab

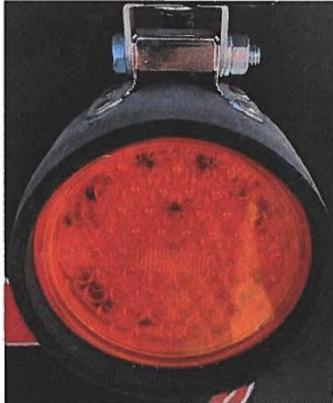
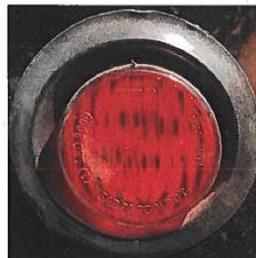


Figure 18: Strobe Lights

- Marker Lights
 - Turn on all marker lights for the truck
 - Ensure all 2.5" amber and red body marker lights are fully lit

Yellow marker lights are located on the bulkhead of the truck and at the front of the body



Red marker lights are at the rear sides of the body

Figure 19: Marker Lights

4. DVR System

4.1. DVR System

- Use the key provided to unlock the DVR and access the SD or SSD
- Lights are described below:

Display	Description	When illuminated...
PWR	Power	the power is ON
REC	Record	the device is recording
USB	Universal Serial Bus	a USB device is connected to the DVR
ERR	Error	one of the hard drives is not working properly
ALM	Alarm	one of the cameras is not plugged in OR a storage device is missing (hard drive, SSD or SD)
NET	Internet	the DVR is connected to the internet *Applies only to trucks with a data plan (additional)

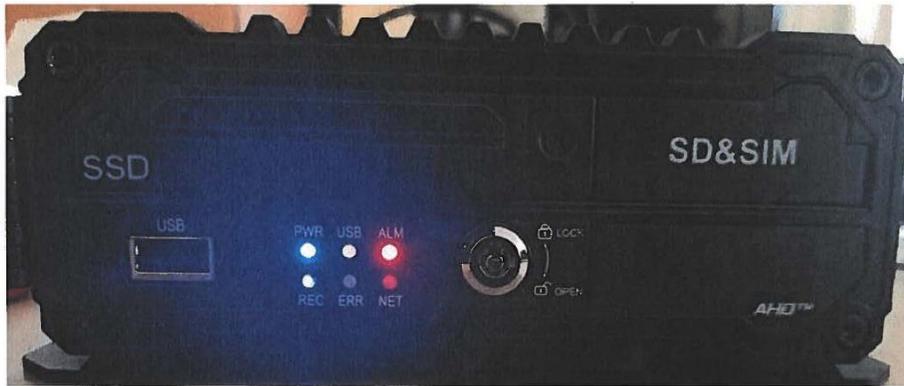


Figure 20: DVR Indicator Lights

4.2. Monitor



Figure 21: Monitor

- Ensure monitor turns on with the key in the on position
- Push numbers 1 through 9 to select a camera for full screen (depending on the number of cameras on your truck, some options may not be available)
- Push the MENU button or the blank button beneath it to log into the DVR
- Push the EXIT button for the sub-menu
 - This allows the user to select the view
 - The below button brings up the log in screen
 - The default password is 222 or 222777. After logging in you can change the password in the settings menu

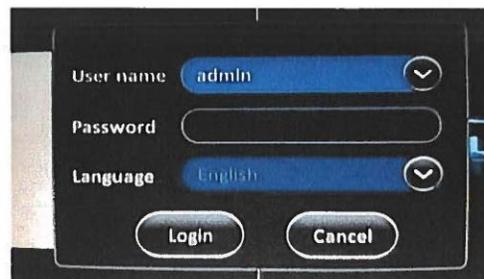


Figure 22: DVR Login Screens

4.3. Playback Function

- This function allows you to view recorded events from within the truck
- There are 2 ways to watch playback on the monitor
 - Bring up the sub-menu by pressing the EXIT button and select Playback
 - This will start the playback from the most recent recording
 - You can fast forward, rewind and change cameras from this screen
 - You can also change the time of recording by dragging the top bar
 - Log in from the menu
 - After logging in, select REC Search from the below screen



