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16. Abstract <p>With the advent of autonomous vehicles, it may be possible to reduce worker exposure and risk by utilizing driverless tractors for mowing operations. The objective of this study is to assess ease of use, safety, and appropriateness of non-line-of-sight, remote control / automated vehicle technologies for Caltrans transportation maintenance operations. To begin, a review of the technical literature was completed. Included in this effort was the development and distribution of a questionnaire to assess Caltrans needs as tabulated in Chapter 3. Based on a preliminary review of the literature, it was apparent industry is developing vehicles which can meet Caltrans needs. For example, in January of 2022, John Deere announced their first fully autonomous tractor which is ready for large-scale production. According to their press release the tractor, which is for agriculture applications, uses GPS guidance and a geofence for navigation along with six cameras which allow for 360-degree obstacle detection (John Deere, 2022). Announcements and concept autonomous tractors have also been released by other companies including New Holland (New Holland, 2017), Massey Ferguson (Wordsworth, 2019), and Kubota (Herath, 2020) to mention a few. Given the significant interest by industry, a draft specification was formulated, a group of potential vendors was identified and efforts to assess their interest and potential involvement are documented in Chapter #5.</p> <p>As the project progressed, it became apparent California Legal Codes did not fully support the use of autonomous vehicles for maintenance activities. Articles 3.7 and 3.8 under Chapter 1 of California Code of Regulations Title 13 – governing the implementation of autonomous vehicles on the State’s streets and highways, states: <i>All self-propelled equipment shall, when under its own power and in motion, have an operator stationed at the vehicular controls...</i></p> <p>Acknowledging the potential legal issues, and in consultation with the Caltrans Technical Advisory Committee (TAC), it was agreed a demonstration should focus more on “education” rather than “evaluation”. Select findings from the demonstration include:</p> <ol style="list-style-type: none"> 1. Continue the dialog with Caltrans and Agency staff to encourage modifications to California Code to allow the eventual deployment of autonomous technology in mowing operations (and eventually other maintenance operations). This would include agreement on definitions of the area to be mowed (i.e., operational zone) 2. Continue development of autonomous technology within the current legal framework oriented toward mowing operations via a Pilot Project in California 3. Perform a cost-benefit analysis to determine whether retrofit of an existing tractor in the Caltrans inventory is economical. 					
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INVESTIGATING TELEOPERATED EQUIPMENT FOR USE IN HIGHWAY MAINTENANCE OPERATIONS

**Final Report
December 2024**

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EXECUTIVE SUMMARY

Connected vehicle technologies are being developed to enable safe, interoperable networked wireless communications among vehicles (V2V), the infrastructure (V2I), and travelers' personal communication devices (V2X). These technologies are intended to reduce highway crashes; provide data for assessing the performance of the transportation system; provide continual access to accurate information on the operation of the system to travelers; and reduce unnecessary stops, delays, and emissions. Automated vehicle technologies are also under development that will significantly change fundamental planning, design, and operational characteristics for the road network. Limited Level 4 vehicle automation [under National Highway Transportation Safety Administration (NHTSA) and Society of Automotive Engineers (SAE) definitions] was available on the market in 2018. It is expected, fully autonomous, driverless vehicles (SAE Level 5 automation) could be on the market by 2025. Connected vehicles and autonomous vehicles are essentially different technologies, though some of the challenges they present to transportation agencies will be similar.

Connected and autonomous vehicles may also provide a solution to safety issues facing highway maintenance and construction crews. Advances in the field of autonomous/self-driving vehicles have demonstrated potential for new and innovative applications that could change how State Departments of Transportation (DOT's) and other public agencies manage roadside vegetation, and roadway construction, among other applications. Primary vegetation control needs include maintenance of roadbed integrity, visibility, drainage, noxious weed control, aesthetic roadside appearance, and fire protection [Caltrans, 2018]. Mowing of medians and right-of-way is an important vegetation management practice for Caltrans, but it is labor intensive and exposes workers to high-speed traffic.

With the advent of autonomous vehicles, it may be possible to reduce worker exposure and risk by utilizing driverless tractors for mowing operations. The objective of this study is to assess ease of use, safety, and appropriateness for Caltrans operations of non-line-of-sight, remote control / automated vehicle technologies for Caltrans transportation maintenance operations. This includes available Original Equipment Manufacturer (OEM) systems and retrofit of existing vehicles (tractors) in the Caltrans inventory.

To begin, a review of the technical literature was completed and is summarized in Chapter 2.0. Included in this effort was the development and distribution of a questionnaire to assess Caltrans needs. The questionnaire and subsequent results are as tabulated in Chapter 3. Based on a preliminary review of the literature, it is apparent industry is developing vehicles which can satisfy Caltrans needs. For example, in January of 2022, John Deere announced their first fully autonomous tractor which is ready for large-scale production. According to their press release the tractor, which is for agriculture applications, uses Global Positioning System (GPS) guidance and a geofence for navigation along with six cameras which allow for 360-degree obstacle detection (John Deere, 2022). Announcements and concept autonomous tractors have also been released by other companies including New Holland (New Holland, 2017), Massey Ferguson (Wordsworth, 2019), Kubota (Herath, 2020), Mahindra (ETAUTO, 2017), Agco (AGCO 2019), Sabanto (DTN/Progressive Farmer, 2020), Raven Autonomy (Raven Precision, 2021), and

Jaybridge Robotics/Kinze Manufacturing (Jaybridge Robotics, 2020). These systems range in capabilities including remote guidance and pre-specified routes, as well as systems for which specifications are not available in public forums. Given the significant interest by industry, a draft specification has been formulated as shown in Chapter 4. Continuing, a group of potential vendors was identified and efforts to assess their interest and potential involvement are documented in Chapter #5.

As the project progressed, it became apparent California Legal Code (and hence Caltrans policy) did not fully support the use of autonomous vehicles for maintenance activities. Articles 3.7 and 3.8 under Chapter 1 of California Code of Regulations Title 13 – governing the implementation of autonomous vehicles on the State’s streets and highways, states: *All self-propelled equipment shall, when under its own power and in motion, have an operator stationed at the vehicular controls...*

Acknowledging the potential legal challenges, and in consultation with the Caltrans Technical Advisory Committee (TAC), it was agreed a demonstration should focus more on “education” rather than “evaluation”. That demonstration would be held in the Sacramento area. The objective of this demonstration would be twofold: (i) provide a demo of an automated tractor system that is currently being used for mowing applications and ensure that mowing can be monitored via a Transportation Management Center (TMC)/Emergency Operations Center (EOC) as appropriate, and (ii) provide case studies of examples where automated technologies have been used or tested in similar operating environments in development, research, or practice.

As a result of this study, findings identified to improve the potential for deployment of autonomous technology in highway maintenance operations include:

1. Continue the dialog with Caltrans and Agency staff to encourage modifications to California Code to allow the eventual deployment of autonomous technology in mowing operations (and eventually other maintenance operations). This would include agreement on definitions of the area to be mowed (i.e., operational zone)
2. Continue development of autonomous technology within the current legal framework oriented toward mowing operations via a Pilot Project in California
 - a. deploy “mowers” at more than one location (e.g., northern California and Central Valley)
 - b. deploy mowers with a driver on-board per California Code
 - c. evaluate different environmental and management “cultures”
 - d. evaluate various mapping software
3. Continue to improve definitions of right-of-way (ROW) and traveled way as begun in this study, including the target values suggested in Table 6.4
4. Perform a cost-benefit analysis to determine whether retrofit of an existing tractor in the Caltrans inventory is economical
5. Extend the technology developed for maintenance operations to constructions (e.g., AV sweeper).

CHAPTER 1. INTRODUCTION

1.1 Background

Connected vehicle technologies are being developed to enable safe, interoperable networked wireless communications among vehicles (V2V), the infrastructure (V2I), and travelers' personal communication devices (V2X). These technologies are intended to reduce highway crashes; provide data for assessing the performance of the transportation system; provide continual access to accurate information on the system's operation to travelers; and reduce unnecessary stops, delays, and emissions.

In addition, automated vehicle technologies are also under development that will significantly change fundamental planning, design, and operational characteristics for the road network. Limited Level 4 vehicle automation (under NHTSA and SAE definitions) was available in 2018. It was expected that fully autonomous, driverless vehicles (SAE Level 5 automation) could be on the market by 2025. However, that deployment will probably be delayed due to existing legislation restricting autonomous vehicles on the traveled way.

Connected and autonomous vehicles are essentially different technologies, though some of the challenges they present to transportation agencies will be similar. These two technologies may converge or diverge from each other based largely on developments in the private sector (e.g., vehicle manufacturers and third-party vendors). While some researchers envision a completely autonomous vehicle that does not require communication with other entities, others see serendipities between the two technologies.

Connected and autonomous vehicles may also provide a solution to safety issues facing highway maintenance crews. California Department of Transportation (Caltrans) highway maintenance and repair activities often require a shadow (trailing) truck equipped with a Truck Mounted Attenuator (TMA), which is intended to absorb the impact of a high or low-speed crash from an errant vehicle collision and provide protection for the workers. While a TMA increases safety for the workers, each collision still compromises the safety and well-being of the TMA truck driver. Similarly, crews are also exposed to other hazards during mowing operations along a state highway route, and it is necessary to reduce those risks.

Advances in the field of autonomous/self-driving vehicles have shown potential for new and innovative applications that could change how State Departments of Transportation (DOTs) and other public agencies manage roadside vegetation and roadside construction, among other applications. Primary vegetation control needs include maintenance of roadbed integrity, visibility, drainage, noxious weed control, aesthetic roadside appearance, and fire protection [1]. Mowing of medians and right-of-way (i.e., operational zone) is an important vegetation management practice for Caltrans, but it is labor-intensive and requires expensive and specialized equipment. Connected and automated vehicles have the potential to improve worker safety by reducing exposure to unwanted events or risks.

Innovation in autonomous vehicle technologies is largely driven by the passenger vehicle market. However, recent announcements and concept autonomous tractors have been released by companies including John Deere [2], New Holland [3], Massey Ferguson [4], Kubota [5], Mahindra [6], Agco [7], Sabanto [8], Raven Autonomy [9], and Jaybridge Robotics/Kinze Manufacturing [10]. These systems range in capabilities including remote guidance and pre-specified routes, as well as systems for which specifications are not available in public forums.

Automation levels are commonly defined using SAE or the National Highway Transportation Safety Administration (NHTSA) classification levels. The SAE [11] definition is:

- Level 0 – The driver controls the vehicle at all times, with some automated functions available (e.g., cruise control, ABS, automatic transmission, etc.)
- Level 1 - Individual vehicle functions are automated, such as automatic braking
- Level 2 – At least two automated technological functions occur in unison, such as adaptive cruise control in combination with lane keeping.
- Level 3 – Autonomous-driving option that the driver can fully cede control of all safety-critical functions in certain conditions, but human monitoring and override are still required.
- Level 4 – High automation requires the vehicle to perform all safety-critical functions for the entire trip, with the driver not expected to control the vehicle at any time. The system only performs under specific circumstances (including geofencing). Human override is still an option.
- Level 5 – Full automation requires the vehicle to perform all safety-critical functions for the entire trip under all conditions. No human attention or interaction is required.

These definitions for autonomous vehicles are targeted to passenger vehicles and, thus, may not be the best taxonomy for tractors and agricultural equipment. Thus, categories of automation for tractors have been defined by Case IH [12].

- Category 1 – Guidance. Vehicles are still manned by an operator but outfitted with Advanced Farming System (AFS) guidance technologies that help improve efficiency (such as reductions in overlaps and skips).
- Category 2 – Coordination & Optimization. This uses both vehicle and environmental data linked to an information hub. This allows plot-wide communication between manned and unmanned equipment. Category 2 technologies control various functions including ground speed and rear Power Take Off (PTO).
- Category 3 – Operator Assisted Autonomy. Technologies in this category allow the vehicle to drive itself (with simple monitoring, backup, and support from the operator when needed) while the on-board operator focuses on the implement behind the vehicle.
- Category 4 – Supervised Autonomy. The technologies that allow this level of autonomy require in-field supervision while the vehicle performs designated tasks.
- Category 5 – Full Autonomy. This category includes the most advanced autonomous vehicle technologies for tractors and agricultural equipment. These vehicles are operated with remote supervision or using artificial intelligence (AI).

Investments in connected and automated agriculture equipment, including tractors, have been increasing due to the potential benefits, including reductions in labor costs, optimized farming operations, and increased yields [13]. As indicated previously, there are also potential benefits from the use of these technologies in maintaining roadside vegetation and other applications including improved worker safety.

1.2 Current State of Technologies

To meet the requirements for roadside vegetation control in diverse conditions and environments, Category 4 or Category 5 autonomous agricultural vehicles will likely be required. The current technologies in the automation of agricultural vehicles are advancing quickly, compared to autonomous systems for passenger vehicles, due to the simpler operating environment. For instance, most Category 4 and Category 5 technologies are based on predetermined routes and/or geofenced areas (e.g., field borders) [Fortuna, 2019]. Some of these systems can avoid driving over and/or crushing crops. However, when the system encounters an unexpected object, it shuts down until an operator intervenes [New Holland Agriculture, 2017]. These systems are not designed to interact with passenger cars, cross highways, or drive on the roadway (i.e., traveled way).

While some agricultural AV systems are capable of being guided using remote controls, current technologies require the operator to be in the field where they can see the tractor. These systems currently have difficulties when encountering humans or other, unexpected objects [Progressive Farmer, 2020]. Systems that can independently detect and avoid known and unknown objects encountered in fields (including deer, fallen trees, etc.) are being developed, but are not commercially available yet [Hamblen, 2020].

Another area of concern is the lack of legislation allowing the flexible use of autonomous agricultural equipment. For instance, California Title 8, Section 3441, Subsection b states [State of California, 2020]:

All self-propelled equipment shall, when under its own power and in motion, have an operator stationed at the vehicular controls. This shall not prohibit the operator occupying or being stationed at a location on the vehicle other than the normal driving position or cab if controls for starting, accelerating, decelerating, and stopping are provided adjacent and convenient to the alternate position. If the machine requires steering other than ground or furrow steering or operates at ground speeds in excess of two miles per hour, steering controls shall also be provided at the alternate location.

