Teleoperated, Connected, and Automated Vehicles and Equipment for Maintenance Operations

Requested by
Ed Hardiman, Caltrans, Division of Equipment

March 1, 2021

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Summary of Findings

The University of California, Berkeley (UCB) conducted this preliminary investigation to review the available technical literature and industry information to identify promising technologies for truck-mounted attenuators (TMA), mowers, and loaders that are ready for implementation and which companies have the technology or expertise to do so. The focus of this project is to find companies who are potentially capable of providing support for teleoperated, connected, and automated vehicles and equipment for the California Department of Transportation (Caltrans) or have promising technologies ready for implementation. This report documents the literature review, outreach, and companies that could potentially provide Caltrans support or products.

The literature review provides the most current information regarding the National Cooperative Highway Research Program (NCHRP) Project 20-102. We reviewed evaluation reports and academic publications, as well as learnings from a recent Transportation Research Board (TRB) webinar, regarding TMAs, mowing tractors, and loaders. The goal was to provide various parameters for consideration when evaluating automated or teleoperated vehicles, such as accuracy and functional requirements, traffic impact, functional safety, and the human-machine interface for teleoperated vehicles. We summarized our outreach activity, which included discussions with academic researchers and other state departments of transportation (DOT), attending the annual meeting of the Autonomous Maintenance Technology Pooled Fund (TPF), and searching and connecting with companies. Based on our outreach, we found ten companies that can provide automation support. This report includes a brief introduction of each company, its relevant product or experience, and whether we recommend further contact.

Section 1. Background

Teleoperation is the technology that enables a human to remotely monitor and control an autonomous vehicle. It is based on a chain of devices ranging from high-speed cameras to modems to the control station itself. Teleoperation is the direct control by a remote operator with “hands on the wheel” driving, providing direct steering, acceleration, and braking commands to the vehicle.[1]

Connected vehicle (CV) technology refers to standardized vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to-everything (V2X) communication, broadly representing communication between vehicles, infrastructure, and other road users (such as pedestrians and cyclists). V2I can potentially interface with advanced traffic applications that use Intelligent Transportation Systems.

Automated vehicle (AV) technology provides driving control in relation to steering, acceleration, and braking. Depending on its intended functionality—from partial to full automation—the automated driving system can include elements of sensing, communicating, monitoring, navigating, decision-making, compensating for human behavior, and driving control required for progressing in traffic. The term AV covers a broad range of automated functions, both in terms of the extent to which it replaces functions of the human driver and the intended operating environment. The Society of Automotive Engineers (SAE) J3016[2] standard defines six levels of driving automation, from SAE Level 0 (no automation) to SAE Level 5 (full vehicle autonomy), as shown in Figure 1.

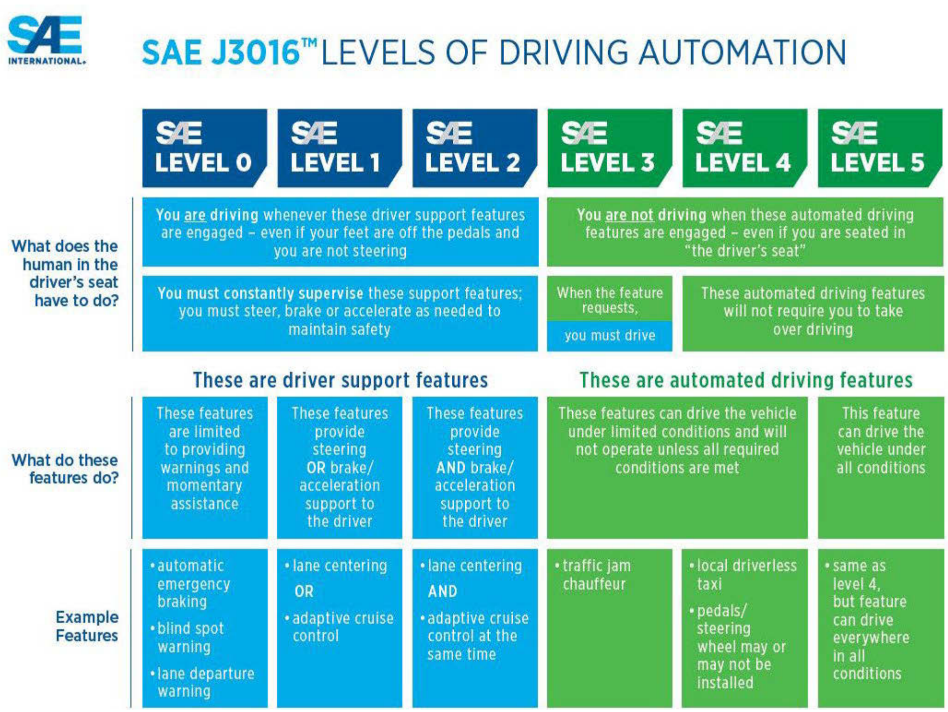

Figure 1. SAE Levels of Automation (source: SAE website)