Figure 23: DVR Menu Screen

- Select the Date you want to search and press Next



Figure 24: DVR Date Search

- Select the Channels you want to preview and then press Next

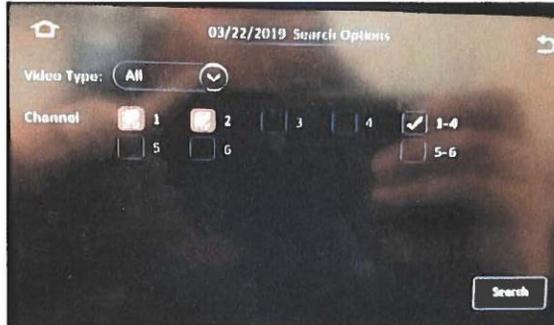


Figure 25: DVR Channel Search

- After selecting channels, you have the option to select Export or Playback. Press the Playback button

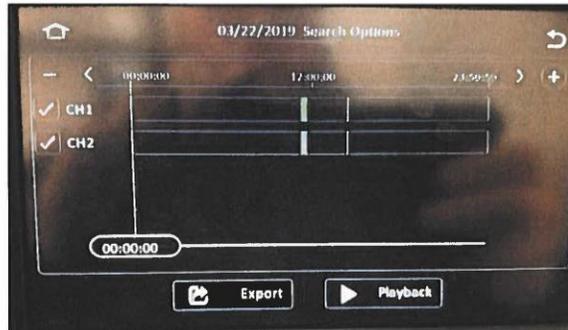


Figure 26: DVR Playback Screen

- Use the arrows on the right side of the screen to change cameras



Figure 27: DVR Playback Navigation

- Use the buttons along the bottom of the screen to control the speed of the playback
- Use the volume buttons on the left side to adjust the playback volume
- Drag the dot at the top of the screen to control the playback time

4.4. Cameras



- 10 Cameras in total
 - Driver facing
 - Forward facing
 - Both are in the cab
 - Bed facing
 - Rear facing on top of arrow board
 - Back up camera with attenuator deployed
 - Hit camera
 - Rear facing under attenuator D module
 - Back up camera with attenuator stowed
 - 2 Bullet cameras on each side (4 total)
- Clean the lenses to ensure clear visibility

5. Generator

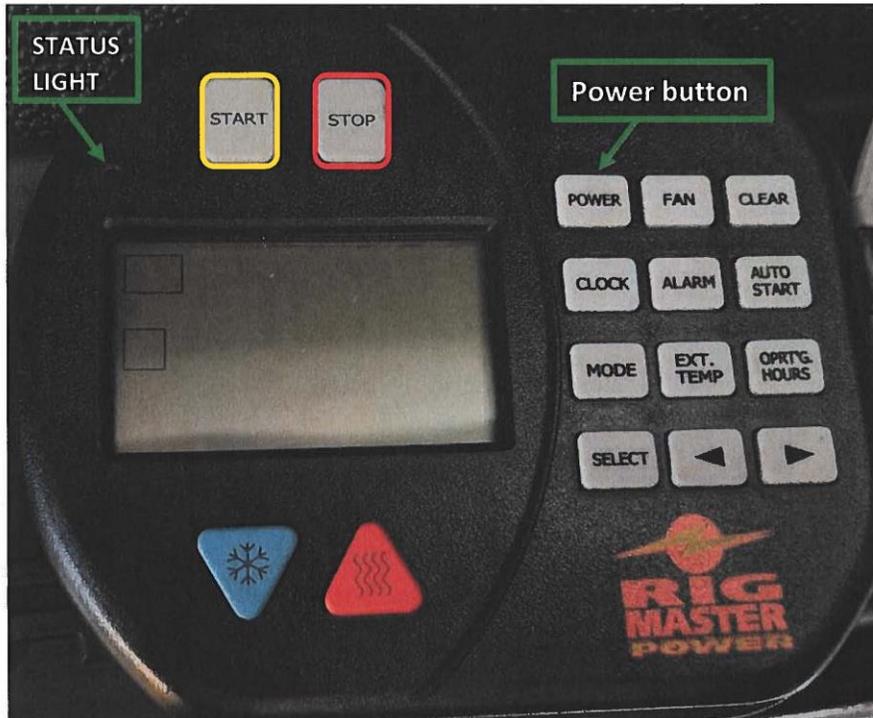


Figure 28: Generator System OFF

5.1. General Operation

- Powering the unit on and off
- Open the gray plastic cover to access all of the buttons available
- Push and hold the power button to turn the unit on and off
 - When the status light is **not** illuminated, the controller is on but the unit is off and the screen will show nothing in the top left-hand box of the screen (as shown above)
 - When the status light is illuminated green and "System On" appears in the top left-hand box on the screen, the controller is on and the unit is on (as shown below)
 - Once powered on, the generator is not on and the controller can now tell the generator to manually turn on