1.3 Potential Solution

Aside from existing legal challenges, the potential for using autonomous agricultural equipment in roadside vegetation maintenance and other common DOT tasks has been the topic of previous research [Arsenault et al., 2010; Creed et al., 2012; Hart and Gharaibeh, 2011]. This research has shown the potential benefits of using autonomous vehicles for roadside vegetation control,

including considerations of potential testing conditions and requirements, such as the presence of guardrails and medians and shoulders, to mention a few [Arsenault et al., 2010]. While these are important to consider when designing testing requirements, other considerations should include weather and lighting conditions, as well as slopes and side slopes. These testing requirements and considerations include [Arsenault et al., 2010]:

- Presence of Guardrails
- Clear Strips (also known as mow strips or fire strips) next to pavement edges
- Medians and Shoulders
- Landscaping
- Highway Interchange Quadrants

While these are important to consider when designing testing requirements, other considerations should include:

- Weather and lighting conditions
- Vegetation types (e.g., weeds, grasses, shrubs, trees)
- Highway / right-of-way grade and Side Slopes
- Interactions with roadway traffic (at intersections and on-road segments)

In addition to testing requirements and considerations, performance metrics for comparison of different systems have also been suggested, including [Arsenault et al., 2010]:

- Mow Rate
- Efficiency (minimizing overlap from previously covered paths)
- Effective Mowing (i.e., minimizing vegetation left behind)

To meet the requirements for roadside vegetation control in diverse conditions and environments, teleoperated (without line-of-sight requirements), Category 4, or Category 5 autonomous agricultural vehicles will likely be required. The technological requirements for these vehicles to work in the roadside environment will likely include multiple types of sensors located at various positions on the vehicle (i.e., cameras, radar, lidar, ultrasonic sensors, and Real Time Kinematics (RTK) GPS. An example of a potential setup for sensors on a tractor for autonomous agricultural applications is shown in Figure 1.1.

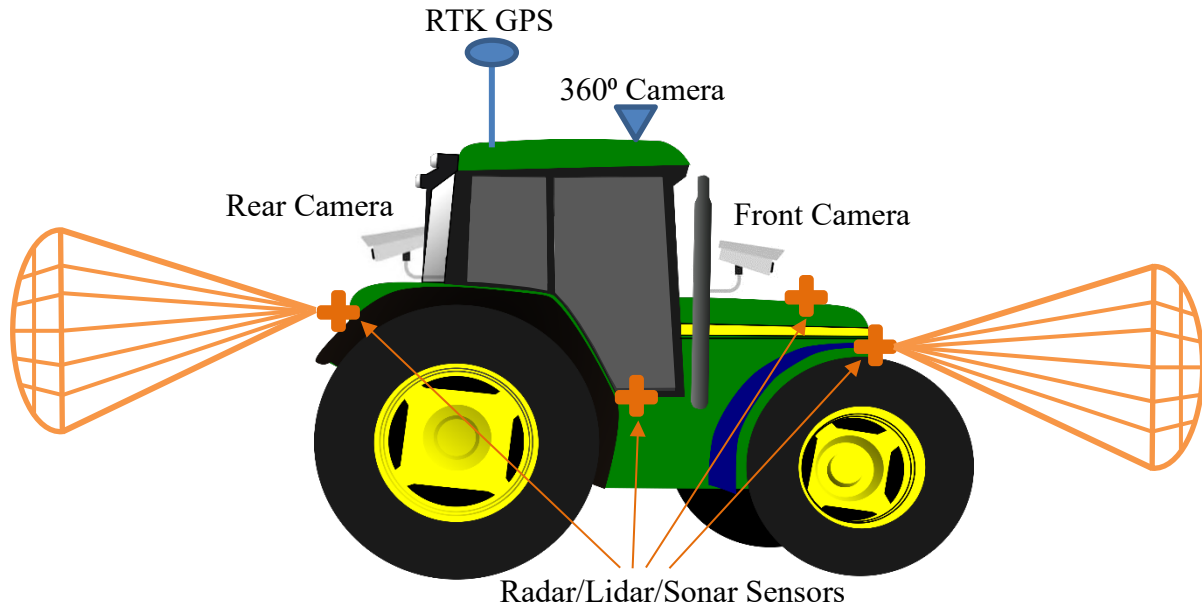


Figure 1.1. Potential sensor setup for autonomous agricultural vehicle

However, there still remains a need to develop operational specifications and use cases based on the needs of Caltrans (and other transportation agencies for that matter). Using these criteria and test cases, testing criteria need to be developed to validate autonomous system performance to satisfy Caltrans needs. Using the test criteria, along with specifications and requirements for an autonomous system, available and upcoming systems can be tested and evaluated for potential use by Caltrans. Another area of research related to autonomous vehicles is non-line of sight, remote control technologies. While some may argue this is included in autonomous vehicles, others will say it is a separate field. For purposes of this study, we shall consider them as one and refer to them as non-line of sight, remote control / automated vehicle technologies.

1.4 Organization of the Work

With the advent of autonomous vehicles, it may be possible to reduce worker exposure and risk by utilizing driverless tractors for mowing operations. The objective of this study is to assess ease of use, safety, and appropriateness for Caltrans operations of non-line-of-sight, remote control / automated vehicle technologies for Caltrans transportation maintenance operations. This includes available OEM systems and retrofit of existing tractors.

To start, a review of the technical literature was completed (Task #2) and is summarized in Chapter 2. Included in this effort was the development and distribution of a questionnaire to better understand user needs. The questionnaire and subsequent results are tabulated in Chapter 3. Based on that work, a draft specification (Task #3) has been formulated and is presented in Chapter 4 and incorporated into the Caltrans Specification (#59218-034-171). The revised specification is included as Appendix A. To evaluate the technology, a group of potential vendors was identified and are summarized in Chapter #5. While the original intent was to

evaluate the products from potential vendors, that objective was modified based on potential legal headwinds to deploying autonomous technologies in highway maintenance operations. In consultation with Caltrans, it was agreed a demonstration of the technology that was more educational in scope was in order to explain the technology to a wide range of transportation managers and officials as to the capabilities of autonomous technology for maintenance operations. Chapter #6 presents a summary of the demonstration and its outcomes. Lastly, a summary of the report and suggested future work are provided in Chapter #7.

CHAPTER 2. LITERATURE REVIEW

2.1 Background

Vegetation control is an important aspect of roadside maintenance. Vegetation control is often accomplished through mechanical control (i.e., mowing and clearing which helps to keep the roadsides with clear sight lines so that drivers can see traffic control devices, approaching vehicles, pedestrians, and bicyclists as well as any wildlife or livestock). It also provides adequate sight distance approaching intersections and throughout curves (Eck and McGee, 2008). In areas that are prone to fires, like California, proper vegetation control can also help to reduce fire risk. Proper vegetation control can also reduce an agencies risk to tort liability lawsuits (Eck and McGee, 2008).

While vegetation control operations are an important task, there is a need to balance the benefits of mowing with the costs. These costs include the actual cost of mowing, which a Wisconsin study found ranged from a little under \$100 per lane mile to almost \$400 per lane mile (Adams, 2011), environmental factors such as increased emissions (Sonntag et al., 2015), and increased risk to workers being in vehicle collisions. Based on Caltrans 2018 Fact Booklet Selected Maintenance Costs, vegetation control (i.e., non-landscaped weed control and maintenance of landscaped property) cost \$85.8 million for 2015-2016 (Caltrans, 2018). This is due to it being labor intensive and requiring specialized equipment. The following sections review literature on vegetation control methods, mowing to control fire risk and how agencies are leveraging technology to improve mowing operations.

2.2 Summary of Literature

2.2.1 *Vegetation Control Methods*

An Agency's vegetation control strategy will generally include a mixture of methods such as mechanical control (e.g., mowing and string trimming), chemical control (i.e., herbicides), permanent control (e.g., paving, laying gravels), and cultural (e.g., mulching, burning, flooding) and biological control (e.g., grazing). While chemical control has been used frequently in the past, many agencies are working to reduce their reliance on the use of herbicides due to the environmental and health concerns. This has increased the reliance on mechanical control, which is labor intensive and thus expensive. This has led to an increased focus on optimizing vegetation control strategies to still provide the safety benefits through mowing where needed but reduce mechanical and chemical control where possible.

American Association of State Highway and Transportation Officials (AASHTO) Guidelines for Vegetation Management (AASHTO, 2011) and National Cooperative Highway Research Program (NCHRP) 14-40 (Storey et al., 2020), break vegetation management areas into three main zones. These zones are demonstrated through the graphic from the AASHTO Guidelines in Figure 2.1 below. The first zone is the roadway surface and shoulder area where vegetation is completely removed; this is referred to as the vegetation free zone. The area where most mowing

by state agencies occurs is within Zone 2, the recovery or operational zone. In most cases this is from the edge of the shoulder to the edge of the clear zone. This area is mowed, and vegetation is controlled to ensure safety with clear sight lines, fire hazard and fixed object control. Some states also maintain the area beyond the clear zone to the boundaries of the ROW, which is Zone 3, the natural zone. However, there has been a push to adopt managed succession for this area outside the clear zone.

Managed succession is a strategy that promotes the establishment of desirable, native plant species to colonize the area outside the clear zone but still within the right of way (ROW). Managed succession uses a combination of zero maintenance, targeted mechanical, and chemical control to maintain these roadsides which results in a significant cost savings due to reduced labor required to maintain the roadsides. Managed succession does however require increased maintenance over the course of the initial 2-5 years to help in the establishment of these native species while removing non-native and noxious weeds. Once established these native plants can not only reduce maintenance needs, but they also provide a habitat for pollinators.

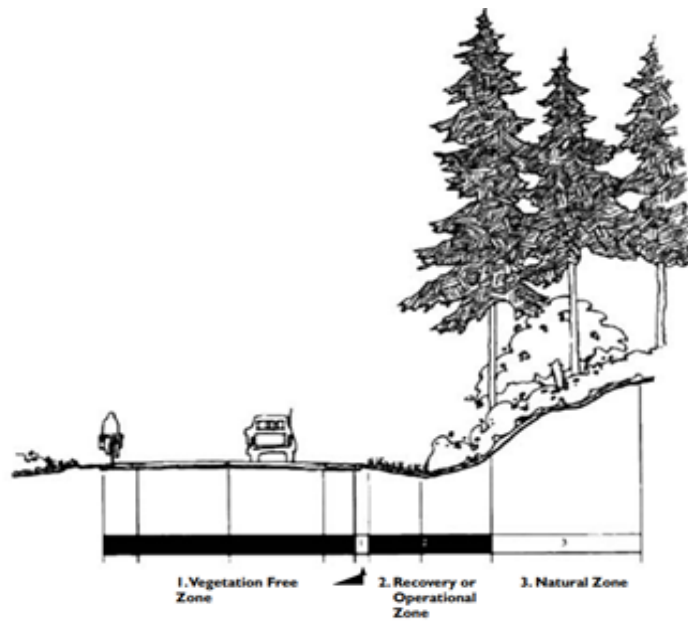


Figure 8-1. Roadside Vegetation Management Zones (diagram adapted from the WSDOT 3 zone system)

AASHTO 2011

Figure 2.1. Roadside vegetation management zones

In addition to managed succession/reduced mowing outside the clear zones, there has also been a push for reduced mowing within Zone 2. A study by Van Dyke et al. (2021) evaluated the Kentucky Transportation Cabinet’s desire to adopt conservation (i.e., reduced) mowing strategies with the goal of reducing expenses related to mowing while also creating roadside landscapes that support pollinators. Until 2020, Kentucky did a full mow from the edge of the pavement to the edge of the ROW. This was repeated 2-6 times depending on how many cycles were contracted. In 2020, they switched to mowing just 10-foot strips adjacent to pavement edges including normal medians and interchange ramps for the first scheduled cycle of mowing. They

calculated cost savings for this and in 2020, by using the reduced mowing method for the first cycle resulted in \$1.6 million in savings. It was estimated that total savings up to approximately \$24 million between 2020 and 2025 could be achieved by converting an additional cycle of mowing each year to the strip mowing. This would save the state significant money as well as protect vegetation used by pollinators

Additionally, Van Dyke et al. (2021) also interviewed other states who had some form of reduced mowing. These states included Alabama, Florida, Illinois, Indiana, Maryland, Minnesota, Missouri, Nebraska, Ohio, Pennsylvania, Tennessee, Texas Virginia, Washington, and Wisconsin. They synthesized each of the individual state policies and came up with general recommendations based off trends. It was found that medians with widths of 40'-70' typically have 15-foot strips mowed adjacent to the roadway. Narrower medians are generally completely mowed. This mowing is generally done 2-3 times per year, or more frequently to maintain adequate sight distance as well as the clear zone. Most agencies mow to heights of 6-8 inches to avoid damaging the vegetation. In addition, medians are usually mowed completely at least once a year in the fall to keep woody vegetation from establishing. Mowing of clear zones generally includes a 10'-15' strip next to the pavement that is mowed 2-3 times per year to heights ranging from 6-8 inches. The remaining area of the clear zone is then mowed either once per year or, at some agencies, once every 2-3 years. In both the median and clear zone, herbicide is used for spot treatment of noxious weeds. The remaining area in the ROW that falls outside the clear zone is generally left alone with some agencies choosing to do a full mow once every 2-3 years. To keep undesirable vegetation out of this area, agencies will also spot mow, manually trim brush and trees and selectively apply herbicide.

Caltrans vegetation policy (Caltrans, 2014) notes that retaining native vegetation on the roadsides is desirable as the presence of vegetation can help “reduce driver fatigue, improve storm water quality, help with erosion control, help maintain slope stability and enhance aesthetics”. However, proper vegetation control is needed to help with fire prevention, safety, reduction of invasive and noxious weeds and to help with bridge inspection needs. As part of their vegetation control strategy, each district within Caltrans develops an annual vegetation control plan or VegCon Plan. As part of the VegCon plan, the district must consider fire risk and must contain information on its mowing program.

The Caltrans vegetation control policy lays out considerations which should be considered by districts within their VegCon plans. One of these considerations is that they maintain control strips up to ten feet wide for traversable slopes along the paved shoulders of the roadside edge and along the median edges for medians 36 feet or more in width, like the synthesis found in the Kentucky study (Van Dyke et al., 2021). For medians 36' or less in width, the entire width should have appropriate vegetation control. For non-traversable slopes, up to a four-foot-wide control strip should be considered. They also try to maintain vegetation within 2 feet of guardrails, delineator posts or other safety hardware that aren't included in shoulder treatments. It is noted that mowing should be completed as needed to ensure visibility and sight distance on horizontal curves, ground mounted signs and near intersections There is also consideration for mowing entire interchange areas in urban and developed areas.

Mowing should be to a height no less than 6 inches and may be higher based on recommendations by the District Landscape Architect or Landscape Specialist. This height was chosen as it avoids scalping the ground which could increase weed propagation. They also note that timing mowing is important to reduce the spread of noxious weeds and that subject matter experts should be consulted to develop a strategy that will optimize native self-sustaining vegetation.