[1] https://www.therobotreport.com/teleoperation-indirect-control-methods-for-autonomous-vehicles
[2] https://www.sae.org/standards/content/j3016_201806

Teleoperated, connected, and automated vehicles may provide a solution to safety issues that the Caltrans Division of Maintenance and Division of Equipment face. Caltrans highway maintenance and repair activities often require a shadow (trailing) truck equipped with a TMA to absorb the impact of a high- or low-speed collision from an errant vehicle and protect the workers. While the TMA increases worker safety, each collision still compromises the safety and well-being of the TMA driver. The goal is to completely remove TMA truck drivers from the risks associated with a collision. Similarly, removing equipment operators from other high-risk maintenance operations, such as mowing along steep inclines of a state highway route or clearing slide debris from the roadway, is also needed.

Section 2. Literature Review

2.1. NCHRP Project 20-102

NCHRP Project 20-102, *Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies*, covers a range of connected and automated vehicle (CAV) initiatives. The NCHRP Project 20-102 objectives are to: (1) identify critical issues associated with CVs and AVs that state and local transportation agencies and the American Association of State Highway and Transportation Officials will face; (2) conduct research to address those issues; and (3) conduct related technology transfer and information exchange activities.

A draft research roadmap was developed in 2015 as part of the NCHRP 20-24 project. The roadmap identified projects under four general clusters:

- Institutional and policy
- Infrastructure design and operations
- Planning
- Modal applications

The topic of “CV/AV applications for maintenance fleets” is defined under the modal applications cluster. As stated: “CV/AVs have great potential in maintenance fleets, such as snow removal, work-zone dampeners, garbage trucks, postal vehicles, etc. Some of these may even be near-term owing to the controlled environments they operate in.” This potential NCHRP project fits the scope of this preliminary investigation. However, the roadmap was only a starting point for projects under NCHRP Project 20-102. All ongoing projects are listed on the NCHRP website, and the “CV/AV applications for maintenance fleets” is not included. The NCHRP 20-102 project, “Determining the Impact of Connected and Automated Vehicle Technology on State DOT Maintenance Programs,” being implemented by Iowa State University, might be the closest research on highway maintenance fleets. It aims to (1) explore the effect of CAV technologies on the roadway and on transportation systems management and operations asset maintenance programs, and (2) develop guidance on measurable standards and resource implications.[3]

2.2. Existing Evaluation Reports and Publications

We reviewed evaluation reports and academic publications that focus on TMAs, mowing tractors, and loaders. The goal was to gather various parameters for consideration when evaluating teleoperated, connected, and automated vehicles.

Highway maintenance and repair activities, such as line painting, sweeping, and weed spraying [1] often require a shadow (trailing) truck equipped with a TMA to provide impact protection for workers from errant vehicles. The nature of shadow trucks, or TMA trucks, expects that they will be hit by errant vehicles. While the TMA truck increases worker safety, each collision compromises the safety and well-being of the shadow truck driver.

From June 27–29, 2017, the Colorado Department of Transportation (CDOT) tested the autonomous truck-mounted attenuator (ATMA) system developed by Kratos under various

[3] https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4571

scenarios.[4] The follower vehicle had three external Emergency Stop (E-Stop) buttons with the capability of stopping the follower vehicle when it is operating autonomously. During each test scenario, the log file generated by the ATMA system on the follower vehicle was collected. To test obstacle detection, a barrel was dropped in the path of the follower right behind the leader. Straight-line accuracy tests were performed using cones to form a lane. When testing over potholes, a small steering correction of the follower was observed when the rear tires hit the pothole. Currently, radar does not have the capability to detect an obstacle that is around a corner. Overall, most of the cross-track errors were within the acceptable range. However, bumpy roads and unreliable or inaccurate Global Positioning System (GPS) data might cause larger cross-track errors (Validation Data Report for Colorado DOT ATMA- Kratos, 2017, [2]).

The Missouri Department of Transportation (MoDOT) also tested the Kratos ATMA to check whether the system's hardware and software components met accuracy and functional requirements and could operate a minimum of 32 hours of operation over several days without needing an operator to take control due to unsatisfactory performance. Before deploying the ATMA for roadway maintenance, the researchers built simulation and analytical models to evaluate how it would impact traffic under different scenarios. The simulation tests demonstrated that the ATMA significantly impacted general traffic, especially on freeways and one-lane arterial roadways. When the ATMA vehicle was running at a slower speed, the impact on traffic was significantly increased. This research could serve as a reference for transportation agencies that are interested in deploying the ATMA system for work zone maintenance (Tang et al., 2020, [3]).