Figure 29: Generator System ON

- Manually starting and stopping the unit
 - With the unit powered on, push the START button
 - The controller will say Glow Plug and start a countdown
 - There are no glow plugs in this unit because it is a gas engine
 - The controller will then say Crank and the engine will crank and begin to run
 - The generator will run for 23 hours if not manually turned off when you manually start the generator
 - To turn the generator off press the STOP button
 - The controller is still on so Auto Start will still enable once the batteries are below the voltage set by the controller
 - The controller will display Stopping and the generator will stop running
 - Master Disconnect
 - When turned to ON, the generator controller has power
 - When turned to OFF, the generator controller has no power
 - This feature is necessary as a lock out safety featured for servicing the unit
 - *When the generator is not being used, turn the Master Disconnect to the OFF position! Failure to follow this step ay result in faster-than-usual depletion of the truck batteries.*

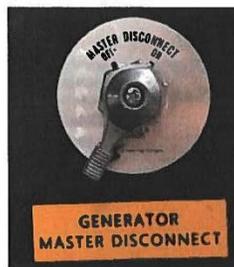


Figure 30: Generator Master Disconnect

- Auto start and stop function
- After the unit is turned on with the power button, the Auto Start feature is automatically enabled
 - Once the batteries dip below the threshold, the controller will tell the generator to start
 - Auto Start will display on the screen and then the normal start up sequence will start
 - When the generator starts via Auto Start, the unit will run for 15 minutes
 - After the first 15 minutes, the unit will turn off and will check the voltage on the batteries
 - If the batteries are still under the threshold, the generator will Auto Start again and run for another 15 minutes
 - If the batteries are charged enough above the voltage threshold, the generator will not start again until the batteries dip below the threshold again

5.2. Troubleshooting

- **You may see error messages even with the unit turned off.** The unit will attempt to warn the operator of any issues **prior** to the operator turning on the controller or starting the engine.
 - Error 3: This is the most common error. This error indicates the batteries are too low but since the controller is off, the unit is not reading the batteries.
 - If there are any other error codes, refer to the owner's manual for further guidance.
- To clear error codes:
 - If there is an error message on the controller and the controller is not on:
 - Make note of the error code
 - Press the STOP button
 - Turn on the unit with the Power button
 - Start the unit either manually or using Auto Start to ensure the generator is working properly
 - **If manually started, remember to shut it off!**
- Changing the voltage threshold:
 - With the controller powered off:
 - Open the gray cover
 - Push the right arrow
 - Push select
 - Using the left and right arrows input the code: **Z123**
 - Press Left Arrow for "Z" then Select
 - Press Right Arrow for "1" then Select
 - Press Right Arrow twice for "2" then Select

- Press Right Arrow three times for "3" then Select
- Push select
- Push the Right Arrow until you find Batt Voltage
- Press select
 - DEF = 12.0 Volts
 - +1 = 12.1 Volts
 - -1 = 11.9 Volts
 - This will change the voltage at which the generator will start when utilizing the auto start feature

6. Sonetics



Figure 31: Sonetics Wireless Base

6.1. Base Station

- Power unit on with either switch or cigarette lighter plug (depending on build and other accessories)

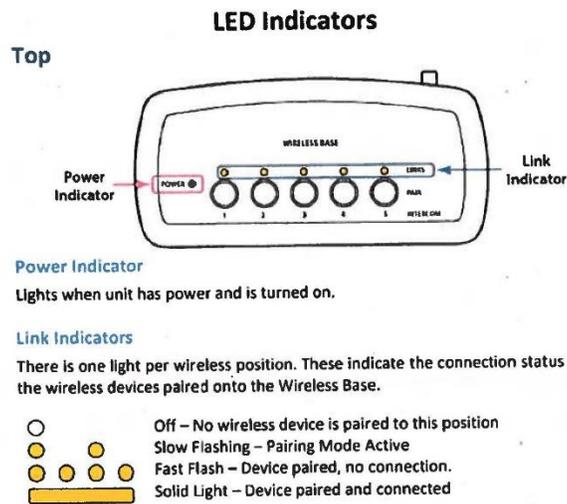


Figure 32: Sonetics LED Indicators

6.2. Pairing the Base Station to the Headsets

Pairing

Pairing creates a connection between the Wireless Base Station and the Headset. This is only required once. After pairing, Headsets will connect automatically.

