Design of an Alternative Work Zone Attenuator Device

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16. Abstract

ODOT currently uses dump-trucks as shadow vehicles to mount crash attenuators in a Work Zone. When used in work zones, these dump trucks may become damaged under a crash, which may render them unavailable to support other operations. Additionally, an assessment of other nuanced facets such as shadow vehicle operator safety, safety of work zone occupants, make the decision for use of dump trucks in work zone, non-trivial in nature. This research investigates whether an Alternative Device can be designed to replace the use of dump-trucks as shadow vehicles in a Work Zone. The research identifies ODOT's needs in a Work Zone, performs Market Research, and develops specifications for such an Alternative Device. The specifications are refined using feedback received from the industry and vendors via a RFI mechanism. Finally, a Cost-Benefit Analysis is performed to evaluate the economic feasibility of using such an Alternative Device against the dump-truck. Findings suggest that use of an Alternative Device with advanced sensor stack that displays limited in Work Zone operational autonomy may provide safety and operational benefits. Final specifications for such an Alternative Device are developed and posted as a part of this research program.

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Table of Contents

List of Figures

List of Tables

1. Problem Statement

The Ohio Department of Transportation (ODOT) commissioned research on RFP 2021-09 "Design of an Alternative Work Zone Attenuator Device" to advance its Work Zone safety goals. The objective of this research project is the development of technical specifications for a device that will be able to perform the functions of the dump truck in Work Zones.

ODOT uses dump trucks with mobile impact attenuators to act as a shadow vehicle in some work zone operations. A mobile attenuator may include Truck Mounted Attenuator (TMA) or a Truck Trailer Mounted Attenuator (TTMA) devices, which provide positive protection for workers and occupants of errant vehicles in work zones. These devices act as a first line of defense and absorb impact energy from a rear end crash. While impact attenuators are well understood, the shadow vehicle, which also plays a critical role in work zone operations, is less understood.

Owing to its geographical location, Ohio's transportation system is heavily impacted by winter weather. ODOT's winter operations cost an estimated $103 million spent annually on labor, equipment, and materials[1]. A critical piece of equipment ensuring the success of ODOT's winter operations is the standard dump truck.

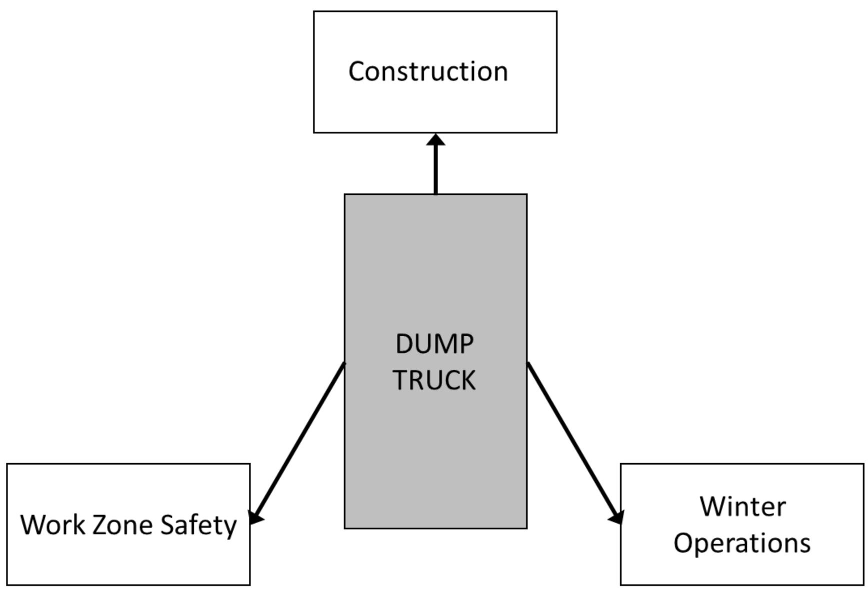

Figure 1 – The versatile dump truck serves competing demands making it a mission critical resource in a DOT's arsenal.