In addition to their vegetation control policy, Caltrans also provides a toolbox of countermeasures which will reduce required vegetation control needs (Caltrans, 2022). Treatments listed that can help reduce mechanical control include things such as weed control mats made of fiber or rubber which are placed around signposts, light poles or under guardrail (especially in new installations). Caltrans also utilizes minor concrete vegetation control as standard treatment to control weeds under new Midwest Guardrail and Thrie Beam installations in areas where repetitive vegetation control would be required. In situations where minor concrete vegetation control can't be used, they suggest asphalt composite vegetation control. They also recommend the use of native vegetation. This can reduce maintenance needs due to the slow growth patterns (Caltrans, 2012).

Through NCHRP 14-41, researchers at Texas Transportation Institute provided guidance on permanent vegetation control treatments that can be utilized in hard to maintain areas such as along barriers, pavement edges, slope embankments, signpost bases, gores and medians and the mowed edge. As part of this project, they put together an online tool (available at: <https://nchrp14-41.tti.tamu.edu/core/facility.htm>) which allows one to select the area where vegetation management is needed, the level of aesthetics which must be maintained (i.e. standard or high) and the construction type (i.e. retrofit or new construction) and the tool will provide various permanent vegetation control treatment that would be appropriate. Some of these permanent treatments include standard and minor concrete pavements, asphalt composites, aggregate base, geosynthetic cementitious composite mats, rock blankets, gravel mulch, and native/non-irrigated vegetation (TTI, 2022).

Researchers from University of California at Davis, in a project sponsored by Caltrans, looked at emerging vegetation control technology to try to reduce the dependence on herbicides and mowing on the roadsides. They performed an analysis on three potential technologies that included hot foam application, hydro-mechanical obliteration, and thermal treatment. While finding there is likely a great benefit to implementing one, or a mixture of these methods, the study did note that further research needs to be done to quantify the benefits of using these technologies instead of traditional methods (Arsenault et al., 2008).

Other industries are also looking to control vegetation through non-chemical means. The rail industry has tried the use of wet infrared systems which apply high heat to weeds located within the ballast surrounding railroad tracks similar to a combination of the thermal and hot foam applications studied by Arsenault et al. (2008). In a study sponsored by the Federal Transit Administration, Vermont studied the use of this technology and found no statistical effects on the number of weeds on sections of rail that had been treated (Burnham et al., 2003).

2.2.2 Mowing to Control Fire Risk

One of the main purposes of vegetation control is to reduce fire risk on the roadsides (AASHTO, 2011). This is accomplished by maintaining vegetation near the roadway as well as in the clear zone that could act as fuel. The potential of an accidental ignition of roadside vegetation which could lead to a forest fire is a large concern for Caltrans. As mentioned earlier, one way they reduce this risk is by mowing a fire control strip. However, the actual act of mowing can be a fire risk if done during public Red Flag Warning or Fire Weather Watch. The Caltrans Division of Maintenance has published Fire Prevention Guidelines for Daily Field Maintenance Activities (Aceves, 2021) which is applicable to the entire Caltrans right of way that helps to try to reduce this risk. It focuses on increased preparedness and situational awareness during mowing and other vegetation control operations. The guidelines are in place to help reduce the risk of ignitions that could potentially lead to a wildfire. One of the ways this is tracked is through Fire Danger Ratings which are based on wind speeds and direction, ambient air temperature and relative humidity.

Caltrans Headquarters notifies Districts of Fire Danger Ratings (by zone) each day by 6pm so that plans can be made for the next day. If the rating is classified as “extreme”, then all planned or ongoing field maintenance work that may have the potential to cause an unplanned ignition, such as mowing, must cease. As the Fire Danger Ratings can cover large areas. Information is also provided on how one can reach out to one of the ten National Weather Service (NWS) offices within the state to within minutes get a detailed briefing for a state highway corridor or isolated spot condition if a Red Flag Warning or Fire Weather watch is anticipated. A chart of Fire Danger Rating and Weather Factors to Monitor is provided which can be found in Figure 2.2 below.




	LOW (GREEN)	MODERATE (BLUE)	HIGH (YELLOW)	VERY HIGH (ORANGE)	EXTREME (RED)
WEATHER SAMPLING	None	2 hours	1 hour	1 hour	RED FLAG WARNING ALL OPERATIONS CEASE
PERMITTED ACTIVITY	ALL	ALL	ALL	ALL	
REQUIRED MITIGATION	Must meet: Public Resource Code Section 4421 No Consistent Wind Wind speed varies 0-10 mph and High Relative Humidity 30% up to 100%	 Next level of mitigation is required if: Wind 0-10 mph and Increasing or Relative Humidity Dropping = < 30%	Must have: <ul style="list-style-type: none"> • 200-gal Water pumper • Communications • Patrol  Next level of mitigation if: Wind > 10 mph and Continues Increasing or Relative Humidity Continues to Drop = < 25% and Ambient Air Temperatures Rising = > 80 degrees	Must have: <ul style="list-style-type: none"> • 200-gal Water pumper • Communications • Patrol  Next level of mitigation if: Wind = > 15 mph Consistently or Relative Humidity Continues to Drop = < 20% and Ambient Air Temperatures Rising = > 80 degrees	

Figure 2.2. Caltrans chart of fire danger ratings and weather factors to monitor

If a public Red Flag Warning or Fire Weather Watch are anticipated, supervisors should use an anemometer to track the changing weather conditions. Anemometers are devices which measure wind speed, temperature, windchill, relative humidity, heat street index and dew point temperature. They are suggested for use in assisting to monitor fire weather factors within an area. These anemometers should be used to check weather conditions at least hourly, and the results documented on a Mowing Activity Tracker Form. This form not only documents change in the weather activity, but also can be used to document when mowing operations are halted due to fire risk.

Also included is a list of equipment which must be on hand before beginning work in a High or Very High Fire Danger Rating. These include one serviceable round-point shovel, one backpack type water pump with at least 5-gallon capacity and one 200-gallon minimum tank. The tank must be located within one mile driving distance from where the work is being performed.

In addition to the Fire Guidance Policy, Caltrans also in 2020 implemented Fire Safety Crews which helped to maintain fire strips along the shoulder, defensible space between brush and trees as well as defensible space for reducing fire risk in areas that already have defensible space in districts with the most shoulder lane miles rated as ‘high’ or ‘very high’.

2.3 Leveraging Technology to Improve Mowing Operations

To make mowing operations more efficient, agencies are starting to utilize advanced technologies. After successful deployment of automated vehicle location (AVL) on snowplows, Minnesota in 2015 and 2016 acquired thirty AVL equipped mowers. These AVL equipped mowers provided real-time data including vehicle position. This real-time data allowed drivers to avoid noxious weeds than the previously used paper map more accurately. This helped cut down on mowing times. It also allowed them to easily capture new locations of these noxious weeds. Operators were also able to automatically capture acres mowed, something they would manually try to do prior to the AVLS. The pilot project found that the use of AVL equipped mowers had the potential to save Minnesota DOT on operational costs, optimize mower routes, reduce paperwork, and reduce spread of and exposure risk of noxious weeds. It was noted that AVL systems could be used with rented equipment when a magnetic Global Positioning System (GPS) antenna is used. However, they did note one of the challenges was software related. Not all updates could be remotely pushed and therefore, mowers could temporarily be taken out of duty during updates. The cost associated with the program was approximately \$3,700 in initial fees per unit and then approximately \$367 per unit per year in ongoing costs (Potter and Bayer, 2017).

As mentioned earlier, one of the major drawbacks of mowing operations is the risk to driver and operator safety having them operating on the roadside. Strong and Shane (2012) in a study using crash data and survey validation developed an integrated risk management model which identified mowing operations as moderate risk. One way to help mitigate some of this risk is to use tele-operated (particularly when line-of-site is not required) or automated mowers which remove operators from the machines.

The use of automated technology for maintenance operations has seen a focus on autonomous truck mounted attenuators (ATMAs) that are used to shadow moving operations. Department of Transportations (DOTs) including Colorado and Missouri have tested these ATMAs (Miller and Pourfalatoun, 2021 and MoDOT, 2022).

Additionally, Transportation Research Board’s National Cooperative Highway Program (NCHRP) has an ongoing set of studies under NCHRP 20-102 which are looking at how state and local agencies can prepare for connected and automated vehicles (CAV). One of these studies, NCHRP 14-42, focused on the effect of CAV on State DOT maintenance programs. This study is not yet finished, but after reaching out to the researchers, it was found that this study has focused on how maintenance programs can better prepare for CAV, such as through increased attention to pavement markings and signing and not on how maintenance programs can leverage automation, however there may be a future component of this under 20-102.

Research has been conducted on mowers for residential lawns. Many automated mowers available for residential use that utilize boundary wires to help guide the mower (Hicks and Hall, 2000). A few newer models have begun using geofences to establish boundaries (Husqvarna, 2022). These mowers, while great for a home lawn, would not hold up to the terrain that could be encountered in roadside mowing.

Research that has been completed looking at the use of teleoperated roadside mowers has been completed through a series of Caltrans sponsored studies completed by the University of California Davis. In the first study and subsequent papers (Arsenault et al., 2008; Arsenault et al., 2010; and Arsenault et al., 2011) developed a test bed roadside mower. In the development of their mower, they determined a set of loose specification they wanted to meet Caltrans needs. These included that the mower be safe to operate, be cost effective, never stray from its bound nor enter onto the pavement, should be easy to setup, operate and collect, have mowing rates similar to those seen in human powered mowing, not leave patches of vegetation behind, require limited monitoring, be relatively small, be reliable and easy to repair, have the ability to cover clear strip sections of vegetation, be able to avoid obstacles and able to cut all roadside vegetation.

The 231-pound test bed that was developed was 40 inches long, 38.3 inches wide and had a 34.5-inch track and operating speeds of 1.5 mph up to a maximum speed of 3 mph It had a hypothetical cutting width of 42" as it did not have a mechanical cutting system. It used a low-cost sensor array and GPS to help maintain its positioning. In a field trial of consecutive mowing paths spaced 36 inches apart it was found that the mower could attain mowing consistency of 4 inches (Arsenault et al., 2008 and Arsenault et al., 2010). Based on the results the authors used estimated mowing rates from a hypothetical situation to calculate potential cost savings which were found to be equal to approximately \$230,000 per year for District 3 assuming they implemented autonomous mowing for only 25% of the total acreage. Overall, an autonomous mower based on the test bed was found to potentially be a means of reducing maintenance costs, reducing dependence on herbicides, and increasing worker safety. It did however have problems with mowing consistency and was not able to avoid obstacles. The authors suggested further research to address these short falls, which was ultimately conducted in another study.

Creed et al. (2011 and 2012) took the test bed that was developed in the Arsenault studies and used simple reactive algorithms, a laser range finder, and a pure pursuit tracking controller to add the ability to detect and avoid obstacles. In the 2011 thesis, testing was also done for two closely spaced obstacles in the 2011 thesis and 2012 study, a field test on rugged terrain was performed for detection and avoidance of one obstacle. Both tests found that the test bed was able to successfully detect and navigate around the obstacles while in autonomous mode, however the author suggested that it was not yet ready to deploy on roadsides as additional safety functions were needed.

Another recent study by Hasegawa and Wians (2018) researched this by attaching Light Detection and Ranging (LIDAR) radar system to a commercial self-driving lawn mower. The small LIDAR scanner in field test was able to detect fences, tall grass, and ground levels.

The most recent study (White and Lasky, 2019) included an evaluation of commercially available remote-control mowers (RCMs) that Caltrans has purchased. The Alamo Traxx and Green Climber remote control mowers, as seen in Figure 2.3, are capable of mowing otherwise non-traversable slopes which tractor-based mowing is too hazardous to complete. Testing was done to determine mow rates as well as maximum slopes they were able to traverse. The mow rates were determined using timed testing of mowing a maximum 2:1 sloped area that represented the slopes found at an overpass. This was done under two conditions including one with no obstacles and one with cones set up as obstacles. It was found that the Traxx was able to mow at a rate of 0.25-1.5 acres per hour. The maximum slope test found that the RCMs as they approached a 2:1 they began to disturb soils. It was also found that operators often had to be within 50 feet of the mowers to be able to guide around obstacles, even though the operating manuals suggested at least 100 feet.

As part of the study White and Lasky (2019) also estimated the operations costs of using the remote-controlled mowers. They found that the use of remote-control mowers was more expensive (275%) however, it was less expensive (75%) than that of a string trimmer. Therefore, remote control mowers were justified to replace areas that were controlled by string trimmers as they were less expensive as well as reduced exposure to hazards for operators. While more expensive than conventional mowing, the remote-control mowers will reduce the risk of tip-over crashes.

Main drawbacks of the systems tested included that there was significant down time where they had to be repaired and parts were often difficult to obtain. Due to this, not only were machines often not operational, but operators when using, were more conservative to avoid causing any damage. The other main drawback listed was the width of the cutting head. Both the Traxx and the Green Climber had cutting widths of 51", which is less than most conventional mowers used as well as slope specific mowers.



Caltrans

Figure 2.3. Photo of Alamo Traxx and Green Climber LV600 remote controlled mowers

Research and development have also been completed by the equipment manufacturers to develop teleoperated and automated heavy equipment which could be used to address some of these issues seen with the currently available mowers. In January of 2022, John Deere announced their first fully autonomous tractor which is ready for large-scale production. According to their press release the tractor, which is for agriculture applications, uses GPS guidance and a geofence for navigation along with six cameras which allow for 360-degree obstacle detection (John Deere, 2022). Announcements and concept autonomous tractors have also been released by other companies including New Holland (New Holland, 2017), Massey Ferguson (Wordsworth, 2019), Kubota (Herath, 2020), Mahindra (ETAuto, 2017), Agco (AGCO 2019), Sabanto (DTN/Progressive Farmer, 2020), Raven Autonomy (Raven Precision, 2021), and Jaybridge Robotics/Kinze Manufacturing (Jaybridge Robotics, 2020). These systems range in capabilities including remote guidance and pre-specified routes, as well as systems for which specifications are not available in public forums.

As more products come on the market, there remains a need to develop operational specifications and use cases based on the needs of Caltrans. Using these criteria and test cases, testing criteria need to be developed to validate autonomous system performance to satisfy Caltrans needs. Using the test criteria, along with specifications and requirements for an autonomous system, available and upcoming systems can be tested and evaluated for potential use by Caltrans.

CHAPTER 3. INVESTING TELEOPERATED EQUIPMENT FOR USE IN CALTRANS OPERATIONS SURVEY

A survey was distributed to relevant district employees on 03/24/2022 to gain insights into what the operating conditions and requirements that are needed across the Caltrans Districts. These responses will be utilized to develop specifications for teleoperated and autonomous roadside mowers and in discussions with OEMs and other relevant companies. The following sections summarize the survey results received. For the majority of questions, some respondents decided to not answer the question. These non-responses are listed as “Blank” within the tables where appropriate. It should be noted the non-responses were from different people for each question.