In 2017, Stolte et al. (2017, [4]) performed a hazard analysis and risk assessment (HARA) of an unmanned protective vehicle developed in Germany according to the ISO-26262 standard: Road vehicle – functional safety.[5] The results of the HARA could be used for developing other similar automated systems and ensuring their functional safety. The vehicle was operated without supervision only on hard shoulders and at a low speed of up to 12 kilometers per hour. The authors identified 17 safety goals for unmanned operation, as shown in Table 1. This example of the unmanned protective vehicle reveals challenges during a HARA for automated vehicles operated without human supervision. It was concluded that conventional HARA approaches are of limited suitability, especially for future applications with a wider functional range. The existing systematic approaches must evolve toward automated driving functionalities without human supervision.

[4] https://www.kratos-msi.com
[5] https://www.iso.org/standard/68383.html

Table 1. Protective Vehicle's Safety Goals (SGs) for Unmanned Operations

SG01	Unintended and not permitted operating mode change must be prevented.	SG10	Leaving tolerance ranges must trigger operating mode change to Safe Halt.
SG02	Intended and permitted operating mode change must be ensured.	SG11	Maximum velocity must not be exceeded.
SG03	Steering actuation beyond specification must be prevented.	SG12	Overrunning hard shoulder markings must be prevented.
SG04	Unintended anti-lock brake actuation must be prevented.	SG13	Detection of and reaction to (deceleration to a standstill) relevant obstacles (humans, vehicles, etc.) must be ensured.
SG05	Unintended acceleration must be prevented.	SG14	Identification of the leading vehicle must be ensured.
SG06	Detection of driver intervention must be ensured.	SG15	Detection of the missing leading vehicle and operating mode change to safe halt must be ensured.
SG07	Display of actual operating mode in HMI must be ensured.	SG16	Anti-lock functionality must be ensured.
SG08	Unintended slow acceleration must be prevented.	SG17	Unintended steering actuation must be prevented.
SG09	Deceleration to standstill must be ensured.		

To teleoperate an unmanned ground vehicle (UGV), one major challenge is the communication time delay introduced in procedures of both the control and sense paths. The time delay when sending the vehicle commands can lead to unresponsiveness. In addition, the time delay in the visual and sensory feedback from the UGV to the human operator can reduce the operator's situational awareness. Research has shown that these issues reduce the capability of the human operator to complete tasks and missions in the teleoperation settings and therefore reduce the effectiveness of the UGV platform. However, a human operator model could be used to develop predictive interfaces to reduce the negative impact induced by the time delay. Li et al. (2020, [5]) tried to address this need and extend the human operator model to varying speed scenarios. The purpose of the model is to predict the best steering performance in terms of the lowest average lane keeping error that can be expected from human operators when they are responsible for controlling both the steering and speed. The findings of this study encourage further development of cognitive models to predict UGV operator performance, which would facilitate the full simulation-based evaluation of UGV technologies.

2.3. TRB Webinar on Safer Work Zones

TRB hosted a webinar on July 9, 2020 to explore technologies for safer work zones. Presenters discussed current technologies that could mitigate work zone intrusion, how ATMA may help minimize work zone injuries, and other topics, such as using artificial intelligence (AI) for improving work zone safety.[6]

During the webinar, Dr. XB Hu from Missouri University of Science and Technology presented the field testing and evaluation of the Kratos ATMA in Missouri. Figure 2 shows the system architecture, where LT is the leader truck, and FT is the follower truck. The field tests included four categories: (1) communication loss; (2) following distance and accuracy; (3) obstacle detection; and (4) emergency situations. The researchers conducted each test three times and used the Friedman test[7] to evaluate the ATMA system's functional consistency. The results showed that the system functioned as expected and passed the predefined criteria.