It is important to assess the sacrificial use of a mission-critical asset, such as a dump truck, in work zone operations (Figure 1). When used in work zones, these dump trucks may become damaged under a crash, which may render them unavailable to support other operations. In months leading up-to winter, damage to the dump truck

[1] Five-year average spend on winter operations between 2015-2020 on labor, materials and equipment is $103,100,979, based on information received from ODOT Office of Maintenance Operations

puts a critical resource out of commission for snowplowing and road salting operations. Additionally, an assessment of other nuanced facets such as shadow vehicle operator safety, safety of work zone occupants, make the decision for use of dump trucks in work zone, non-trivial in nature.

This report summarizes research performed in satisfying key goals of the RFP listed below:

- Research applicability of other types of low-cost devices on the market, which can replace the dump truck in a work zone.
- Develop specification for a device, which can perform functions of the dump truck in a work zone.

A research program was designed to achieve the goals of the RFP by categorically achieving objectives detailed below:

- Review of ODOT's current work zone practices and procedures
- Market research on currently available products
- Alternative devices used by industry and DOTs
- Development of specification for an alternative device to replace the use of dump trucks in work zones.

2. Research Background

Work Zones are one of the most operationally challenging areas to manage for DOTs in their roadway network system. A Work Zone design, logistics, and operation has to deal with competing demands of roadway users and workers. The nation's roadways have proved to be a dangerous place for workers. In 2018, 754 fatalities were recorded, amongst which 124 workers lost their lives in work zones across the nation. The State of Ohio recorded a total of 17 fatalities in work zones, 6 people of which were workers. These statistics point to the need to investigate solutions to increase protection of workers, and manage competing demands from roadway users, while helping DOTs maintain and effectively use their critical assets.

Many DOTs use dump trucks as shadow vehicles to provide positive protection to workers in a Work Zone. However, dump trucks are also used by many DOTs as primary snow and ice operation vehicles during winter months. Owing to its particular geographical location, Ohio's transportation system is heavily impacted by winter weather. ODOT's winter operations cost an estimated $103 million spent annually on labor, equipment, and materials. A critical piece of equipment ensuring the success of ODOT's winter operations is the standard dump truck. A dump truck that becomes damaged due to a Work Zone crash becomes unavailable for mission critical snow and ice operations. Hence, there is a desire to understand if these dump trucks can be replaced with alternative devices that may be used as a shadow vehicle in a Work Zone.

In work zones across the country, the use of shadow vehicles during mobile operations and the use of barrier vehicles in stationary operation is a common technique to protect workers from crashes. Advancements in the industry have led to an increased focus on research, design and validation of the mobile attenuators as they play a critical role in crash safety. However, the role of shadow vehicle is often less understood. This research looks at exploring the role of shadow vehicles holistically in a Work Zone. Literature review explored the roles played by shadow vehicle as a positive protection device. This role is typically governed by the make, model, and standard rating of the attenuator attached to the shadow vehicle. The MASH Standard (AASHTO, 2016) recognizes that the mass of the support vehicle plays an important role in the impact of an errant vehicle with the TMA. Another important parameter, given lower consideration is the roll ahead distance, i.e. distance a support vehicle may travel in case of an impact.

The research staff also reviewed additional literature that captures the role of shadow vehicles and TMA use. Information published by organizations such as AASHTO, ATSSA and outcomes of FHWA's Work Zone Grant were reviewed to identify relevant research on use of shadow vehicles in a Work Zone. This research revealed that there is an increasing national focus on whether additional guidance should be provided on choice of shadow vehicles and their placement in Work Zones on high speed facilities. Additionally, a review was performed on current state of best practices in rural, one-lane, two-way temporary traffic control during maintenance operations. This research report outlined the need and importance of appropriate advance warning signs, portable traffic signals (PTS), and automated flagger assistance devices (AFAD) in these settings. Additional work was also performed on the use of TMAs and shadow vehicles in a Work Zone.