3.1 Summary Characteristics of Respondents

In total we received 89 valid responses. These included at least one response from all twelve districts as well as headquarters. A summary of the results we received by district is included in Table 3.1 below.

Table 3.1. Summary of responses by district

Answer	Count
District 1	6
District 2	2
District 3	3
District 4	12
District 5	5
District 6	16
District 7	9
District 8	17
District 9	6
District 10	5
District 11	5
District 12	1
Headquarters	2
Total	89

The responses came from employees with a variety of job titles. The job titles of those who responded included:

- Maintenance supervisors (44)
- Maintenance superintendents (23)
- Maintenance manager II (7)
- Equipment managers (4)
- CEO II
- Maintenance worker

- CLML (Landscape maintenance lead)
- Tree maintenance supervisor
- Staff services manager
- CEAS
- Deputy division chief
- Sr. landscape architect

3.2 Weather-Related Operating Conditions

The first set of questions asked about weather conditions in which they mow. The first question that was asked was whether they mow while it is raining. As seen in Table 3.2, 6 respondents said yes, while 11 said they do in certain circumstances.

Table 3.2. Responses to if they mow in rain

Answer	Count
Certain circumstances (please elaborate)	11
No	56
Yes	6
Blanks	16

Yes responses came from District 1 (4), District 9 and District 10. Districts which listed they mowed in certain circumstances included districts 10, 3 4, 5, 8, 9 and Headquarters. The certain circumstances that were listed in included:

- depends on how heavy or intense the rain was. Most that responded to this, said that in light rain to mist they would.
- depends on the stability of the soil
- only mow in rain on flatter terrain
- one noted that light rain helps with dust control.
- they would mow in rain if the mowing will be effective and won't leave mohawks

For those that responded no, the next question asked how long after rain do they resume mowing. The responses ranged from 1-2 hours to up to two weeks. The majority of answers fell within 1-3 days. A total of 18 responses did not give an exact timeline, instead they noted that it depends on conditions, but generally when the roadside is dry and no longer muddy. The results were synthesized in Table 3.3 below.

Table 3.3. Responses to “How long after rain before you resume mowing?”

Time Frame	Count
1-2 hours (as long as conditions warrant)	5
1 – < 2 days	16
2-3 days	12
4-5 days	5
1 week	3
Up to two weeks	1
Depends on conditions, but generally when dry and not muddy	18
Unknown or comment not related	3
Blank	23

The next two questions focused on wind speeds and if they mow below 32 degrees. The responses for wind speeds are summarized in Table 3.4. The wind speed ranged from 10-30 mph. Most had caveats that it would depend on Fire Danger Rating, including humidity and or temperature.

Table 3.4. Summary of wind speeds at which mowing stops

Responses	Count	Notes
10 mph +	5	1 was only at high danger, 1 was for median at 20% humidity and the other 24% humidity
15 mph +	8	1 was at moderate danger, 1 was potentially less if cut material is blowing into traffic, 1 was depends on but generally start considering at 15+
20 mph +	5	3 were 15-20mph and 1 said temperature and humidity play a part
25 mph +	1	
30 mph +	2	
Depends on temperature and humidity (i.e., fire danger)	2	
Follow HQ Fire Danger Rating	6	
Depends on dust and visibility	3	
None	2	

Table 3.5 lists the responses to the question pertaining to if they mow at temperatures below 32 degrees. Those districts who responded yes included districts 1, 4, 8, 9 (5 responses), 10 and 11. Those that responded they do under certain circumstances included the following elaborations:

- their region doesn’t usually get that cold, but would not stop their operations
- if there is no rain, ice or snow and would depend on priority.
- they don’t usually mow in the winter but might if there is a sight issue or complaint that needs mowing completed, they would.

Table 3.5. Responses to mowing below 32 degrees F

Response	Count
Blank	16
Certain circumstances (please elaborate)	9
No	51
Yes	13

3.3 Characteristics of Roadsides Mowed

The first question asked about roadside characteristics related to cross-slopes they traverse. Tables 3.6 summarizes the range of slopes reported by district while Table 3.7 summarizes the number of responses based off the steepest cross-slope reported. The steepest end of the range across all districts is 1:4, with half the districts mowing 1:2 or steeper.

Table 3.6. Range of cross-slopes that are mowed by district

District	Range
1	1:6 to 1:2 or steeper
2	1:6 to 1:3
3	1:6 to 1:2 or steeper
4	1:6 to 1:4 and 1 said 1:2 of steeper
5	1:5 to 1:4
6	1:6 to 1:2 or steeper, most in 1:6-1:3 range
7	1:6 to 1:2 or steeper
8	1:6 to 1:2 or steeper
9	1:6 to 1:2 or steeper, most in 1:6 to 1:3 range
10	1:6 – 1:3
11	1:6 – 1:4
12	1:6 – 1:4

Table 3.7. Responses based of steepest cross-slope mowed

Response	Count
Blank	23
1V:2H or steeper	15
1V:4H to 1V:3H	19
1V:5H to 1V:4H	19
1V:6H or flatter	13

The next question was related to the grades at which they mow. Table 3.8 includes the ranges of grades reported by district while Table 3.9 includes the number of responses received that said they mowed within each range. The majority of districts mow areas at greater than a 6% grade. Districts 4, 5, 11, 12 and headquarters all reported max grades mowed ranging from ~4%-6%.

Table 3.8. Range of grades mowed by district

District	Range
1	Less than 2% to greater than 6%
2	Greater than 6%
3	Less than 2% to greater than 6%
4	Less than 2% to less than 6%
5	2% to less than 6%
6	Less than 2% to greater than 6%
7	Less than 2% to greater than 6%
8	Less than 2% to greater than 6%
9	Less than 2% to greater than 6%
10	Less than 2% to greater than 6%
11	Less than 2% to less than 6%
12	2% to less than 4%
HQ	Less than 2% to less than 4%

Table 3.9. Responses received by grade range

Response	Count
less than 2%	37
2% - <4%	47
4% - <6%	33
greater than 6%	19

The next two questions asked how narrow of an area they mowed followed by how wide of an area do they mow. Table 3.10 includes responses on how narrow of an area was mowed. The smallest number provided in a range, if a range was provided, was used for this table. The majority of responses fell in the 4'-8' range. There were a few responses which noted that the width was determined by the mower deck (e.g., 6' as that was as wide as the mower deck).

Table 3.10. Narrowest area mowed

Response	Count
Blank	17
1 foot	2
2 feet	8
3 feet	5
4 feet	13
5 feet	1
6 feet	15
8 feet	14
9 feet	1
10 feet	3
12 feet	5
15 feet	1
16 feet	1
25 feet	2
100 feet	1

Table 3.11 summarizes the responses on how wide of area is mowed. The majority of responses fell within the 20'-200' range. There were other, non-number answers included. These answers included things such as:

- as far as we need to
- could be the entire ROW or depends on ROW
- feet up to acres
- from 4' to quadrants
- sometimes the areas are the size of football fields
- it varies
- width of mower (it was assumed this response thought the question was in relation to width per pass).
- Depends on the size of the interchange

Table 3.11. Responses to “How wide of an area mowed?”

Response	Count
Blank	17
Under 10'	6
10-<20'	4
20-<50'	12
50-<100'	16
100-<200'	16
200'-<300'	7
300'-<500'	1
500'+	2
Other answer	11

After that, respondents reported the range of heights at which they mow to. Based off the responses, it seems this question could have been clearer. It appears some responses were more for at what heights of grass they mow, while we were looking more at the height, they mow grass to, which would impact mower head height specifications. Table 3.12 below includes all the responses received. Most responses noted 4"-6". Six inches was not by one respondent as the height which minimizes damage to irrigation and sparking potential. A few responses noted that it was depended on flail or rotary mower.

Table 3.12. Heights that vegetation was mowed to

Response	Count
Blank	19
2"	1
2-3"	1
2-4"	1
4"	18
4-6"	12
4-8"	1
4-12"	2
6"	20
6-8"	1
6-12"	1
8"	1
8-12"	1
10"	1
12"	1
12-15"	1
24"	2
60"	1
72"	1
0-20"	1
1800"	1
Other answer	1

The next series of questions were related to obstacles. These included what obstacles are often encountered, how often they must enter the roadway to avoid obstacles and how close to traffic do they mow without setting up a lane closure or rolling block. Table 3.13 includes responses to obstacles encountered. As seen, the majority of the obstacles included were encountered. Other responses included:

- Environmentally sensitive areas
- Foreign/unknown objects
- Guardrail
- Irrigation
- Large litter and debris from illegal dumping (e.g., mattresses)
- Large rocks

- Dirt humps
- 10-32 [Caltrans Radio Code for dead animal]
- Hidden objects
- Survey markers
- Utility polls
- Well heads
- Tree stumps

Table 3.13. Obstacles encountered

Response	Count
Blank	17
Barrier, including sound walls	65
Bridges	66
Culverts	71
Drainage ditches / riprap	71
Electrical boxes	69
Guide markers	70
Homeless encampments	44
Roadside debris (e.g., tires)	60
Signposts and structures, including billboards	72
Stalled or crashed vehicles	38
Trees	71
Other objects	15

The next questions asked how often per mile avoiding obstacles forced them into the roadway/traffic. Responses ranged from 1 time per mile to over 5 times per mile.

Table 3.14. Times per mile they must enter traffic to avoid obstacles

Response	Count
Blank	23
1 time	18
2-3 times	22
3-4 times	9
4-5 times	2
More than 5 times	15

The last question was on how many linear miles they mow within their jurisdiction. The majority of responses ranged from less than 100-300 miles. There were two respondents who said none in the last 3 years and not much. Additionally, there were two who noted they don't mow in their position (one was a tree crew) while 3 were not sure. Four responses had other non-quantifiable answers that included "It's a lot, many miles, and a bunch". The responses are summarized in Table 3.15.

Table 3.15. Miles of ROW mowed

Response	Count
Blank	21
None or not much	2
<100	21
100-200	15
200-300	10
300-400	7
400-500	1
500+	3
Other	4
Unknown	3
Don't Mow	2

3.4 Vegetation Mowed

A question was asked to identify what types of vegetation were encountered during mowing operations. A summary of the response can be seen in Table 3.16. Other responses included Spanish broom, tumble weeds, willows, any weeds that need to for vegetation controls and slopes using a slope mower for brush.

Table 3.16. Summary of vegetation controlled through mowing

Response	Count
Blank	21
Native grasses	54
Non-native grasses	50
Brush	51
Weeds	62
Saplings	27
Other	8

3.5 Characteristics and Policies of Mowing Operations

The next set of reported were related to characteristics and policies of mowing operations. This includes things such as times when mowing occurs, how often they mow, any production targets, when they require lane closures or rolling blocks. It also includes open response questions on how vegetation maintenance operations are planned and managed.

The first set of questions were related to the months and hours in which mowing occurs. Table 3.17 summarizes months in which mowing operations occur. As seen, most mow during spring and early summer (i.e., April – July). In addition to the responses noted in the table, other responses included spring, spring-summer, spring, and fall depending on fire danger,

spring/summer/fall depending on fire danger, summer, when equipment is available, whenever possible, winter for brush and spring for grass and early spring/spring, early fall/late fall.

Table 3.17. Months when mowing operations occur

Response	Count
January	8
February	11
March	17
April	39
May	50
June	50
July	42
August	34
September	26
October	19
November	13
December	8

The hours in which they mow are summarized in Table 3.18. The majority of mowing was noted as taking place between 7 am and 3 pm. A few responses noted they had recently started mowing at night. Other responses received which are not included in the table were 5-6 hours a day, 8 hours, daylight, depends on fire dangers/humidity and temperature, depends on weather, sometimes work nights, early morning until fire danger is too extreme, morning when cooler and stopping around 12 and normal work hours.

Table 3.18. Operating hours for mowing

Response	Count
Blank	19
00:00 - 01:00	1
01:00 - 02:00	1
02:00 - 03:00	1
03:00 - 04:00	1
04:00 - 05:00	2
05:00 - 06:00	11
06:00 - 07:00	31
07:00 - 08:00	52
08:00 - 09:00	58
09:00 - 10:00	58
10:00 - 11:00	58
11:00 - 12:00	57
12:00 - 13:00	55
13:00 - 14:00	53
14:00 - 15:00	47
15:00 - 16:00	27
16:00 - 17:00	11
17:00 - 18:00	0
18:00 - 19:00	0
19:00 - 20:00	0
20:00 - 21:00	0
21:00 - 22:00	0
22:00 - 23:00	1
23:00 - 24:00	1

The next question related to how frequently they mowed. Results are provided in Table 3.19. The majority of respondents noted they mow once to twice a year. The districts which had those who mowed monthly were from 7 and 8 while the twice per season and every other week responses came from District 4.

Table 3.19. Frequency of mowing

Response	Count
Blank	20
1x per year	26
1-2x per year	10
2x per year	22
3-4x per year	5
Twice per season	1
Monthly	3
Every other week	1

The next question inquired if they have production targets for their mowing operations. Only six districts responded that they did have targets as shown in Table 3.20. This included districts 3, 4, 5, 7, 8 and 9. When asked to elaborate on what their targets were, responses included specific amounts as well as that just that things are maintained. The responses include:

- 1500 acres
- Acreage
- As long as our section of highway gets mowed before the weeds are too high and we get complaints.
- As much as you can get done safely
- Complete all area and complaints in special areas. Fire Dept. dictates mow areas along with CT Management
- keep mowed and clean
- Scheduled mowing & completing 1 Quadrant @ A time. N/B , S/B , W/B , E/B
- Varies from year to year
- With the speed and terrain and the routes. Usually from 1 mile to as high as 24 miles for and experience operator.