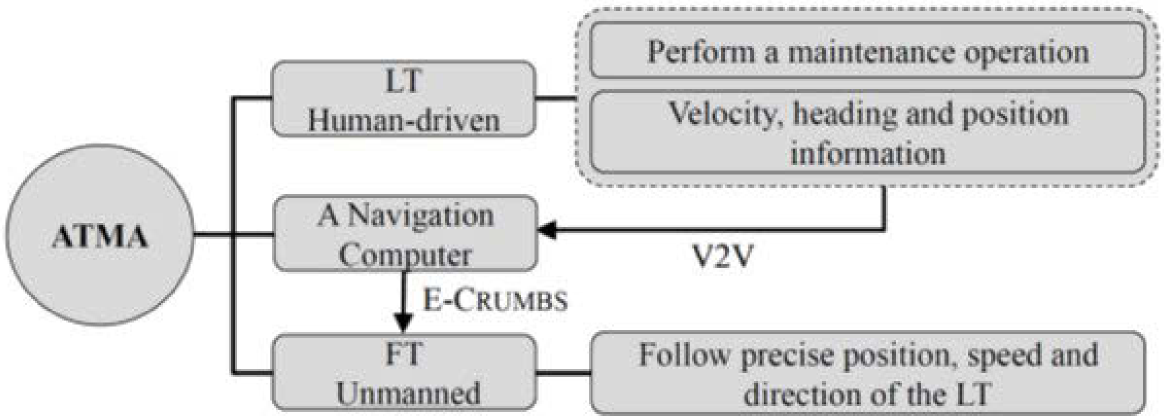

Figure 2. System Architecture of the ATMA Developed by Kratos

Dr. John Gambatese from Oregon State University shared his insights about work zone intrusion. To safely guide the driving public through a work zone, commonly used traffic control measures include temporary channelizing devices (for example, drums and cones), striping, concrete barriers, and signs. One of his research projects used survey methods to investigate work zone challenges with an emphasis on temporary sign. The study revealed that the presence of temporary signs distracted drivers less than the presence of construction equipment, workers, and lighting in work zones. Drivers are generally satisfied with current practices regarding the number of signs, the spacing between them, and the clarity of the messages displayed. Issues related to sign obstructions were mostly caused by construction equipment and trucks, which were confirmed through the field data collection. Transportation agencies could use the study recommendations to further improve the placement of temporary signs and ensure safe site conditions and passage through work zones (Jin et al., 2019, [6]).

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[6] http://www.trb.org/Main/Blurbs/180727.aspx
[7] https://en.wikipedia.org/wiki/Friedman_test

Section 3. Outreach Activity

Our outreach activities included discussions with academic researchers and state DOTs, attending the annual meeting of the Autonomous Maintenance Technology TPF-5 (380), and searching for and connecting with industrial companies.

3.1. Discussions with Academic Researchers

The UCB team contacted the researchers at the University of California, Davis Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, who are leading the ATMA pilot testing in California. We learned more details about the scope of the pilot testing, the performance of the Kratos ATMA, the challenges (such as misalignment and miscalibration) that they have encountered during the testing, and the plan for further evaluation in higher-speed conditions. We also learned about the Autonomous Maintenance TPF. In a previous study, the AHMCT Research Center had evaluated different models of remote-controlled slope mowers. They shared their report and insights regarding autonomous mowing tractors, which our project also focuses on.

We met with Dr. XB Hu from Missouri University of Science and Technology, who is an active member of the Autonomous Maintenance TPF and has tremendous research experience in ATMAs. Dr. Hu started working on ATMA-related research in 2017 and is now the principal investigator of multiple ATMA projects funded by both federal and state DOTs. Dr. Hu provided information on his research about the traffic impact of the ATMA system during work-zone maintenance which is included in the literature review of this report. He shared information about the vendors who showed interest in supplying ATMAs to MoDOT. We later contacted those vendors to determine whether their products or solutions fall within the scope of this project. Dr. Hu also introduced us to Theresa Drum, Caltrans' point of contact for the Autonomous Maintenance TPF.

3.2. State DOTs

To gather more information about the Autonomous Maintenance TPF, we contacted Theresa Drum, Caltrans' point of contact. We learned that CDOT leads the pooled fund, a coalition of transportation-related groups with interest in autonomous maintenance technology research that jointly funds and unifies research efforts that will benefit all contributing parties. Participating DOTs are Alabama, California, Colorado, Illinois, Kansas, Michigan, Minnesota, Missouri, Nevada, North Dakota, Ohio, Oklahoma, Texas, Virginia, and Washington. Five states, including California, have deployed an ATMA. Ms. Drum also expressed her interest in technologies that could be applied to work zone signs and smart cone technologies. We shared with her information and presentation materials that we had collected from the 2020 Automated Vehicle Symposium.[8]

Ms. Drum introduced us to the TPF contacts at the Colorado, Minnesota, Ohio, and Virginia DOTs. Due to availability, we held Zoom meetings and had email exchanges with the CDOT contacts. We learned that CDOT is the first state DOT to purchase the ATMA and start

[8] https://automatedvehiclessymposium.org/home

deployment, mainly for highway striping. As of mid-September 2020, the ATMA has been in operation on about 150 miles of Colorado public roads. For the next step, CDOT will use the ATMA under higher-volume traffic conditions. CDOT will also deploy a second ATMA in the southwestern part of the state, which is mostly rural. The CDOT contacts expressed interest in our PI work and invited the UCB team to the monthly and annual meetings of the pooled fund.

3.3. Annual Meeting of Autonomous Maintenance TPF-5 (380)

A pooled fund allows larger and more significant research projects to be undertaken by consolidating different DOTs' research efforts and investments. The initial scope of Autonomous Maintenance TPF focuses on:

- Improvements on existing ATMAs or autonomous impact protection vehicles (AIPV)
- Expansion of the use of ATMA and AIPV platforms beyond striping
- Refining policy and operational procedures for autonomous work vehicles
- Investigating additional applications for AVs in maintenance operations
- Other new technology

The annual meeting was held on October 26, 2020 on Zoom, mainly focusing on the following.