Thus, a review of existing literature pointed to the need for:

- Developing an understanding of the role of shadow vehicles in a Work Zone
- Exploring if additional guidance around the choice of shadow vehicles and their use is beneficial to DOTs
- Developing possible alternative devices that may be used in a Work Zone that have the opportunity to minimize impact on DOT's mission critical snow and ice operations

Additional information and review of literature is available in Sec 9 – Appendix C.

3. Research Approach

This section presents TRC's categorical approach towards answering ODOT's central question: *"Evaluate applicability of other low-cost devices already on the market, and develop a specification for a device which can perform the function of dump truck in work zones"*. Research findings are presented in Sec 4.

TRC Inc.'s work plan is divided into three tasks below:

1. Task 1: ODOT Work Zone Analysis
2. Task 2: Market Survey
3. Task 3: Specification Development

Each task is made up of sub-tasks that deconstruct the nuances involved in the use of dump trucks in a Work Zone. Execution of a sub-task produces a deliverable, which contains valuable information for the next sub-task. TRC Inc.'s proposed work plan for research execution is tailor made to ensure efficient, accountable, and to-the-point delivery of work products to ODOT. Figure 2 deconstructs the information flow between tasks, sub-tasks and deliverables.

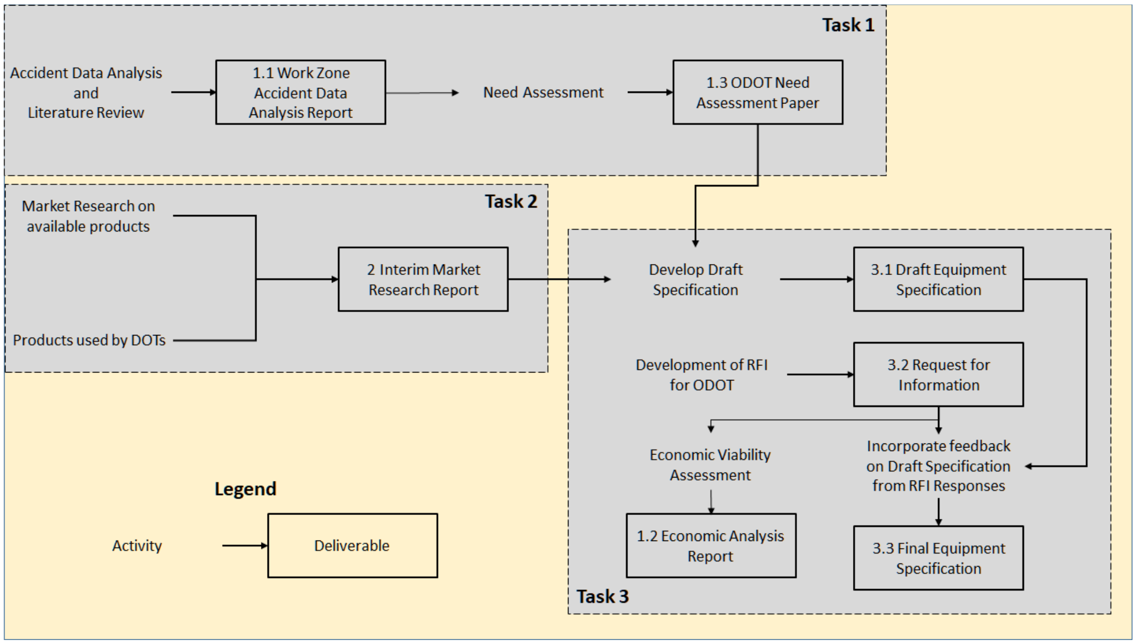

Figure 2 - Graphical illustration of work plan with tasks and information flow between deliverables.

The sections below introduce these tasks and outline TRC's research method.

3.1. Task 1 – ODOT Work Zone Analysis

The research team developed a work plan that is designed to develop a comprehensive understanding of ODOT's needs with regards to the shadow vehicle, in order to find solutions that may improve work zone safety. The focus of this task is to understand the role of the shadow vehicle in ODOT's work zones. Such a functional assessment of the shadow vehicle's roles and desired functionality will facilitate search for an alternative device that may replace the dump truck in a Work Zone. This task was sub-divided into three sub-tasks and a research approach for these activities is detailed below.