Full-Duplex Pairing

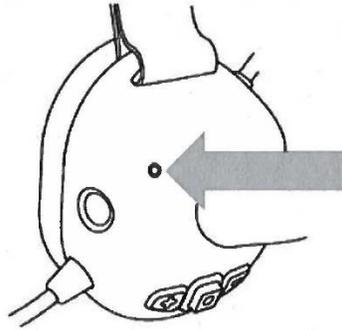
1. Press and hold the desired pairing button until its link indicator begins to flash slowly. Any previous pairing will be forgotten.
2. Place the Sonetics Headset into pairing mode by pressing the right PTT button and the power button until you hear "base station registering".
3. The Base Station will automatically connect, showing a solid link led.
4. If the pairing was unsuccessful, repeat all steps above.

Figure 33: Pairing the Base Station with Headsets

- When pairing the headsets to the base station, ensure the headset is off
- Push and hold the channel you want the headset to connect to
- Once the light on the channel you want to pair is flashing slowly you will then need the headset
- With the headset off, first push and hold the PTT button on the right side of the headset
- While still holding the PTT button, push and hold the power button
- You will hear "Sonetics On, Base Station Registering"
- The LED on the headset will also start blinking between red and green colors
- The base station will blink fast and then stay on solid. This tells you the channel is connected to the headset.
- *It is important that the headset is off before you try to pair to the Base Station*
- Continue the process for the rest of the headsets that you want to be paired to the base station

6.3. Headset

The Sonetics Electronic Headset uses a multicolor LED indicator to give additional information on the exterior of the Headset. The table below describes the behavior while charging or in use.

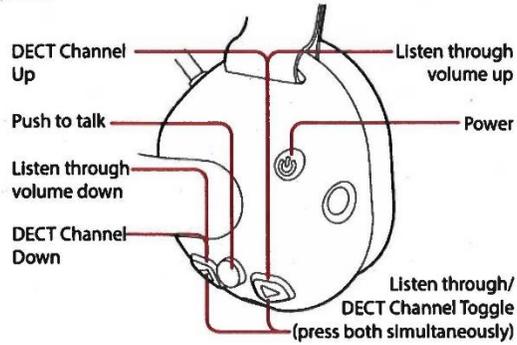


Charging	Non-Charging	Function
	Red Flash ●●●●	Headset On
	Blue Flash ●●●●	Bluetooth® Connection Established and in progress
	Red/Green ●●●●	Headset in DECT pairing mode
	Green Flash ●●●●	DECT Connection Established and in progress
	Blue/Green ●●●●●●	Both Bluetooth and DECT connections Established and in progress
	Flash ●●●● Led color will vary Depending on connection type	Battery Level ●●●● = Battery >75% ●●● = Battery 50-75% ●● = Battery 25-50% ● = Battery <25%
Red Solid		Charging
Green Solid		Fully Charged

Figure 34: Sonetics Headset

Buttons

Right Side



Turn On

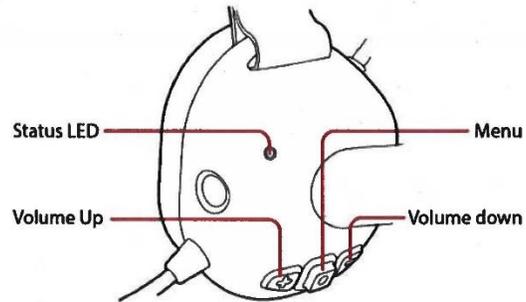
Press and briefly hold the power  button. You will hear the welcome message and the LED on the right hand side of the unit will begin to flash periodically.

Turn Off

Press and briefly hold the power  button. You will hear the Headset powering down message and the LED will turn off.