- Updates from California, Colorado, Missouri, and Virginia, four of the five states that have deployed an ATMA, regarding challenges that they have faced in deploying an ATMA and how they have overcome them. Theresa Drum from Caltrans discussed the ATMA pilot and testing in California. California, Colorado, and Missouri have purchased the AMTA from Kratos. Virginia is developing in-house technology with researchers from the Virginia Tech Transportation Institute. North Dakota also deployed an ATMA, but did not give an update during the meeting.
- Presentations of two research projects funded by the TPF: "Evaluating the Human-Automated Maintenance Vehicle Interaction for Improved Safety and Facilitating Long-Term Trust" by researchers from Colorado State University and "Quantification of Traffic Impact by Leader-Follower Autonomous Truck Mounted Attenuator Vehicle System for Work Zone Maintenance" by researchers from Missouri University of Science and Technology.
- Progress reports from the Deployment Toolkit Themes and Overview workgroup and the Policy and Legislative workgroup.

The meeting minutes and presentation materials are available at:
https://drive.google.com/drive/folders/1viR7KyhxWnDLSC26GvDJsCEf4hvQJ7sH

3.4. Searching for and Connecting with Vendors

The focus of this project is to find companies who can provide teleoperated, connected, and automated vehicle support or have promising technology ready for transportation maintenance operations. The strategies of looking for relevant companies included:

- Asking academic researchers and state DOT contacts for recommendations
- Asking Caltrans project stakeholders for recommendations
- Contacting AV testing companies who have been authorized to operate AVs on California streets and highways

- Web searching using the keywords, including but not limited to, autonomous/automated/teleoperated truck mounted attenuator, mower, loader, protection vehicle, work zone maintenance
- Deep-diving during communication with companies—typically, there are other technology providers for well-established agriculture or construction equipment companies

After identifying the list of companies who are potentially capable of providing the relevant technologies, we used the following approaches to connect with the responsible person at each company:

- Contact information of the AV testing companies shared by the California Department of Motor Vehicles
- Contact information or request form on the company website
- Contacting dealers
- LinkedIn connections
- Referrals from the researchers' personal contacts

Section 4. Companies

We identified several companies who are potentially capable of providing Caltrans support for teleoperated, connected, and automated vehicles and equipment or having promising technologies ready for implementation.

4.1. Kratos: ATMA

Kratos develops and fields affordable systems, platforms, and products for national security and communications needs. To date, it has deployed several ATMA systems in Great Britain and the United States, including California.

Relevant product or experience: The Kratos ATMA (as shown in Figure 3) is an innovative system that uses the leader-follower concept. A human driver operates the leader truck, which is equipped with a GPS instrument that drops electronic crumbs (eCrumbs) containing the position information for the follower. The autonomous follower vehicle, usually a TMA truck, follows the eCrumbs at a configured gap distance. The ATMA can be deployed during the day and night, supporting highway maintenance line painting, sweeping, and weed spraying operations.

Contact: Maynard Factor (Vice President of Business Development)
Phone: 850-461-4457
Email: maynard.factor@kratosdefense.com
www.kratosdefense.com
https://www.kratosdefense.com/systems-and-platforms/unmanned-systems/ground/autonomous-truck-mounted-attenuator

Figure 3. Kratos ATMA

4.2. MAN Truck & Bus: Unmanned Protective Vehicle

MAN Truck & Bus, a German company of Traton Group (formerly Volkswagen Truck & Bus AG), is one of Europe’s leading commercial vehicle manufacturers and transport solution providers. The company's portfolio includes vans, trucks, buses, coaches, diesel and gas engines, and services related to passenger and cargo transport.

Relevant product or experience: Starting in 2014, with seven other partners and funding of 3.4 million Euros from the German Ministry of Economic Affairs and Energy, MAN developed an autonomous and unmanned protective vehicle called aFAS. The acronym aFAS is derived from the German meaning "automatic driverless safety vehicle for work sites on German highways." While not yet commercially available, MAN's aFAS won the "Truck Innovation Award 2019." [9]

The test vehicle, TGM 18.340, was equipped with cameras and radar for environment sensing as well as various assistance systems. The steering and braking systems, sensors, and control software components had to meet the strictest criteria. The prototype vehicle relied largely on series components for both regular controls and for the implementation of functional security aspects. Specially designed surround sensors with a high-security level and integrated, reliable object and lane recognition enable data on route characteristics and traffic situation to be analyzed. Data is communicated between the work vehicle at the front and the safety vehicle at the back via wireless LAN and displays in both vehicles show the operating status of the driverless prototype.

Contact: www.mantruckandbus.com/en/index.html

4.3. Designated Driver: Teleoperation

Designated Driver, founded in September 2018, is headquartered in Portland, Oregon. Its focus is on building safe, reliable software for remote monitoring, assistance, and driving of autonomous and non-autonomous vehicles.

Relevant product or experience: To date, Designated Driver has worked with passenger cars, Tier 1 suppliers, passenger shuttles, and small robots. The company is actively pursuing projects with commercial trucks, delivery bots, and agriculture, mining, and industrial applications. All classes and types of vehicles can use remote monitoring, assistance, and driving to support development and testing as well as accelerate deployment. At the Goodwood Festival of Speed, the latency in remotely driving up a hill and drifting was under 50 milliseconds over 5G and under 120 milliseconds over 4G. Figure 4 shows a professional drifter remote controlling a vehicle using Designated Driver's telecommunication system. Its customers include AutonomouStuff, Texas A&M, Samsung, Visteon, and various telco providers. Moreover, its teleoperated shuttles have been developed and tested on Texas public roads. Designated Driver plans to meet the highest software quality standard of ISO 26262 by 2021.