3.1.1. Task 1.1 – Work Zone Accident Analysis

While the function and role of a crash attenuator is well understood, the roles performed by the shadow vehicle have not been previously highlighted in literature. A spotlight on the role performed by dump trucks used as shadow vehicles will reveal strengths and lacunae of these vehicles in a Work Zone application. In order to develop this functional understanding of dump truck's current roles in the Work Zone, the research team

- Reviewed existing literature and research relevant to shadow vehicles.

A literature review was performed and findings are detailed in Sec 9. A summary of the literature review was presented in Sec 2.

- Developed a life-cycle view of a Work Zone.

  An attempt is made to categorize activities involved in execution of a Work Zone – from setup to tear-down, into appropriate phases that represent a part of its life-cycle. These activities can be broadly classified into three buckets – At-Garage, In-Transit, and at active work site.

- Reviewed the role performed by a dump truck in a Work Zone's life-cycle.

  It is recognized that dump truck performs various roles throughout the phases of a Work Zone's life-cycle. An analysis of these roles and appropriate categorization allows for the development of a functional view of the dump truck in a Work Zone.

- Studied Ohio MUTCD (O-MUTCD) typical Work Zone Applications to identify demands on Truck Mounted Attenuators.

  Guidelines provided by FHWA and ODOT for traffic control in Work Zones arrange Work Zones into various types of Typical Applications. These Work Zones are categorized into Typical Applications based on factors such as location of work, type of operations, duration of work and characteristics of the roadway. This research particularly focuses on the typical applications where TMA and shadow vehicles are recommended. These configurations are analyzed to understand the expected role of the shadow vehicles at a Work Zone during Active Operation.

- Derived functional requirements to be placed on shadow vehicles when used in Work Zone Typical Applications identified in O-MUTCD.

  A parametric analysis was performed on information obtained during the review of O-MUTCD Typical Work Zone Applications and an assessment of dump trucks' role in a Work Zone life cycle. This revealed key requirements from a TMA and Shadow Vehicle system in Work Zones. These requirements were classified into appropriate functional categories.

- Performed analysis on Work Zone Crash and Accident Data to understand operating envelope of crash events.

  ODOT provided TRC's researchers with a list of all reported traffic crash accidents in Ohio's Work Zones during the years 2016-2020. This dataset included traffic crash reports for over 26,700 traffic incidents in Ohio's Work Zones. Data analysis was conducted using the data workflow described below.

The research team applied filters to reduce the set of traffic crash reports to identify traffic incidents of interest to the scope of this research. Filters used are described below (Figure 3):

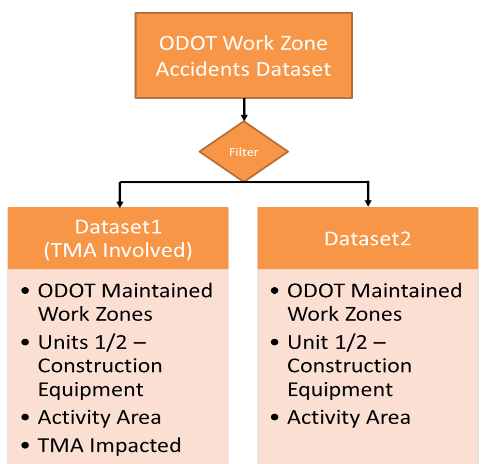

Figure 3 - Filtering and classification of ODOT Work Zone Traffic Crash Report datasets.

- Were Work Zones ODOT maintained?
- Did accidents involve construction equipment?
- Were there accidents in the activity area of the Work Zone?
- Was a Truck Mounted Crash Attenuator involved in the accidents?

The researchers performed additional analysis on these subsets in a compare-and-contrast fashion to understand the nature and characteristics of select set of traffic incidents. The researchers used both subjective and objective methods to glean insights from these datasets.