Table 3.20. Production targets for mowing operations by district

Response	Count	Districts
Blank	19	
No	43	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 11
Unsure	17	4, 6, 7, 8, 9, 11, 12 and HQ
Yes	10	3, 4, 5, 7, 8, and 9

The last question was on how their vegetation maintenance operations are currently planned and managed. A variety of responses were included, but common themes included set (i.e., annual, or seasonal) schedules, VegCon Plan, or Integrated Vegetation Management, based on fire risk and equipment availability. Some mentioned that they do a mix of mowing, chemical and manual control. One noted they use both in-house as well as contracted forces. A list of all responses received is included:

- Annual cycle of all locations previously mowed. Caltrans and contract forces
- Annual Scheduled Chemical control and Mowing
- As needed
- AS NEEDED BIANNUALLY
- Based on equipment availability and fire danger ratings
- based on fire danger and availability
- Brush control ops are conducted year around on an as needed basis. Mowing ops are typically conducted from June-September annually although if necessary mowing is conducted throughout the year.
- By a District vegetation control plan
- By area supervisor

- Chemical control and Mechanical control once the grasses start to dry out
- CMS decides
- DAILY SCHEDULING
- District Vegetation Control Plan
- Every Year Caltrans does vegetation control for Safety on sight clearance and fire danger
- fire safety/fuel reduction/intersection sight distance/aesthetics/ at the Supervisors discretion but usually following historical patterns
- I get mowers as soon as weeds are high, we mow as quick as possible to beat high fire danger
- In conjunction with our landscape specialist and the County of Orange
- It's planned to be done in the spring. But mower availability and fire danger may alter this.
- IVM (Integrated Vegetation Management)
- landscape specialist
- Manual Veg Con, Mechanical Veg Con, Chemical Veg Con
- Many of our areas especially near the coast have a year round growing season. Spring and early Summer are usually the busiest.
- MOW A SAFETY STRIP AT LEAST 8 FT FROM EDGE OF RW
- MOWERS WHEN AVAILABLE AND RUNNING
- Mowing - April through October. Chemical - Through landscape specialists PCR's frequencies. Manual - As conditions permit.
- mowing areas wide enough to mow and weeding areas that mower can't get too.
- Mowing in spring to prevent summer overgrowth and fire hazards
- mowing plan
- normally after grasses have headed out and start dying off, mow as we don't tend to have regrowth until/unless we get heavy rains in summer. This limits the number of times that we have to mow, also use a spray program to assist/reduce mowing needs
- per d-09 mowing plan
- Planned by supervisor
- Pre-emerge prior in fall prior to mowing during summer
- Prior to and during summer months, as needed and per complaints
- right of way, vegcon plan, sight distance
- Schedule and completed, based on vegcon plan
- scheduling
- Seasonal
- seasonal
- Seasonal mowing, with intermittent mowing in problem areas
- Spray and mow
- Spray operation and manual control - seasonal
- start on the south end and work north since the south end dries out first
- String trimmers, Loppers & Hoes. Handwork
- They are based on safety and fire protection guidelines
- They are planned around when rental tractors are available. Just before the summer season to mitigate sight distance & fire prevention
- They are scheduled yearly and managed year around in areas.
- Throughout fuel reduction plan.

- VegCon Coord gives recommendations, and we try to complete and open up more mowing space as resources allow.
- Vegcon plan
- Veg-con plans. Mow, weed, spray as scheduled.
- We mow from April till we have it done
- WE mow when the grass has gone to seed and begins to yellow
- We plan to start right after the rain season, and we get Tractors
- We use mechanical, hand crews and are recently using more herbicides to control
- we work around spraying and mowing operations to get the vegetation under control
- weekly sing in sheet
- WHEN A MOWER SHOWES UP
- When it needs to be mowed, we mow it
- When the grass dries, we mow it.
- When the grasses/vegetation turn color (Mature) we send mowers out

3.6 Equipment

The final set of questions were related to the equipment used, specifically if brush hogs were used as well as any special considerations that mowers need to handle as well as any special considerations need to be tested. Table 3.21 below summarizes the equipment used, including the districts who use them. Other responses included:

- 5510 rear mowers,
- cat 938K and Kubota sv 75-2
- Fendt FT410
- Rent with bat wings 12'
- John Deer HX15 rotary mower pull behind with Massey tractor
- Kubota tractor with rear mower and bat wings,
- Multihog mower
- New Holland
- Rentals
- Shulte XH1500 batwing
- Skid steers with front mower attachment
- we tow 15' batwing mower decks with rental tractors
- whatever we can get

Table 3.21. Equipment used by district

Response	Yes	Districts
John Deere 6130M	16	1, 3, 4, 5, 6, 7, 8, 9, 10 and 11
John Deere 7030	8	1,4,5,7, and 8
John Deere 7210	12	1, 4, 5, 7, and 8
John Deere 7220	7	1, 2, 5, 7, and 8
Kubota M126GX	7	1, 4, 8 and 11
Bobcat 863	11	2, 4, 6, 7, 8 and 11
Bobcat T300	14	4, 6, 7, 8, 9, 10 and 11
Caterpillar 277	4	3, 4, 5 and 7
John Deere 332D	5	3, 4, 5 and 8
John Deere 6130M2	22	1, 3, 4, 6, 7, 8, 9 and 11
Case 4240	7	3, 7 and 8
John Deere 6410	18	1, 4, 5, 6, 7, 8, 9 and 10
John Deere 6420	9	1, 2, 4, 5,6, 8 and 9
John Deere 6430	11	1, 4, 5, 6, 7, 8 and 10
Case 521E	6	4, 6, 7, 8 and 9
Caterpillar 924G	2	6 and 7
Dresser 518	2	4 and 6
John Deere 444H	5	3, 5, 6 and 8
John Deere 444K	2	5 and 8
John Deere 524K	5	4, 5, 6 and 8
Komatsu 200PT	1	7
Komatsu WA180	6	4, 7 and 8
Komatsu WA200PT5L	1	8
Caterpillar IT14G Tractor Wheel w/ Multiple Tool Carrier 95 HP	4	1, 3, 7 and 9
Komatsu200PT5L Tractor Wheel w/ Multiple Tool Carrier 95 HP	4	4, 6 and 8
Alamo Traxxrf – Multitool Track Remove Control	1	11
Kanga TR825 – Loader Compact Track Remote Control	0	Na
Other (describe)	10	3, 6, 7, 8 and 9

The following question asked if they utilize a brush hog to control vegetation. The responses are summarized in Table 3.22. Approximately half of respondents noted they used them. At least one respondent from each district noted they did use them.

Table 3.22. Brush hog usage by district

Response	Count	Districts
Blank	21	
No	22	1, 4, 6, 7, 8, and 9
Unsure	7	4, 5, 7, 8, 11 and HQ
Yes	39	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12

The final two questions were open ended response questions relating to special considerations that the mower would need to be able to handle as well as any that should be included in a testing program for tele-operated and autonomous vegetation maintenance equipment.

Responses to the first question, Are there any special considerations on what mowers need to be able to handle in your jurisdiction include:

- 4-wheel drive or track
- 4 x 4 and large enough to pull larger Sat wing stye mower decks - Enclosed Cabs for AC
- Anything we can get
- behind guard rail and steep slopes
- Boom and side flail
- Boom mowers required in ESA Areas
- Experienced Operators that know the capabilities and risks of mowing per equipment that they are operating, not just driving. They have to pay close attention on Mountainous terrain.
- Heavy Duty Mowers are preferred
- Horsepower/Maintenance workers and Operator II
- moderately steep slopes/maneuverable due to multiple obstacles
- Needs to be able to cut at least 6 inches or less.
- being able to mow 2/1 or 1/1 slopes would be nice. Heavy woody stocks in desert area are hard on equipment. Southern California, we need water suppression on hand if/when fires start due to mowing / hitting rocks or metal debris in grasses
- Rotary mowers
- Slopes
- Slopes, narrow areas, mowing around/near guardrails, culvert outlets, etc.
- Terrain, Traffic, Weather (fire danger)
- The slopes, embankments, and flat grounds utilizing the most efficient mowers available
- These mowers take a lot of abuse on a daily basis, need to be built strong and capable of handling rough terrain. Mower attachments must be heavy duty and easy/quick to replace blades & maintain
- They need to be very durable for the current mowers. We need better brush mowers/masticators excavator and skid steer mount
- Track mower for slopes.
- traffic, slopes
- Unlevel banks and slopes
- unstable terrain & super tough blades
- Use what is supplied by equipment division
- we have to rent tractors for bat wings and mowers since what we have is not enough
- We have wide center median areas that we could use a mower with both sides and rear
- We need a brush mower that can mow banks and narrow 1 lane highway
- We use a big Rotary blade MX15 and a smaller Half the size rotary blade for smaller areas.
- we use batwing mowers
- safer equipment: operator safety, avoid fires, objects flying out from mowing.
- stay on level ground

Responses to the last question, Are there any special considerations you can think of that should be part of a testing program for tele-operated and autonomous equipment used in vegetation maintenance operations include:

- a good reach and stability
- auto height adjustment to avoid rocks
- Autonomous mowers are impractical and cannot circumvent the hazards that change daily.
- Can they work at night or does it only work during daylight hours.
- Certain slopes and sections with narrow shoulders. Heavy traffic areas in bigger cities.
- Degree of slope that can be operated on without causing rutting of the soil surface, ability to cut through larger material like tree saplings and shrubby material. How far can remote operator be from device and maintain full control of remote vehicle.
- Dusty environments - the need for water trucks and also fire suppression
- for steep slopes so they do not have to be done manually with weed trimmers
- Heavy Duty mowers decks
- Homeless encampments Utilities
- I feel Skid Steer mounted mowers would be very beneficial and a remote mower. In the past we have used a Green Climber LV600 Remote Mower and had very positive feedback. It was able to mow on slopes that hadn't been touch in many many years.
- It needs to be heavy duty, user friendly and productive.
- Large debris and litter
- LIVE PEOPLE
- maybe on the belt drive keep coming off
- obstacles and boundaries of the areas to be mowed
- possible infrared detectors to detect fires when accidentally started.
- roadside debris, anything from pieces of tire to whole tires, rocks/metal debris starting fires, snakes and wildlife that could be potential issue if people have to walk on the ground if repairs/ retrieval of equipment
- Safety shutdown switch, tipping sensor, real-time engine readings, long range and must be able to operate for at least 8 hours per day.
- Safety? Never thought of an autonomous mower?
- should be able to know if it starts a fire, if there are pedestrians walking through and if limbs are too big to cut
- since it is running down the side of the highway where would it be operated from how far away
- Slopes, around ice plant and narrow gore points
- Spot weed control
- terrain, fire danger
- Test them in the Mountainous Areas so they will understand risk vs. rewards of mowing too steep or too far off the shoulder.
- They should be able to be operated by Workers also
- This area would be a poor choice for autonomous mowing. Steep drop offs/tons of obstacles/multiple ESAs/better terrain exists within the State and D1
- tractors with mower decks that don't hit the rear tires.

- Training is key. Training materials and key notes to assist.
- WEATHER

CHAPTER 4. DRAFT VENDOR SPECIFICATION (AUTONOMOUS)

Based on information identified in the literature review and questionnaire, the specification shown in Table 4.1 was developed to evaluate available autonomous vehicles (i.e., tractors) for mowing operations. These specifications are designed to allow for detailed testing of prospective systems that could be used for roadside vegetation maintenance.

Table 4.1. Draft vendor specification

Performance Measure	Minimum Specification	Preferred Value
Grade On Which Mowing Can Occur	Operate safely at a minimum of 6% grade	Operate safely at a grade greater than 6%
Cross-Slope	Operate safely at a minimum 1V:3H slope	Operate safely at a 1V:2H or steeper slope
Mowing Height (If Mower Is Part of Unit)	Mow to a minimum of 4"	n/a
Obstacles (Fixed)	<p>Be able to identify and appropriately act or avoid the following obstacles (at a minimum):</p> <ul style="list-style-type: none"> • Signposts • Bridges • Culverts • Drainage ditches & rip-rap • Electrical boxes • Guide markers • Trees and tree stumps • Irrigation • Environmentally sensitive areas • Large rocks / rock outcroppings • Survey markers • Well heads • Steep drop-offs • Foreign/unknown objects 	
Obstacles (Mobile)	<p>Identify and appropriately act to obstacles (at a minimum):</p> <ul style="list-style-type: none"> • Homeless encampments • Humans • Stalled vehicles • Roadside debris • Large rocks • Large litter and debris from illegal dumping (e.g., mattress) • Foreign/unknown objects 	
Fire Detection and Mitigation	Must be able to identify sparks and have a means to suppress if ignition happens	A fire suppression system that is capable of putting out a fire.
Safety Features	Include at a minimum a safety shutdown switch, a tipping sensor and real-time engine readings	
Efficiency	Able to operate at a rate similar to the rate of manually operated tractors or be cost effective enough that multiple units can operate at the same rate.	

Performance Measure	Minimum Specification	Preferred Value
<p>Other Features</p>		<ul style="list-style-type: none"> • 4-wheel drive or track • Able to mow around/under guardrail and near culvert outlets • Ability to pull bat wing mowers • Spot weed control • If mower is part of unit: <ul style="list-style-type: none"> ○ Auto height adjustment ○ Ability to mow thick wood stocks, tree saplings or shrubs.

CHAPTER 5. POTENTIAL VENDORS

Given the responses from the survey summarized in Chapter 3, a draft specification was developed. The following vendors were contacted to assess their interest in participating in this project, as well as obtain their feedback on the proposed specification. Initial contact was via e-mail followed by a phone call if the vendor expressed interest. The outcome of this effort is summarized below:

5.1 MACH

Jonathan and Nicole met with Michal and Rhett on January 26th 2023. After discussing their product, which they work with manufacturers to install on new equipment, it appears that it will likely meet at least some of our testing criteria. They further inquired about our needs in testing and we let them know we would contact them with the needs and our specifications once we had more finalized plans/

Contact: Michal Grinnell (Director of Business Development) michal@mach.io and Rhett Schildroth (CTO)

5.2 Sabanto

Jonathan and Nicole met with Craig Rupp, CEO, of Sabanto in October of 2022 to discuss their product. Sabanto's product is currently retrofit onto two tractors. The first was a Kubota tractor and the other included a CLAAS that was retrofit for a specific client. They currently do some mowing for the Air Force and were able to demonstrate the ability of their product. They use a system which captures video when driving through once and then plays it back and if there is something that is not new, it pauses. Their software lets you determine the mowing path and outline areas where you don't want mowing completed. They use GPS and Lidar.

Contact: Craig Rupp ruppinator@sabantoag.com

5.3 Bobcat (Doosan)

From the contact information provided by Melissa/Nathan at Emerging Prairie we reached out to Lincoln. He responded and shared that their first solution is based on a commercial zero-turn mower. They are currently working on other solutions which may work on severe slopes. He asked for our specifications, which were shared on 3/16 and noted that we were free to discuss further, but have not heard back.

Contact: Lincoln Voss lincoln.voss@doosan.com or Sawyer Hanson (sawyer.hanson@doosan.com)

5.4 John Deere

John Deere had signed a letter of interest in the proposal phase. Jonathan has been in contact with first Robert Moore and then Kristen Cadman. We are still working on setting up a timeline to meet and discuss. Jonathan had shared the specification with them.

Contact: Kristen Cadman CadmanKristenD@JohnDeere.com

5.5 Kubota

Reached out to them via their website and received the following response “Thank you for contacting Kubota Customer Satisfaction. All of Kubota's current offerings are available on the KubotaUSA website. We do have telematics available on most of our units but at this point nothing we currently offer is autonomous. However, Kubota does have a group that's developing autonomous concept tractors. You can read about that [here](#).”