What and how to provide support for Caltrans: Designated Driver showed great interest in potential collaboration with Caltrans. It can provide and adjust the software and hardware kit for different road maintenance equipment. It can also provide customized vehicle and software through the following services:

- Driver Station hardware and software kit: A seamless experience for the remote operator, passengers, and autonomous vehicle

[9] https://traton.com/en/newsroom/press_releases/press_release_19092018_2.html

- In-vehicle hardware and software kit: Componentized kit offering customers the flexibility to integrate with different vehicles
- Teleoperation as a service: Primarily for the development of fleets and trained, certified remote drivers; includes in-vehicle teleoperation software
- Integration services: Get help with kit integration and customizing the software for different needs

Contact: Walter Sullivan (Chief Technology Officer)
Email: sullivan@designateddriver.ai
https://designateddriver.ai

Figure 4. Designated Driver Telecommunication System

4.4. RCT: Teleoperation and Automation

RCT specializes in machine automation and control, protection, and information systems. It offers an array of proven solutions that are agnostic, fully interoperable, and can be integrated into third-party systems. Its automation and control capabilities are versatile enough to cater to specific requirements, ranging from the automation of a single machine to a fully autonomous fleet. Figure 5 shows RCT's automation path.

Relevant product or experience: RCT provides the following solutions for teleoperation and automation.

- Automation center—Numerous options, from customized solutions to prefabricated rooms, surface solutions, and more.
- Driverless technology—Delivers consistent machine operation and cycle times by significantly reducing damage and unplanned downtime caused by a machine impacting with surrounding infrastructure.
- Point-to-point—With a push of a button, the machine navigates itself to the destination; steering, braking, and speed are automatically controlled. The system uses laser technology to ensure that the machine remains on the center of the drive, avoiding walls and other major obstacles.

- G-Dash—Provides operators a real-time graphical representation on a separate designated display.
- Laser guard—Prevents driverless machines from leaving the operations area and restricts personnel from entering.
- Multiple machine select—Operators can switch controlling one machine to another from one station.

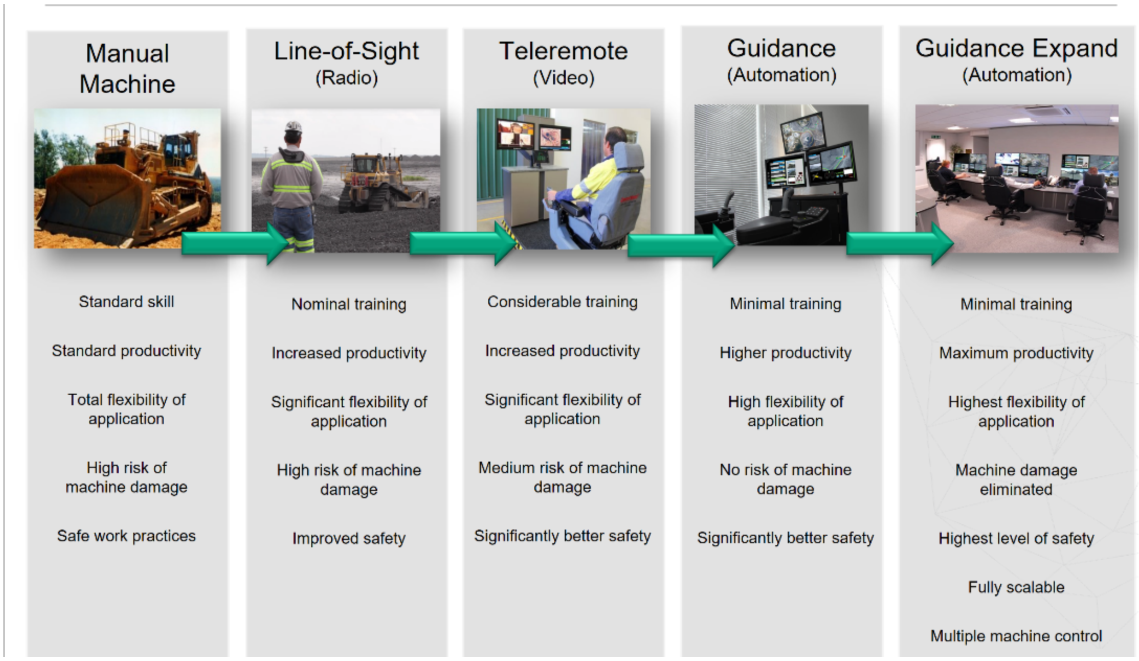

Figure 5. RCT's Automation Path

RCT works with clients in over 71 countries. Its lead time for new machine fitment and commissioning runs from 10–16 weeks. RCT claims that it can remotely control any piece of equipment regardless of the original equipment manufacturer (OEM). Its modular automation platform enables clients to choose the level of automation to start with and the ability to add higher levels of automation in the future.