Figure 35: Headset Right Side Buttons

Left Side



Adjusting the Main Volume

Press the plus **+** or minus **-** buttons on the left-hand side of the Headset.

Adjusting the Listen Through Volume / DECT7 Channel Select

Press the forward **▶** or back **◀** button on the right-hand side of the Headset.

Pressing the forward **▶** and back **◀** buttons will toggle between listen through and DECT7 Channel (if the Headset has a DECT7 connection).

Figure 36: Headset Left Side Buttons



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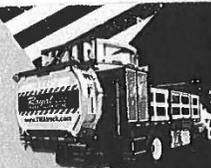
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Appendix H:

Kratos ATMA System Enhancements

The ATMA performance evaluation project involved a series of customer-driven system enhancements. Kratos was provided interim test results and devised system improvements to enhance the ATMA performance. These enhancements progressed through several distinct phases: the initial Kratos ATMA system validation and commissioning, a Kratos repair operation when Caltrans DOE damaged the radio antennas, and AHMCT testing that resulted in four separate rounds of Kratos ATMA system upgrades. AHMCT conducted multiple rounds of ATMA testing during and after each of these phases.

Caltrans ATMA Damage Incident Repair

Subsequent to the Kratos initial ATMA commissioning, the ATMA FV was returned to Caltrans DOE to complete their standard vehicle highway safety marking procedure. During that process, the antenna array on the FV contacted a roll-up door at the shop and the plastic radio antennas were broken. Caltrans DOE replaced the broken antennas and the ATMA was returned to META to verify that the ATMA system was still functioning correctly. The ATMA failed to operate after the antenna replacement. AHMCT and Caltrans DOE contacted Kratos and working over the phone, tried to mitigate the problem. After a couple of days of testing and trying different solutions, Kratos determined that an engineer would need to be dispatched. AHMCT and Caltrans DOE worked with the Kratos engineer once on-site and were, after a week, able to resolve the problem. It remains unclear what was (were) the source(s) or the extent of the problem(s). With the ATMA system functioning correctly again, AHMCT and Caltrans DOE partnered with a Kratos engineer to conduct another round of system adjustments, and Kratos prescribed validation testing to ensure the ATMA system was fully operational. Kratos recommissioned the ATMA in late January 2020, which allowed AHMCT to begin the next research phase of performing autonomous performance testing.

Initial Caltrans ATMA AHMCT Evaluation Results

By May 2020, AHMCT had conducted about half of the test scenarios and had already revealed three significant safety issues. When these issues were presented to Caltrans, they officially requested that these safety issues be mitigated before testing continued. The three safety issues were an FV adrift state, object detection failures, and FV steering failure during autonomous driving under an overcrossing.

Adrift State: The first ATMA safety issue occurred when attempting to simulate a power failure to the FV SCU by switching off system power while in

autonomous driving mode. When the SCU power was switched off, the FV was set adrift and kept driving out of control of the LV. AHMCT, in further discussions with Kratos, agreed that simulating an SCU power loss would be more realistically modeled by turning off the SCU power breaker. When this procedure was tested, tripping the FV SCU main power circuit breaker caused the FV engine to immediately cut-off as required.

Object Detection: The second ATMA safety issue occurred when an object was placed within 10 ft of the front of the FV or in a curved path in front of the FV. In both of these cases, the objects were not detected by the ATMA and the FV would drive into these objects.