5.6 Greenzie

Had reached out to them their website. Nathan from Emerging Prairie provided contact information, but it sounds like they are working with Bobcat/Doosan, with Bobcat leading. We've been in contact with Bobcat, but can reach out to Greenzie if necessary.

Contact: Charles cbq@greenzie.com

5.7 Advanced Navigation

Reached out via their website and never received a response.

5.8 Autonomous Solutions Inc (ASI)

Reached out via their website and did not receive a response, but was placed on their e-mail list. From one of their e-mails it appears they are working with Case.

5.9 Bear Flag Robotics

Attempted to contact through their “contact” e-mail, however did not receive a response to initial e-mail or follow up.

Contact: contact@bearflagrobotics.com

5.10 Case/New Holland

Attempted to reach out via their website and never heard back. Caltrans nor Nathan at Emerging Prairie had contacts either.

5.11 Electric Sheep

Tried reaching out via their website and never heard back. Was given a direct contact for their director of sales from Nathan and Emerging Prairie, however the e-mail bounced when we sent.

5.12 Monarch

Reached out to them via their website and got on their mailing list. No other contact has been made. Nathan at Emerging Prairie that Melissa used to get some contact information also noted that he never received anything back from them.

5.13 Phantom

Reached out via e-mail with the contact that was provided by Ed Hardiman. No response was received from the initial e-mail or follow-up.

Contact: Elliot Katz elliott@phantomauto.com

5.14 Raven Autonomy

Attempted to reach out via their website and through a contact e-mail, but never received a response.

CHAPTER 6. AUTONOMOUS TECHNOLOGY DEMONSTRATION

As described in the title of the proposal, the objective of this study was to assess ease of use, safety, and appropriateness of non-line-of-sight, remote control / automated vehicle technologies for Caltrans transportation maintenance operations. Included in the proposal was a task to test the various vendor's technologies in the field and evaluate their performance based on the predefined needs and requirements of Caltrans. During the execution of the work, it became apparent the commercial sector had abandoned "teleoperated" technologies in favor of "autonomous" technologies. In fact, advances in autonomous technologies have been so rapid that upgrading from a "teleoperated" system to an "autonomous" one would not be economically feasible. Furthermore, the California Legal Statutes do not align well with advances in autonomous technologies. This chapter discusses that misalignment and the associated impact on this project.

6.1 Background

Based on the research performed thus far, the companies developing teleoperated systems that could have been utilized for roadside vegetation maintenance have abandoned the development of such options in favor of automated (or autonomous) systems. Feedback from these companies indicated that teleoperated systems are not feasible from a business standpoint due to limited use cases and the potential for automated systems to produce equal or better performance than teleoperated systems in most, if not all, situations within the next few years. Thus, existing teleoperated systems have limited applications and it is anticipated that additional, improved teleoperated options will not be available for either transportation construction or maintenance activities. Additionally, automated systems continue to advance and handle increasingly complex situations appropriately, making them a desirable option for both construction and maintenance activities.

Based on this observation, the focus of the research turned toward autonomous technologies. Initial response from Industry was positive as evidenced by vendor feedback summarized in Chapter 5. For example, in January of 2022, John Deere announced their first fully autonomous tractor which is ready for large-scale production. According to their press release, the tractor, which is for agriculture applications, uses GPS guidance and a geofence for navigation along with six cameras, which allow for 360-degree obstacle detection (John Deere, 2022). Figure 6.1 shows a picture of this tractor taken at the 2023 Iowa Farm Show in Boone, IA. Also, at the 2023 Iowa Farm Show, New Holland / Case (New Holland, 2017) showcased their autonomous tractor, shown in Figure 6.2. As noted in the figure, Case is partnering with Raven Autonomy to develop their autonomous tractor. Announcements of concept autonomous tractors have also been released by other companies including Massey Ferguson (Wordsworth, 2019), Kubota (Herath, 2020), Mahindra (ETAUTO, 2017), Agco (AGCO 2019), Sabanto (DTN/Progressive Farmer, 2020), Raven Autonomy (Raven Precision, 2021), and Jaybridge Robotics/Kinze Manufacturing (Jaybridge Robotics, 2020). These systems range in capabilities that include remote guidance and pre-specified routes, as well as systems for which specifications are not available in public forums.



Figure 6.1. John Deere Autonomous Tractor: Front and side view showing the guidance systems



Figure 6.2. New Holland/Case IH Autonomous Tractor: Front and side view showing the guidance systems

As the project progressed, it became apparent Caltrans policy did not fully support the use of autonomous vehicles for maintenance activities. Articles 3.7 and 3.8 under Chapter 1 of California Code of Regulations Title 13, governing the implementation of autonomous vehicles on the State's streets and highways, states: *All self-propelled equipment shall, when under its own power and in motion, have an operator stationed at the vehicular controls...*

In addition, definitions of autonomous vehicles (i.e., for passenger cars) were initially developed by the Society of Automotive Engineers (SAE). It should also be noted that the referenced legislation relies on definitions of autonomous vehicles developed by SAE for vehicles to be used on streets and highways (i.e., the traveled way).

As the research progressed, it became apparent that a different set of definitions is needed for agricultural or maintenance operations. These definitions should focus more on the purpose or intended use of the equipment, rather than the autonomous features available from vendors.

For ease of comparison, the SAE and Case definitions are summarized below:

Automation levels are commonly defined using SAE or the National Highway Transportation Safety Administration (NHTSA) classification levels. The SAE [11] definition is:

- Level 0 – The driver completely controls the vehicle at all times, with some automated functions available (e.g. cruise control, ABS, automatic transmission, etc.)
- Level 1 - Individual vehicle functions are automated, such as automatic braking.
- Level 2 – At least two automated technological functions occur in unison, such as adaptive cruise control in combination with lane keeping.
- Level 3 – Autonomous-driving option that the driver can fully cede control of all safety-critical functions in certain conditions, but human monitoring and override is still required.
- Level 4 – High automation requires the vehicle to perform all safety-critical functions for the entire trip, with the driver not expected to control the vehicle at any time. The system only performs under specific circumstances (including geofencing). Human override is still an option.
- Level 5 – Full automation requires the vehicle to perform all safety-critical functions for the entire trip under all conditions. No human attention or interaction is required

These definitions for autonomous vehicles are targeted to passenger vehicles and, thus, may not be the best taxonomy for tractors and agricultural equipment. Realizing this potential drawback, Case IH developed the following categories of automation for tractors [12].

- Category 1 – Guidance. Vehicles are still manned by an operator but outfitted with Advanced Farming System (AFS) guidance technologies that help improve efficiency (such as reductions in overlaps and skips).
- Category 2 – Coordination & Optimization. This uses both vehicle and environmental data linked to an information hub. This allows plot wide communication between manned and unmanned equipment. Category 2 technologies control various functions including ground speed and rear Power Take Off (PTO).
- Category 3 – Operator Assisted Autonomy. Technologies in this category allows the vehicle to drive itself (with simple monitoring, backup, and support from the operator when needed) while the on-board operator focuses on the implement behind the vehicle.
- Category 4 – Supervised Autonomy. The technologies that allow this level of autonomy requires in-field supervision while the vehicle performs designated tasks.
- Category 5 – Full Autonomy. This category includes the most advanced autonomous vehicle technologies for tractors and agricultural equipment. These vehicles are operated with remote supervision or using artificial intelligence (AI).

Given the apparent confusion resulting from the application of SAE definitions for a passenger vehicle to a maintenance environment (i.e., mowing), and in consultation with the Caltrans Technical Advisory Committee (TAC), it was agreed a demonstration should be more “educational” rather than “evaluatory” in nature. That demonstration would be held in the Sacramento area to allow greater participation by interested parties, including Caltrans, as well as policymakers within the California Transportation Agency and Department of Motor Vehicles (DMV). The objective of this demonstration would be twofold: (i) provide a demo of an automated tractor system that is currently being used for mowing applications and ensure that mowing can be monitored via a Transportation Management Center (TMC)/Emergency Operations Center (EOC) as appropriate, and (ii) provide case studies of examples where automated technologies have been used or tested in similar operating environments in development, research, or practice.

Given contractual obligations between Caltrans and Iowa State University, as well as wildfire concerns in California, a date in June was selected, and the vendors mentioned in Chapter #5 were invited to participate. In the end, only one vendor, Greenline Autonomy agreed to participate. While other vendors were interested in the project, the June date conflicted with trade shows they were preparing to showcase their products and generate sales. The autonomous mover to be demonstrated by Greenline operates at several solar farms in the Midwest. In the following sections more details are provided on the mower demonstrated, as well as the findings from the demonstration.

6.2 Greenline Autonomy Mower

The Greenline autonomous system combines accurate GNSS GPS with IMU (Inertial Measurement Unit – a unit containing accelerometers and gyroscopes), wheel odometry, and other sources of location information to accurately measure robot location. An array of cameras, LIDAR, and radar monitor the environment and provide both obstacle detection and even greater navigation accuracy. A robust path planning, execution, and monitoring stack enables the robot to navigate a solar field, roadside, or other environment (within a predefined geofence) and respond intelligently to problems, usually by reporting them to a human-in-the-loop operator. A cellular communication modem enables time telemetry and allows our team to support operators in real-time, as needed.

This section describes the capabilities of the autonomous mower. Please note this is a prototyping platform and multiple alternatives (electric, tractor-based, etc.) are already under development with mower specifications detailed in Table 6.1. Figures 6.3 to 6.9 illustrate the various features of the mower. It should be noted that Figures 6.3 and 6.4 show a separate mowing attachment that allows the mower to mow around obstacles, such as trees, stumps, and rock outcroppings. Lastly, Figure 6.9 shows the mower operating on sloped terrain.

Most stats are derived from <https://www.dixiechopper.com/wp-content/uploads/2024/01/DC-2024-Tear-Sheets-Eagle-HP.pdf> - the platform we are currently prototyping.

Table 6.1. Mower specifications

Weight	1515 lbs – 1800 lbs (flexible as we are actively improving)
HP	40
Speed	2.5/5/14 mph (mowing/autonomous/manual)
Deck Width	72"
Dimensions (HxWxL)	52" x 79" x 90" (flexible as we are actively improving)
Reaction Time	0.25-0.5s (occurrence-to-reaction time. time-to-stop tests have not been completed)
Detectable Object Size	Variable. For visible objects, ~2" across minimum. For objects not visible to the naked eye (camouflage colors or covered by grass), fallback radar will likely require larger objects (no numbers yet, ballpark 1-6" across)
Safety Features	Redundant E-Stop buttons in controller, remote switch, and on robot. E-Stop kills engine and stops robot. People Detection, Visible Anomaly Detection, Lidar- and Radar-based invisible object detection. If a human is spotted, robot will not continue without manual intervention.
Drive wheels	2WD (it's a standard zero-turn). Upcoming Tractor model is 4WD articulating chasis.
Operating Tolerance	+/- 2"
Maintenance Schedule	N/A (about as much maintenance as the platform – ballpark every 100 hours, so biweekly for a full-time robot running 8-12 hours/day)
Operating Temperatures	N/A
Max Incline	15 deg current model – upcoming tractor model supports 30 deg (58% grade)



Figure 6.3. Front view of autonomous mower in operation mowing around a signpost



Figure 6.4. Side view of mower in operation with the side mower attachment



Figure 6.5. Top view of mower showing LIDAR, GPS, and power controls



Figure 6.6. Close-up view of LIDAR

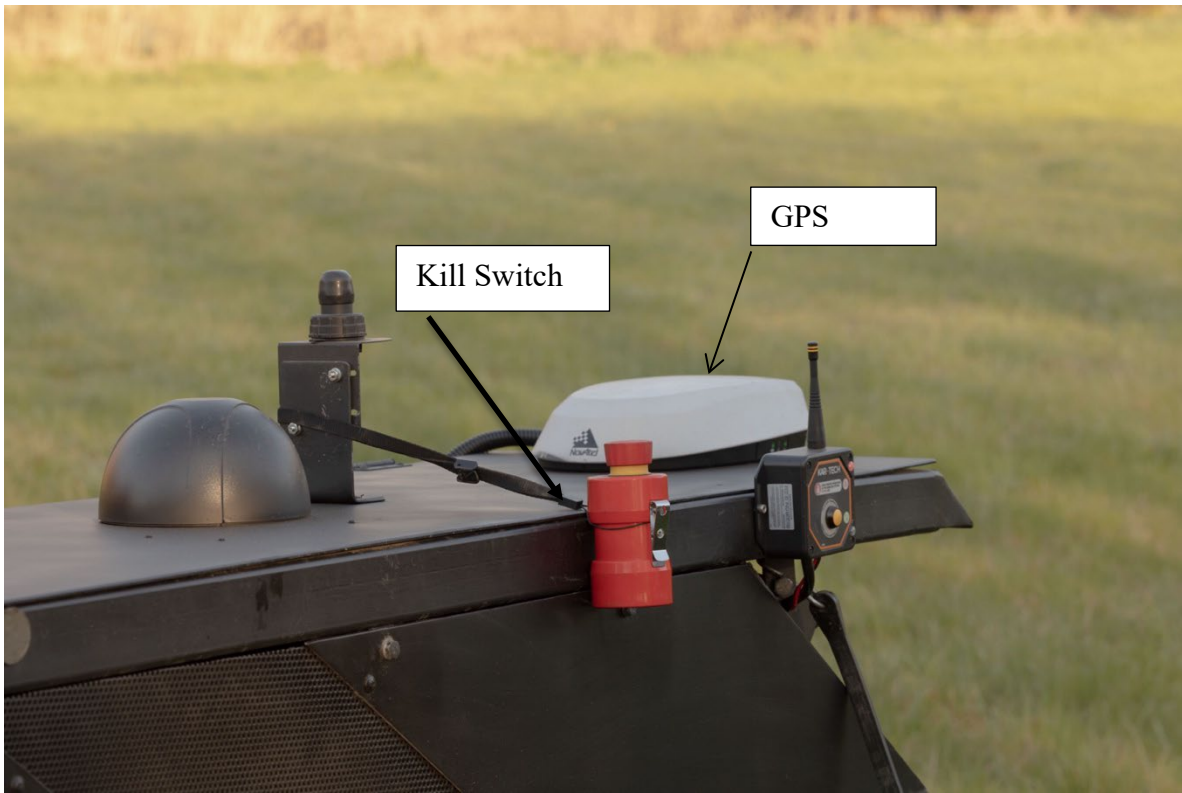


Figure 6.7. Close-up view of the kill switch and GPS unit



Figure 6.8. Rear view of mower in operation

The field demonstration agenda, as performed, is shown in Table 6.2. This included attendees from multiple agencies including CALTRANS, CHP, and CalSTA. An image from the demonstration is provided in Figure 6.9.