What and how to provide support for Caltrans: This depends on the types of machines and automation that Caltrans wants to start with. RCT is more confident about loaders and mower tractors. It has automated hundreds of loaders, mostly for the mining industry. Automating tractors requires going through engineering and software development processes. RCT fits and commissions the solutions onto the equipment. It also offers safety and productivity packages for skills training, parts supply, technical support, and customer service support for all its proprietary products, including OEM maintenance agreement; auditing and installation; operational servicing; preventive maintenance; customized servicing schedule; servicing documentation; service exchange equipment; and online support.

Contact: Landon Lounsbury (Account Manager)
Phone: 801-938-9214
Email: LandonL@rct-global.com
https://rct-global.com

4.5. Northstar Robotics: Automation

Northstar Robotics is a Canadian company that has developed a platform to power networks of autonomous industrial vehicles. Its technology is available to industrial equipment manufacturers to accelerate autonomous development for agriculture, snow removal, and a wide range of other industrial applications. Northstar Robotics is launching an aftermarket autonomy retrofit kit and cloud platform for heavy equipment.

Relevant product or experience: Northstar Robotics has automated large runway snowplow machines (as shown in Figure 6), golf course fairway mowers, and small John Deere tractors. Because the company is located in Canada, due to COVID-19, it is not currently available to work on U.S. projects.

Contact: Shawn Schaerer (Chief Executive Officer)
Phone: 204-293-0150
Email: shawn@northstar-robotics.com
https://northstar-robotics.com

Figure 6. Northstar's Automated Runway Snowplow Machine

4.6. Phantom Auto: Teleoperation

Phantom Auto's software enables humans to remotely drive, assist, and monitor all types of unmanned vehicles from thousands of miles away, including forklifts, trucks, robots, and cars. The monitoring process is conducted through live video, audio, and data monitoring. The Phantom Core Software Development Kit is a vehicle-agnostic, secure software and cloud platform that delivers low-latency network communication to enable teleoperation.

Relevant product or experience: Phantom Auto's plug-and-play service can be provided for any vehicle through any network (4G LTE, Wi-Fi, 5G, etc.) and for any use case. Moreover, they can also guarantee enterprise-grade security, including ISO-27001, Secure Socket Layer, full data encryption, and robust authentication. Figure 7 is one example of drivers remotely controlling forklifts using Phantom Auto's technology during the COVID-19 pandemic.

Contact: We emailed Shai Magzimof, the company CEO, (shai@phantomauto.com), but we haven't received confirmed interest in participating in the follow-up project.
https://phantom.auto

Figure 7. Using Phantom Auto's System, Drivers Remotely Control Forklifts at Warehouses During the COVID-19 Pandemic

4.7. John Deere, Autonomous Tractor Concept

John Deere is a world leader in providing advanced products, technology, and services for agriculture and construction. In 2017, John Deere purchased the startup Blue River Technology, which brings the robotics platforms to their agricultural equipment.[10]

Relevant product or experience: John Deere's autonomous tractor concept is a compact, electric drive unit with an integrated attachment. The tractor has a total output of 500 kW and can be equipped with either wheels or tracks. Flexible ballasting from 5–15 is possible, depending on the application. Although this tractor is not yet commercially available, John Deere has an Autonomous 8370R Tractor[11] that is on the market. It uses a Controller Area Network. Although it is called an autonomous tractor, it is still driver-based and requires a driver to be behind the wheel all the time.

Contact for the 8370R tractor: Jeffrey Kerley (Sales Manager of John Deere's Dealer in Stockton, California)
Phone: 209-482-1081
Email: JKerley@belkorpag.com
www.deere.co.uk/en/agriculture/future-of-farming

4.8. CNH Industrial: Autonomous Tractor Concept

CNH Industrial has a global presence in the capital goods sector with established industrial experience and a wide range of products. Through its various businesses, it designs, produces and sells agricultural and construction equipment, trucks, commercial vehicles, buses and

[10] https://www.wired.com/story/why-john-deere-just-spent-dollar305-million-on-a-lettuce-farming-robot
[11] https://www.youtube.com/watch?v=yCtbFFEm7r0

specialty vehicles: Case IH, New Holland Agriculture, and Steyr for tractors and agricultural machinery; Case and New Holland Construction for earth-moving equipment; Iveco for commercial vehicles; Iveco Bus and Helieuz Bus for buses and coaches; Iveco Astra for quarry and construction vehicles; Magirus for firefighting vehicles; Iveco Defense Vehicles for defense and civil protection; and FPT Industrial for engines and transmissions.