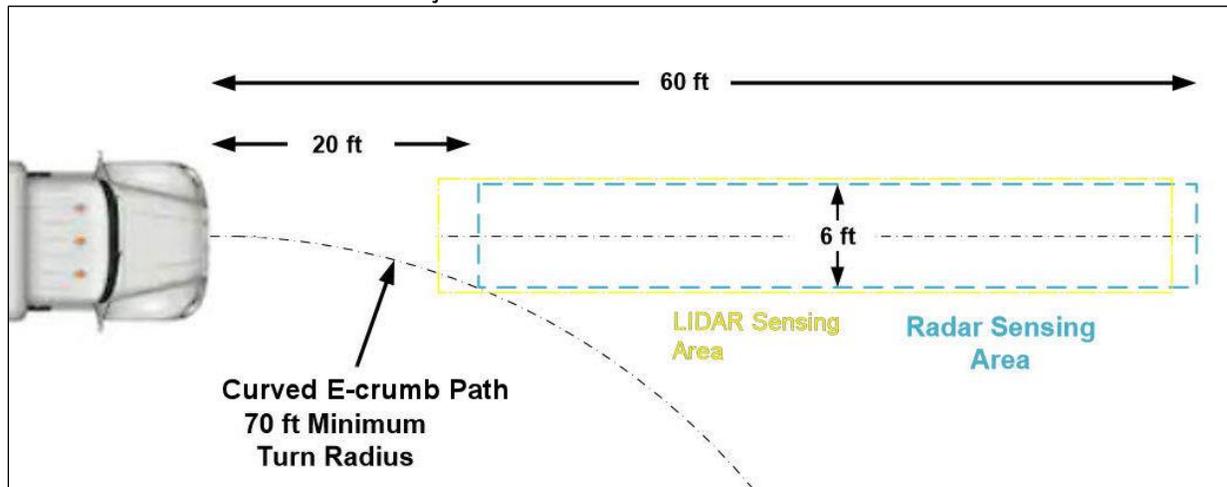


Figure H.1: Object detection map for curved E-crumb path

Highway Overcrossing: The third ATMA safety issue occurred when the ATMA was driven under a highway overcrossing at the Old Davis Road test site. The ATMA is designed to switch to a secondary INS guidance system when the primary guidance GPS signals are blocked. This enables the FV to continue autonomously following under highway concrete overcrossings. Once the FV clears the structure and re-establishes the GPS signal, the FV switches back to GPS guidance mode. In both of the test runs attempted, the FV experienced a violent steering correction as the FV switched back to GPS guidance. In both of these trials, the safety rider stationed in the FV had to press the vehicle brake to prevent the FV from running off the road.

Caltrans considered these three ATMA safety issues to be critical and requested that AHMCT pause any further ATMA testing until these safety issues were mitigated by the manufacturer. The three system safety deficiencies were brought to Kratos' attention.

First Kratos ATMA System Upgrade

Kratos engineered mitigations for each of the three Caltrans-identified safety deficiencies. In July 2020, Kratos sent an engineering team to AHMCT to install the designed mitigations on the ATMA.

Adrift State Mitigation: This fault proved to be unrealistic since an actual OCU power failure results in an E-Stop. The adrift state could only occur when a safety rider in the FV switched off the OCU power, so Kratos installed a locking OCU power On/Off switch in the FV to eliminate the unlikely possibility of the switch getting accidentally bumped by the safety rider. Kratos sufficiently resolved the only adrift state this test scenario had discovered.

Object Detection Mitigation: To mitigate the object detection deficiency, Kratos installed a new and more sensitive LiDAR sensor with a 190-degree field of view on the front of the FV. The LiDAR control software was upgraded with a far more sophisticated object detection algorithm that enables objects to be detected directly in front of the FV and also has the capability to bend the object detection zone in an arc along the E-crumb path to detect objects in a curve.



Figure H.2: Upgraded LiDAR sensor



Figure H.3: Upgraded side LiDAR sensor

Highway Overcrossing Mitigation: Kratos upgraded the Caltrans ATMA with the latest version of the Kratos ATMA guidance and control software. This updated control software, together with a realignment of the GPS antennas, were the Kratos-prescribed mitigations to solve the overcrossing FV steering swerve problem. With further ATMA testing limited to closed secure testing facilities, driving the ATMA under an actual highway overcrossing to validate the Kratos mitigation was not an immediate possibility. As such, Kratos engineers suggested that a simulation involving driving the ATMA in a large circle in autonomous mode and comparing the positional data between the beginning point and final point would be sufficient proof. After running several trials with AHMCT, the positional data between the INS and GPS tracking systems were within design limits.

As an additional test, AHMCT had Kratos shield the GPS antenna to switch the ATMA into INS guidance mode, then drive in a straight line and uncover the GPS antenna after driving 150 ft. The ATMA would regain the lost GPS signal and

switch back into GPS guidance mode. The ATMA was able to successfully make the switch from INS to GPS guidance without swerving. The overcrossing simulation trials were conducted eight times in different locations and directions at META, and all were completed successfully.