Table 6.2. Field demonstration agenda

Date	June 20, 2024
Location	California Highway Patrol, West Sacramento, CA
Attendees	CalSTA, CHP, Caltrans Div of Equipment, Maintenance and Research and Innovation
Field Demonstration Protocol	Opening remarks and safety briefing
	Mowing operations within geo-fencing, flat terrain near pavement
	Mowing operations within geo-fencing on sloped grade
	LIDAR image broadcast simultaneously while mower was in operation
	Tethered drone operated by UC-Davis collected videos of mower in operation



Figure 6.9. Greenline Autonomous Mower operating on level terrain

The demonstration was used for educational purposes and to obtain feedback from the attendees. A summary of comments made is provided in Table 6.3. These comments are representative of discussions had between the research team and the attendees at the demonstration.

Table 6.3. Summary of comments collected during the demonstration

Comment No.	Comment
1	Mowing operations using autonomous technology must be efficient
2	Autonomous technology must improve worker safety as well as the safety of the traveling public
3	Long term interest is in larger tractors as are currently in use
4	Technology should be tested at the District level in “real world” conditions
5	Districts mow “high” grass – radar must be able to see through the grass
6	Interested in mower accuracy (i.e., how far will the mower deviate from the “mapped” route)
7	Interest expressed in application to construction. For example, sweeper operations
8	Speed of vehicle reduced when mowing. Top speed of the Greenline unit is 18 mph
9	Discussion over the SAE definitions vs the need to develop “agricultural definitions
10	DOT may need a separate set of definitions to implement
11	<i>Q: How long till you have an electric mower? A; 1-3 years. Dependent on demand – generally, utility-scale operations have shown interest in a gas-power unit similar to their existing units. We plan to expand to smaller-scale operations and roadside mowing customers, who show more interest in electric models.</i>
12	Can the Autonomous technology be applied to an existing tractor (i.e., JD) Yes, with relative ease. One tractor unit is already in testing, and other units (if desired) can easily be retrofit with our technology. Some unit-specific development is required to accommodate different size, shape, reactions to controls, sensor positioning, etc. Expected timeline from start to operating in a field is 2-6 months.

6.3 Outcome of Demonstration

Based on the discussion that developed during the demonstration and continued afterward, it became apparent better definitions of the area Division of Maintenance is required to maintain within the right-of-way (ROW) were needed. Similarly, the TAC agreed a better description of the levels of autonomous technology available for deployment in maintenance activities was needed. First, an improved definition of the area to be mowed in the ROW as it pertains to maintenance activities is developed, followed by a prototype matrix to assist the owner in defining the autonomous technology needed for a given maintenance activity (mowing in this case). Rather than define the autonomous technology in terms of the features industry feels they can provide, the intent of the matrix is to define the requirements of the owner to allow implementation of the technology.

6.3.1 ROW (or operational zone) to be maintained

To begin, FHWA Order 5160.1A “Policy on Sponsorship Acknowledgment and Agreements within the Highway Right-of-Way” defines the highway right of way as:

A strip of property, owned by a highway agency, within which a highway exists or is planned to be built. The highway right-of-way consists of all lands within the defined highway right-of-way limits, including airspace above and below the facility. This area typically includes, but is not limited to, the roadway(s), shoulders, and sidewalk(s), if any; areas for drainage, utilities, landscaping, berms, and fencing; rest areas; and the defined clear zone.

Similarly, the California Vehicle Code defines a “street” or highways as follows:

VEHICLE CODE – VEH
DIVISION 1. WORDS AND PHRASES DEFINED [100 - 681]
(Division 1 enacted by Stats. 1959, Ch. 3.)

591. A “street” or “highway” shall not include those portions of a way or place in or upon which construction, alteration, or repair work is being performed insofar as the equipment performing such work and its operation are concerned. Where the work consists of a street or highway project, the limits of the project as shown or described in the plans or specifications of the awarding body shall be so excluded with reference to the equipment actually engaged in performing the work. The authority having jurisdiction over such way or place may include any or all of the requirements set forth in Divisions 11, 12, 13, 14 and 15 in any permit issued for work on such way or place and the awarding body on any such street or highway project may include such requirements in the specifications for such project. It is the intention of the Legislature, in enacting this section, that this section shall not be construed to relieve any person from the duty of exercising due care.

(Added by Stats. 1959, Ch. 659.)

Lastly, another definition of highway is found in the California Streets and Highway Code

STREETS AND HIGHWAYS CODE – SHC
GENERAL PROVISIONS
(General Provisions enacted by Stats. 1935, Ch. 29.)

23. As used in this code, unless the particular provision or the context otherwise requires, “highway” includes bridges, culverts, curbs, drains, and all works incidental to highway construction, improvement, and maintenance.

(Enacted by Stats. 1935, Ch. 29.)

For this work, highway or “traveled way” is taken as that area within the ROW where the traveling public is able to safely travel at the posted speed limit. In the ROW, there can be a median and shoulder. As noted in NCHRP Project 14-40 Report (Storey et al., 2020) the shoulder and roadway (or traveled way) are the “vegetation free” zone and hence do not require mowing.

A median is the area between opposing lanes of traffic, excluding turn lanes. Medians in urban and suburban areas can be defined by pavement markings, raised medians, or islands to separate motorized and non-motorized road users. A median may or may not be part of the “vegetation free” zone.

Note the definition of the right of way (ROW) as given by FHWA, the California Vehicle Code and Street and Highway Code (SHC) include all possible components of the ROW. What is not provided is a clear definition of the area to be mowed or the operational zone (OZ) as defined by Storey et al (2020). Figure 6.10 provides a graphical definition of the operational zone for a typical undivided highway. The area where the autonomous mower will operate is the remaining area in the ROW after the traveled way (TW) and shoulder (SH) are removed, which is the operational zone (OZ) as defined by Storey et al. (2020). Similarly, for a divided highway with median (ME), Figure 6.11 shows the operational zone graphically.

In equation form then the area to be mowed is the remaining area after the traveled way, shoulder and median are removed from the right of way or:

$$OZ = ROW - TW - SH - ME^1$$

¹ If the median (ME) is not in the “vegetation free” zone, then it is included in the operational zone.

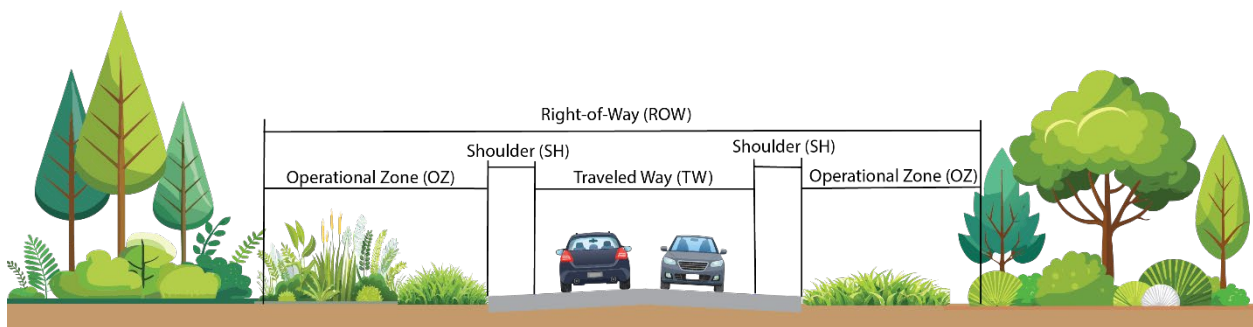


Figure 6.10. Highway operational zone

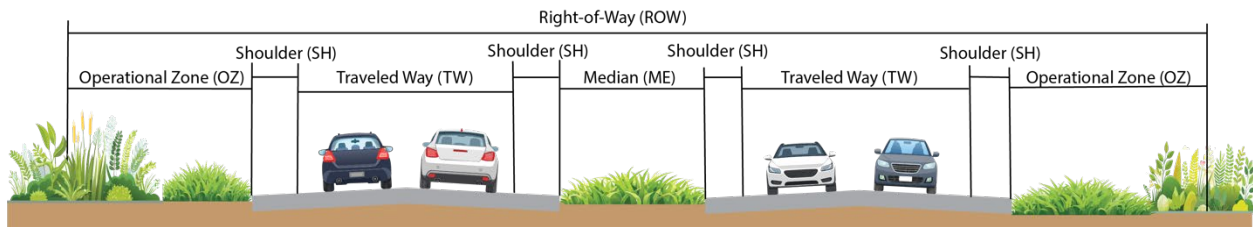


Figure 6.11. Divided highway operational zone

6.3.2 Autonomous Technology

The California Department of Motor Vehicles defines autonomous technology as a technology that includes a combination of hardware and software, remote and/or on-board, that has the capability to drive a vehicle without active physical control or monitoring by a human operator. While this is a rather broad definition, resulting in various levels of autonomy as defined by SAE (J3016-202104) and Case for vehicles on the “traveled way”. For maintenance operations such as mowing, a similar set of criteria is needed to define the technology suitable to the maintenance task which is not on the “traveled way”.

Defining autonomous technology for maintenance operations (i.e., mowing operations in this case) differs from an automobile, in that maintenance operations tend to be more repetitive. That is, the areas to be mowed within the right of way (ROW) do not change drastically over time. Changes that do occur are typically due to natural events, such as floods, wildfires and earthquakes, and the changes are documented. Similarly for changes resulting from realignment or expansion of the highway system. When those changes do occur, the operator would merely “reprogram” the software to recognize environmental changes, similarly to when the autonomous mower was initially deployed. (Note during the demonstration of the Greenline Mower, an operator was present on the first pass to “map” the terrain.) The software can also be programmed such that if the mower detects a “large” variance from the last mow, it will shut down and wait for human intervention. Given that difference, the following matrix (Table 6.4) was developed to enable a DOT to define the technology needed for a particular application, mowing in the case. Note that some values have been entered based on “experience”, however an experimental plan is required to populate the matrix. This can begin in area away from a public highway or road before being tested on a public road.

6.3.2.1 Geofencing/Geogrid

[Geofencing](#) refers to the use of Global Positioning System (GPS) technology to create a virtual boundary around a particular geographic location. This technology leverages the geographical location of devices to deliver targeted actions based on their movements within these boundaries.

Once this digital fence is established, software can be programmed to trigger specific actions when a device enters, leaves, or dwells within this fenced area. These actions can range from sending [location-based notifications](#) to tracking movement within a defined space, creating a myriad of opportunities for personalized, contextually aware interactions.

Table 6.4. Target values for autonomous mowing operations

Equipment Attribute	Target Values	
	Target	Variance (+/-)
Terrain¹		
Flat (m < 2%)	1%	1%
Moderate (2%<m<10%)	6%	4%
Steep (m>10%)	15%	5%
Obstacle detection²		
By size	TBD	TBD
By distance	TBD	TBD
Control²		
GPS (accuracy)	TBD	TBD
Geo-fencing (accuracy)	TBD	TBD
GPS & Geo-Fence Combo	TBD	TBD
Mapping²		
None	TBD	TBD
Last x routes	TBD	TBD
Last x+10 routes	TBD	TBD
Mower Speed²		
Mowing (fps)	TBD	TBD
Mower disengaged mph)	TBD	TBD

² Field experimentation / verification required to quantify target values

For mowing operations geo-fencing is a suitable control mechanism as much of the area to be mowed is “static”, that is, it does not change significantly from year to year.

6.3.2.2 LIDAR

Lidar, which stands for *Light Detection and Ranging*, is a [remote sensing](#) method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses—combined with other data recorded by the airborne system — generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

6.4 Future Work

As a result of this study, the following tasks have been identified to improve the potential for deployment of autonomous technology in highway maintenance operations.

1. Continue the dialog with Caltrans and Agency staff to encourage modifications to California Code to allow the eventual deployment of autonomous technology in mowing operations

(and eventually other maintenance operations). This would include agreement on definitions of the area to be mowed (i.e., operational zone)

2. Continue development of autonomous technology within the current legal framework oriented toward mowing operations via a Pilot Project in California
 - a. deploy “mowers” at more than one location (e.g., northern California and Central Valley)
 - b. deploy mowers with a driver on-board per California Code
 - c. evaluate different environmental and management “cultures”
 - d. evaluate various mapping software
3. Continue to improve definitions of right-of-way (ROW) and traveled way as begun in this study, including the target values suggested in Table 6.4
4. Perform a cost-benefit analysis to determine whether retrofit of an existing tractor in the Caltrans inventory is economical
5. Extend the technology developed for maintenance operations to constructions (e.g., AV sweeper).

CHAPTER 7. CONCLUSION

7.1 Summary

With the advent of autonomous vehicles, it may be possible to reduce worker exposure and risk by utilizing driverless tractors for mowing operations. The objective of this study is to assess ease of use, safety, and appropriateness of non-line-of-sight, remote control / automated vehicle technologies for Caltrans transportation maintenance operations. This includes available OEM systems and retrofit of existing vehicles (tractors) in the Caltrans inventory.

This report summarized completed work to accomplish the above objective. A review of the technical literature was completed and is summarized in Chapter 2.0. Included in this effort was the development and distribution of a questionnaire. The questionnaire and subsequent results are as tabulated in Chapter 3. Based on a preliminary review of the literature, it is apparent industry is developing vehicles which can satisfy Caltrans needs. For example, in January of 2022, John Deere announced their first fully autonomous tractor which is ready for large-scale production. According to their press release the tractor, which is for agriculture applications, uses GPS guidance and a geofence for navigation along with six cameras which allow for 360-degree obstacle detection (John Deere, 2022). Announcements and concept autonomous tractors have also been released by other companies including New Holland (New Holland, 2017), Massey Ferguson (Wordsworth, 2019), Kubota (Herath, 2020), Mahindra (ETAUTO, 2017), Agco (AGCO 2019), Sabanto (DTN/Progressive Farmer, 2020), Raven Autonomy (Raven Precision, 2021), and Jaybridge Robotics/Kinze Manufacturing (Jaybridge Robotics, 2020). These systems range in capabilities including remote guidance and pre-specified routes, as well as systems for which specifications are not available in public forums. Given the significant interest by industry, a draft specification was formulated as shown in Chapter 4. Continuing, a group of potential vendors was identified and efforts to assess their interest and potential involvement are documented in Chapter #5.