Relevant product or experience: Case IH's driverless tractor, called the Autonomous Concept Vehicle, was first shown at the 2016 US Farm Progress Show.[12] The vehicle can be integrated into fleets of existing machines to work alongside them. It retains much of the conventional technology of a modern tractor and uses a real-time kinematic form of ultra-accurate GPS[13] to provide parallel steering capability with a variation of fewer than 2.5 centimeters. The tractor is still a concept vehicle and is not commercially available.

Contact: www.cnhindustrial.com/en-us/Pages/homepage.aspx

4.9. Kubota Corporation: Autonomous Tractor Concept

Kubota Corporation introduced its first tractor to the United States in 1969. Filling a product void in the American marketplace for a subcompact tractor, the Kubota 21 HP L200 was a success. Kubota Tractor Corporation (KTC) was formed in 1972, and the company continued to expand its product line for the U.S. market. Kubota now offers products in a wide variety of segments, including lawn mowers, utility vehicles, construction equipment, agriculture tractors, and hay equipment.

Relevant product or experience: In January 2020, Kubota demonstrated its autonomous tractor concept at a new product exhibition in Kyoto, Japan. Equipped with AI and electrification technology, the tractor is completely autonomous. Kubota plans to continue developing products to realize smart agriculture with cutting-edge technology to address the challenges that farmers face.

Contact: We reached out to the contacts provided on the company website and tried to connect through LinkedIn, but did not receive any responses. We also contacted the dealer of Kubota and learned that an autonomous product is not currently available.

www.kubota.com

4.10. Caterpillar: Autonomous Mining Trucks

Caterpillar is a Fortune 100 company that designs, develops, engineers, manufactures, markets, and sells machinery, engines, financial products, and insurance to customers via a worldwide dealer network. It is the world's largest construction equipment manufacturer.

Relevant product or experience: Caterpillar's initial development of Cat autonomous mining trucks began more than 20 years ago. In 1996, Caterpillar demonstrated its first autonomous mining truck at the National Mining Association MINExpo. Caterpillar was an early adopter of GPS guidance technology and had success with it in several applications. Caterpillar focused

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[12] https://media.cnhindustrial.com/EUROPE/CASE-IH/autonomous-tractor-technology-shows-way-forward-for-farming--enhancing-efficiency-and-working-condit/s/d9d11785-2881-4577-afc2-23e6dadbfc91
[13] https://en.wikipedia.org/wiki/Real-time_kinematic

on developing the building blocks for automation. These technologies are now the core of MineStar (Caterpillar's mine operations and mobile equipment management system), which assist onboard operators and enable teleremote, semi-autonomous, and autonomous machine operations.[14]

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www.petersoncat.com
www.caterpillar.com/en/news/caterpillarNews/customer-dealer-product/a-world-leader-in-autonomous-mining.html

Section 5. Next Steps

CAV technologies have advanced significantly in recent years. They have the potential to reduce traffic incidents, enhance quality of life, and improve the efficiency of transportation systems. At the same time, various technical challenges are impeding the commercialization and implementation of these technologies for consumer use or purchase (for example, passenger vehicles). However, because highway maintenance occurs in a specific domain, such as certain sections of a freeway, it could be much less complicated to implement CAV technologies and offer safety advantages.

In Section 4, we listed 10 companies that have the potential of providing Caltrans support for teleoperated, connected, or automated vehicles and equipment or having promising technologies ready for implementation. For the next step of this preliminary investigation—the investigation of teleoperated, connected, and automated equipment for Caltrans operations—we strongly recommend following up with the following companies based on their technology maturity, experience relevant to Caltrans' needs, and potential interest for collaboration:

- Kratos
- Designated Driver
- RCT
- Northstar
- Phantom Auto

We also recommend monitoring progress and report-releases coming from the NCHRP projects for forthcoming information on CAV applications for the maintenance fleet. Beyond the NCHRP projects, many states have put their effort and resources into exploring opportunities of using CAV technologies for enhancing the efficiency and safety of highway maintenance. Therefore, it would be beneficial for Caltrans to leverage or join the efforts with other state DOTs for the same cause.

[14] https://www.cat.com/en_US/news/machine-press-releases/cat-autonomous-mining-trucks-haul-one-billion-tonnes.html

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Abbreviations and Acronyms

AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
AI	Artificial intelligence
AIPV	Autonomous impact protection vehicle
ATMA	Autonomous truck-mounted attenuator
AV	Automated vehicle
CAV	Connected and automated vehicle
Caltrans	California Department of Transportation
CDOT	Colorado Department of Transportation
CV	Connected vehicle
DOT	Department of Transportation
GPS	Global Positioning System
HARA	Hazard Analysis and Risk Assessment
MoDOT	Missouri Department of Transportation
NCHRP	National Cooperative Highway Research Program
OEM	Original equipment manufacturer
SAE	Society of Automotive Engineers
TMA	Truck-mounted attenuator
TPF	Transportation Pooled Fund
TRB	Transportation Research Board
UCB	University of California, Berkeley
UGV	Unmanned ground vehicle
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

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