All three of the Caltrans identified ATMA safety deficiencies were demonstrated to be successfully mitigated. The first Kratos upgrade also incorporated additional extended functionality features, including follower path offset control and a more interactive gap control to be more compatible with standard Caltrans highway operational safety procedures. Kratos also upgraded the many side sonar sensors to a single LiDAR sensor on each front corner of the FV. These side sensors are only informational and generate warnings that are displayed in the LV. These warnings do not control or interrupt autonomous driving control.

AHMCT/Kratos Testing of First Kratos ATMA upgrade

Following the Kratos upgrade, AHMCT and Kratos engineers partnered to conduct a full regiment of Kratos-prescribed validation testing and several AHMCT-recommended safety tests to ensure that the three discovered safety deficiencies had been corrected. AHMCT completed a safety and performance evaluation of the upgraded ATMA system. Two of the three identified ATMA safety deficiencies were demonstrated to be successfully mitigated during Kratos validation testing, but due to Caltrans safety concerns, the ATMA driving under the overcrossing test scenario could not be repeated at the Old Davis Road highway overcrossing test site. Therefore, Kratos simulated this scenario by shielding the GPS antennas while driving in autonomous mode. The trials were successful with a minimal steering correction when switching between Inertial and GPS navigation modes. Kratos was confident that this guidance safety issue had been mitigated. The overcrossing test scenario simulation was also successfully completed. The simulation results had to suffice as verification of the overcrossing test until a time when a safe and secure actual highway overcrossing test site could be located.

During validation testing of the Kratos first upgrades, a transmission problem occurred with the Hino truck only while transporting the vehicle at highway speeds, i.e., under manual control. UCD heavy vehicle mechanics determined the fault was caused by how Kratos was electrically tapping into the transmission speed sensor. The temporary mitigation to enable validation testing to continue was to remove the speed sensor input to the OCU when transporting the Hino truck and reconnecting when operating in autonomous mode.

First Caltrans Otay Mesa ATMA Overcrossing Test

Caltrans identified a suitable overcrossing test site on SR 905 in the Otay Mesa area in Caltrans District 11. In October 2020, Caltrans closed an eastbound

section of SR 905 at the Caliente Avenue overcrossing for a few hours to allow AHMCT to test the ATMA performance under an actual highway overcrossing. AHMCT drove the ATMA system to the Otay Mesa test site and conducted about a dozen test runs navigating the ATMA autonomously in both directions under the wide Caliente Avenue concrete overcrossing. In all the tests, the FV steering swerved and most times resulted in an unrecoverable guidance failure. Caltrans terminated any further testing until Kratos could mitigate the overcrossing navigation issue.



Figure H.4: Caltrans Otay Mesa overcrossing trial – ATMA FV swerving

Kratos Second ATMA System Upgrade

Kratos analyzed the failed overcrossing trial data and engineered a software solution. In June 2021, Kratos dispatched another engineering team to install a second ATMA system upgrade that included a guidance system software change designed to reduce or eliminate the overcrossing swerving issue. The Kratos engineering team installed the software upgrade and adjusted some of the guidance system input components. AHMCT then partnered with Kratos to successfully complete another series of Kratos-mandated validation tests. Kratos developed a new method of simulating the overcrossing navigation test that is a closer indicator that the guidance system software fix was successful. The absolute proof would not occur until the ATMA could return to the Otay Mesa test site and successfully demonstrate autonomous driving under an actual highway overcrossing. Kratos engineers also solved the transmission speed sensor problem by changing from a direct electrical connection to a software connection. This solved the Hino transmission problem.

Kratos Third ATMA System Upgrade

Kratos dispatched another engineering team to install the latest ATMA control operating system. The primary change was the addition of an E-crumb error when the LV is driven backwards while in autonomous driving mode. Following the Kratos system software upgrade, AHMCT and Kratos engineers partnered to conduct a full regiment of Kratos-prescribed validation testing.

Second Caltrans Otay Mesa ATMA Overcrossing Test

In September 2021, Caltrans once again scheduled a closure of the Otay Mesa test site. The overcrossing test scenario was repeated with the ATMA driven autonomously under Caliente Avenue highway overcrossing about a dozen times in both directions and in multiple lanes. In all the test runs, the FV never swerved when switching from INS to GPS guidance mode. These test results indicated that the ATMA overcrossing issue had been successfully mitigated. Since there was additional testing time available, AHMCT conducted high-speed autonomous driving test scenarios. AHMCT also provided a demonstration of the new ATMA offset feature (taking-the-lane), which provides a better fit with standard Caltrans highway traffic safety procedures.