As the project progressed, it became apparent Caltrans policy did not fully support the use of autonomous vehicles for maintenance activities. Articles 3.7 and 3.8 under Chapter 1 of California Code of Regulations Title 13 – governing the implementation of autonomous vehicles on the State’s streets and highways, states: *All self-propelled equipment shall, when under its own power and in motion, have an operator stationed at the vehicular controls...*

Given the apparent confusion resulting from application of SAE definitions in a maintenance environment, and in consultation with the Caltrans Technical Advisory Committee (TAC), it was agreed a demonstration should be more “educational” rather than “evaluatory”. That demonstration would be held in the Sacramento area. The objective of this demonstration would be twofold: (i) provide a demo of an automated tractor system that is currently being used for mowing applications and ensure that mowing can be monitored via a Transportation Management Center (TMC)/Emergency Operations Center (EOC) as appropriate, and (ii) provide case studies of examples where automated technologies have been used or tested in similar operating environments in development, research, or practice. A summary of the demonstration and outcome is described in Chapter 6.

7.2 Future Work

As a result of this study, findings identified to improve the potential for deployment of autonomous technology in highway maintenance operations include:

1. Continue the dialog with Caltrans and Agency staff to encourage modifications to California Code to allow the eventual deployment of autonomous technology in mowing operations (and eventually other maintenance operations). This would include agreement on definitions of the area to be mowed (i.e., operational zone)
2. Continue development of autonomous technology within the current legal framework oriented toward mowing operations via a Pilot Project in California
 - a. deploy “mowers” at more than one location (e.g., northern California and Central Valley)
 - b. deploy mowers with a driver on-board per California Code
 - c. evaluate different environmental and management “cultures”
 - d. evaluate various mapping software
3. Continue to improve definitions of right-of-way (ROW) and traveled way as begun in this study, including the target values suggested in Table 6.4
4. Perform a cost-benefit analysis to determine whether retrofit of an existing tractor in the Caltrans inventory is economical
5. Extend the technology developed for maintenance operations to constructions (e.g., AV sweeper).

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APPENDIX: DRAFT SPECIFICATION

STATE OF CALIFORNIA, DEPARTMENT OF TRANSPORTATION DIVISION OF EQUIPMENT DRAFT

SPECIFICATION NUMBER: 59218-034-171 - Autonomous
SPECIFICATIONS FOR: Tractor, Wheel, with Side and Rear Mowers
PURCHASE ESTIMATE NUMBER: 32-12-6118

It is the intent of these specifications to describe the minimum requirements for a standard Four Wheel Drive Utility Tractor with Side and Rear Mowers.

The unit shall be the manufacturer's standard production model(s) and may only be modified to meet these specifications where specifically allowed. The unit may not be modified from its original configuration to meet the basic requirements of this specification. It shall be equipped with all of the manufacturer's standard equipment and accessories which are part of the standard published literature. If optional equipment is identified on the invitation for bid it shall only be supplied and installed where identified on the Individual Line Item.

Only technical changes authorized by the Division of Equipment Specification Engineer in writing will be accepted. Technical changes made by any other Division of Equipment, Caltrans or State employees will not be accepted. Any interpretation of the technical drawings or specifications shall only be provided by the Specification Engineer in writing.

The unit shall comply with Caltrans Equipment Quality Standards for Electrical, Welding, Paint and Coatings as defined at: <http://www.dot.ca.gov/hq/eqsc/qualstand.htm>.

This Specification will consist of three parts, the first two will be the technical specifications consisting of: Tractor, standard equipment not to be modified from current factory standards as published in a factory brochure provided at the time of bid; second section, Tractor, equipment may be modified to meet the specification. The third and final part shall be the Administrative Section, which includes the mowers under "options".

TECHNICAL SECTION 1: TRACTOR, STANDARD EQUIPMENT SHALL NOT BE MODIFIED FROM
CURRENT FACTORY STANDARDS AS PUBLISHED IN FACTORY BROCHURE AT THE TIME OF BID
ADVERTIZING.

1. FRAME: The tractor shall be equipped with a full frame extending from the front axle to the rear axle.
2. WEIGHT: The published shipping weight of the base tractor, exclusive of all implements, shall be not less than 11,000 lbs, including the enclosed cab, exclusive of the implements. Tractor shall have sufficient GVWR to carry all implements including optional variations without exceeding the GVWR of the unit or any of the GAWRs.
3. DIMENSIONS: The following dimensions are given to insure proper vehicle configuration, use, transport and storage. All dimensional requirements shall be applicable to the tractor equipped with the optional mowers requested.
 - a. Width: The Tractor and all attachments shall not be greater than 119.75 inches in width in the transport position.
 - b. Length: The Tractor and all attachments shall not be greater than 25 feet in length in the transport position.
 - c. Height: The tractor and all attachments shall not be greater than 121 inches in height in the transport position (tractor on a trailer - including beacon light).
 - d. Minimum Clearance: No point of the tractor or mower attachments shall be less than 8 inches from level ground.
4. ENGINE: The Tractor shall be equipped with a turbo charged, multiple valve, diesel fueled engine with a minimum of 130 engine horsepower (HP) and a net torque rating of 570 lb.-ft. The turbo charged engine shall have a minimum of 4 cylinders, and a minimum piston displacement of 4 liters. The engine shall meet Tier IV Final standards and shall be listed on a current Air Resources Board Executive Order for the "Engine Family" supplied (emission credits will not be accepted). The vendor shall supply a copy of the California Air Resources Board executive order for the engine family supplied, verifying that the engine as configured is Tier IV Final certified. Documentation is required at the pre-delivery inspection. Unit(s) will not be accepted for delivery until documentation has been provided.

The engine shall be equipped with hand and foot throttle control, a governor, factory set to engine manufacturer's recommended RPM for tractor/mower applications and shall be electrically started and shut off with a key.
5. ENGINE GAUGES AND WARNING DEVICES: This entire section may be included in the manufacturer's Engine Control Module (ECM), except as noted below. The tractor shall be

equipped with visual and/or audible warning devices, in addition to gauges, to alert the operator of conditions critical to engine and equipment operation.

- a. Speedometer: The unit shall have a separate Speedometer conveniently located in an instrument panel visible to the operator when in the operator's seat.
- b. Engine tachometer: The unit shall have a separate engine tachometer conveniently located within the instrument panel.
- c. Engine Temperature: The unit shall have an engine temperature gauge within the instrument panel.
- d. Fuel Gauge: The unit shall have a fuel gauge within the instrument panel.

All engine/hydraulic monitoring instrumentation and warning devices shall be permanently labeled to identify their functions with a simple and readable lettering style, or equivalent international symbols. The gauges shall be labeled to indicate maximum allowable operating range (AKA redlined). All gauges and instrumentation shall be backlighted for nighttime operation.

6. TRANSMISSION: The transmission shall utilize an oil immersed wet clutch to engage the transmission. The transmission shall be capable of fully synchronized shifts within certain ranges, four speeds per range. No clutching is required to shift speed gears within range, but in order to shift between ranges, the operator may be required to engage the clutch (can be done on the go). The transmission shall have a minimum of twenty four (24) forward and twenty four (24) reverse gears and a "creeper" mode. The transmission shall include an electronic power reverser to allow shifts from forward to reverse and back to forward without using the clutch. At a minimum, the transmission shall provide eight (8) speeds below 1.0 MPH at the manufacturer's recommended RPM for tractor/mower applications and have a minimum travel speed of 0.2 MPH at the manufacturer's recommended RPM for tractor/mower applications. The tractor shall be equipped with a transmission safety device that - in the event the transmission is engaged - will prevent the engine from starting or prevent the machine from moving if the engine is started. The tractor shall also be capable of traveling at a minimum of 20 mph when in the highest forward gear with the specified wheels and tires.
7. FRONT AXLE: The front axle shall be a Mechanical Front Wheel Drive (MFWD) type equipped with a drive disconnect to disengage the drive to the front wheels and allow the front wheels to spin freely. The front axle shall oscillate, allowing the axle to deflect vertically as well as tilt horizontally. The axle shall be capable of allowing one tire to ride over a standard timber 4 by 4 while the other tire remains in contact with level ground. The front axle shall be equipped with tubeless tires as specified. The tire and wheel load ratings shall exceed the minimum operating weight requirements of the tractor as equipped. The axle shall be of sufficient capacity to carry all imposed loads as equipped during mowing operations shall exceed the tire/wheel capacity and shall be mounted on welded steel disc rims.
8. REAR AXLE: The drive to the rear wheels shall be through a differential assembly having lockup capability. The rear wheel tread width shall be set at the maximum possible width for increased tractor stability without exceeding 120 inches. The rear axle capacity shall be adequate to

support all the attachments specified under all loading conditions, shall exceed the capacity of the tires and wheels and shall be mounted on welded steel disc rims.

9. STEERING: The tractor shall employ front wheel steering, controlled by a steering wheel with hydraulic power assist or hydrostatic steering. The tractor steering shall provide a maximum turning radius of not greater than 24.0 ft. with the tires and wheels specified.

The tractor shall have emergency steering capability that will allow the operator to maintain steering control in the event of an engine failure.

10. TIRES AND WHEELS: The tractor shall be equipped with the largest available R1, or R4 radial tubeless tires (not turf tires) on the front and rear axles that allow for the required clearances and shall have load ratings which exceed the imposed loads of the tractor as equipped in all mowing configurations – (i.e. boom extended fully) and shall be mounted on factory standard wheels. If the tractor is to be provided with both a boom mounted mower, and a rear flail mower, then Nokian Tri-2 tires may be used if necessary to meet the load rating requirement. Tire load ratings used for this requirement shall be at 25 mph, and shall be imprinted on the tire, or verified by the use of tire manufacturer charts.

The tires ***shall not*** be filled with liquid ballast for additional counterweight purposes. Flexible foam filled tires are acceptable – if one tire is filled with foam, all tires must be filled with foam, high density where needed, low density in other tires.

The wheel wells shall provide for a minimum 1.5 inches of tire clearance. For the rear tires, this means vertically to the wheel wells. For the front tires, this means in all directions with all attachments mounted, and at all turning angles. The rear wheel wells shall be completely unobstructed. All dimensional and operational requirements shall be applicable to the tractor equipped with these specified tires and wheels when inflated to the tire manufacturer's recommended pressure.

11. BRAKES: The service brakes shall be foot-operated and installed to apply braking force on both rear wheels. The service brakes shall be self-adjusting, sealed and immersed in oil to protect against the influence of dust, mud, sand or water (e.g., wet-disk brakes).

Hydraulically boosted or hydraulically actuated power braking systems shall incorporate emergency braking capability to allow the operator to stop the tractor in the event of an engine failure.

The tractor shall also be equipped with a parking brake or transmission lock to prevent the wheels from rolling while the tractor is parked. A red warning light shall be installed on the instrument panel, in full view of the operator, to indicate when the parking brake is applied while the engine is running. A transmission lock type device does not require a red warning light.

12. AIR AND OIL FILTRATION: The engine air filtration system shall be a 2-stage unit consisting of a centrifugal precleaner stage and water evacuator, incorporated in the air cleaner, and two dry element type, final stage filters of the correct capacity as indicated in the engine manufacturer's published instructions. The final stage filters shall consist of a replaceable outer primary filter and an inner safety element.

An engine air intake restriction gauge shall be located in the operator's compartment and mounted in plain view of the operator; an electronic alarm may be substituted in place of a

gauge if the alarm provides adequate time for the operator to replace the filter at the end of the day.

The engine oil filtration system shall utilize full flow filtration with a replaceable filter of the correct capacity as indicated in the engine manufacturer's published instructions.

13. EXHAUST SYSTEM: The exhaust system shall utilize a vertical exhaust stack either curved at the tip or equipped with a rain cap.

14. LIGHTING SYSTEM: The tractor lighting system shall comply with all applicable requirements as prescribed by FMVSS/CMVSS 108 and shall be equipped with the following minimum electrical lighting components:

- a. Two front driving lights
- b. Two front work lights
- c. Two rear work lights
- d. Rear tail and stop lights
- e. Front and rear mounted turn signals
- f. Rear license plate lamp with bracket
- g. Rotator Beacon meeting FMVSS and CMVSS (Reference Whelen L31 Series with Caltrans flash pattern, part # 01-0687752-00, or equivalent). NOTE: factory unit may not be acceptable, if factory unit is to be supplied as equivalent, documentation demonstrating compliance with FMVSS and CMVSS is required prior to pre-delivery inspection.

In addition to the mentioned lighting system, the tractor shall be equipped with side and rear reflectors or reflector tape in accordance with FMVSS 108 requirements.

15. EQUIPMENT: Equipment with access doors and shields, which can be opened or removed while components continue to rotate, shall have visible or audible indication of rotation. Access doors, guards and shields that must be opened for normal servicing, shall be easily opened and closed without tools. All shields shall remain functional under the forces that would be applied by a 250 lb. individual leaning on, falling against, or stepping on them.

Three-Point Hitch: The tractor shall be equipped with a rear mounted, hydraulically controlled, category II three-point hitch in accordance with ASABE 217.12. The three-point hitch hydraulic lift system shall be furnished with float capability.

Power Take-Off: The tractor shall be equipped with an independent, 540/1000 RPM power take-off (PTO) in accordance with ASABE S203.14. The PTO shall be located at the rear of the tractor and deliver a minimum of 100 HP.

16. CAB: The tractor shall be equipped with a fully enclosed cab with key type locking doors. The cab shall be equipped with safety glass windows. The cab shall be constructed to afford the operator visibility throughout the entire operation. The cab shall be completely sealed and pressurized to protect the operator from the external environment. The cab shall include a HEPA filtration system capable of filtering out normal particulates encountered during roadside mowing operations (e.g., dust, pollen, poison oak, etc.). The cab shall be furnished with a recirculating type heater with an integrated pressurized air conditioning system with front and rear window defrosters (defoggers). The cab shall be equipped with front and rear windshield wipers and washers.

The cab shall be equipped with a fully adjustable (fore and aft), fully padded air suspension seat with backrest and seat belt.

The cab shall be equipped with an AM/FM radio with weather band.

The cab shall be equipped with front and rear retractable sun screens.

The cab shall be equipped with a minimum of 1 cup holder.

The cab shall be equipped with a 3/8" thick right side and rear replacement polycarbonate windows to protect the operator from flying debris created by operation of mower. The right side door may be made inoperable where required by the mounting of the mowers. The replacement windows shall feature anti-abrasion coating with integrated UV protection (Ref. Lexan® MR10 or equivalent) and shall be mounted in place of the original glass, no exterior glass with frame will be acceptable. All other windows shall be safety glass.

The cab shall incorporate a Rollover Protective Structure (ROPS) conforming to SAE J1194 standards.

17. CONTROLS

a. Operator Controls:

- i. Placement of hand and foot controls shall be conveniently located to provide the operator maximum comfort. Controls, which influence the movement of the machine and the operational direction of equipment, shall conform to the requirements as established by SAE J1814 Standard "Operator Controls for Off Road Machines". Where confusion may result from the movement of a control, the effect of the control shall be clearly and permanently identified.