Appendix I: ATMA Test Sites

AHMCT ATIRC test site

AHMCT conducted the majority of ATMA testing at the ATIRC test track, which is located three miles west of the UCD central campus and just west of the UCD airport. This facility is entirely enclosed by a chain link fence and includes two approximately 500-ft straight legs connected by an approximate 65-ft inside radius 90-degree curve. It was used to perform the majority of ATMA testing scenarios. The red line in Figure I.1 illustrates the test track path. Markings were added to the test track to facilitate testing and evaluation scenarios.



Figure I.1: ATIRC closed test track

Caltrans META test site

The Caltrans META test site is located in the North Highlands section of Sacramento. Kratos conducted most of their early ATMA validation testing at this site primarily because it offers a longer stretch of pavement than what is

available at the ATIRC site. META contains a 550-ft square paved section area, which is large enough to drive the ATMA in a circle.

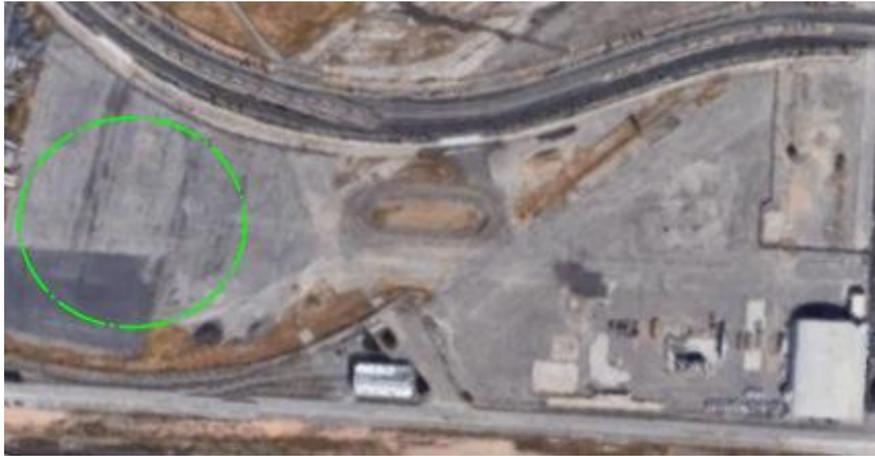


Figure I.2: Caltrans META test site

Old Davis Road overcrossing test site

The Old Davis Road test site is adjacent to the UCD main campus where Old Davis Road passes under Interstate 80. The Caltrans Old Davis Road overcrossing consists of two parallel concrete structures having six surface lanes each bridging a separated four-lane rural roadway and bike path. AHMCT utilized this test site to run the initial ATMA overcrossing test. As this site is not closed to the public, based on the system behavior, further testing was proscribed for this site.



Figure I.3: Old Davis Road test site

Kratos test site (McClellan Park)

The Kratos McClellan test site is located in the North Highlands section of Sacramento. Kratos conducted the later ATMA upgrade validation testing at this site primarily because it provides a paved area large enough to conduct higher-speed ATMA test scenarios.



Figure I.4: Kratos McClellan test site

Caltrans Otay Mesa Overcrossing test site

The Caltrans Otay Mesa test site is located at the Caliente Avenue overcrossing in the Otay Mesa region south of San Diego on SR 905 near the international border with Mexico. The Caliente Avenue overcrossing consists of a six-surface-lane-wide concrete overcrossing structure bridging a six-lane separated highway. AHMCT conducted the final two ATMA overcrossing and the high-speed test scenarios at this test site. Caltrans District 11 closed the eastbound highway lanes and detoured traffic to the off ramp, across Caliente Avenue, and back on the entry ramp. This closure enabled AHMCT to run the ATMA in autonomous driving mode under the wide concrete overcrossing in both directions at maximum ATMA traveling speeds. AHMCT also tested the new ATMA taking-the-lane feature at this site.



Figure I.5: Caltrans District 11 Otay Mesa SR 905 overcrossing test site