3.1.2. Task 1.2 – Economic Analysis

The goal of this activity was to determine the total cost of ownership and use of a dump truck against the proposed alternative device that may be used to replace them in a Work Zone. While this activity was originally nested within Task 1, it was performed after feedback was received from vendors via the RFI in Task 2 and 3.

The RFI mechanism gave us feedback on the technical feasibility of alternative device concept. TRC Inc. packaged the obtained information into three hypothetical buying options providing ODOT a range of technological upgrades for each option. Cost Benefit Analysis method was considered to be the most appropriate method for conducting economic analysis of feasibility of the alternative device concept over the existing dump truck. In this method the cost of an option is weighed against the benefits offered by it and a determination is made on its economic feasibility. In this analysis for the research project, the total projected cost and the benefits of the choosing the alternative device are calculated. If the benefits outweigh the cost, the project is considered to be feasible.

3.1.3. Task 1.3 – ODOT Needs Assessment

This needs assessment activity is designed to capture key ODOT needs from analysis of data, interaction with ODOT staff, and review of test standards. The goal of this activity is to answer the following key questions:

1. Do key operating conditions emerge from an analysis of crash data?
2. If yes, can a more widespread use of TMAs reduce crash risk in these operating conditions?
3. If yes, understand the impediments to a more widespread use of TMAs. What characteristics of shadow vehicles contribute to these impediments?

There were over 26,700 crashes in Ohio's Work Zones. The team applied select filters on key parameters to cluster the data and arrive at a refined dataset. The following parameters were used:

- Roadway Functional Class
- Roadway Contour / Geometry
- Weather, Road-weather
- Type of Work Zones

This data clustering technique (Figure 4) allowed for the emergence of patterns. These patterns were analyzed to identify operating cases relevant for the use of TMAs and shadow vehicles.

The research team also conducted a brief field study to observe operation of TMA and discuss operational challenges with the current shadow vehicle with ODOT's Highway Technicians (HTs) and Transportation Managers (TMs).

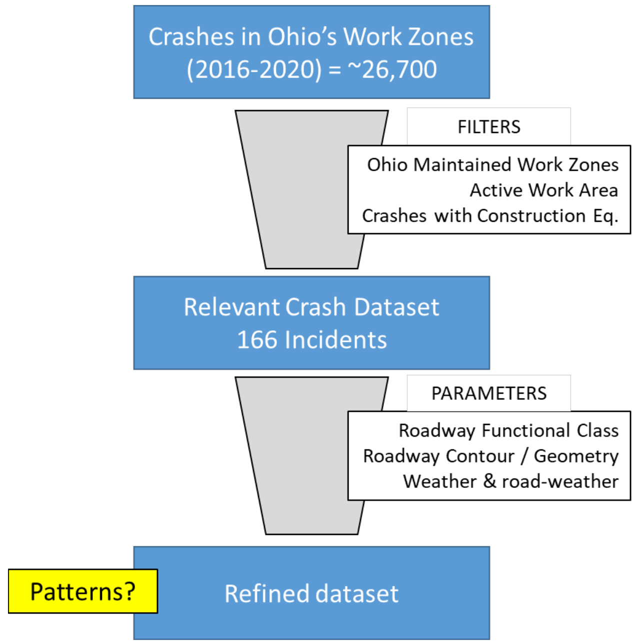

Figure 4 - Approach for data refinement and clustering

Task 2 – Market Survey

The conclusion of Task 1 provides ODOT with an understanding of the role performed by the dump truck in a Work Zone. A review of O-MUTCD's Work Zone Typical Applications enables an assessment of the role performed by shadow vehicles used with TMAs in an active Work Zone. A classification of these roles in appropriate functional categories enabled the conceptualization of an alternative device, which may be used to replace dump trucks in a Work Zone.

Task 2 is geared towards developing alternative device concepts that satisfy ODOT's needs. An iterative approach was used towards the completion of Task 2 and Task 3 activities on the project. The concepts were developed with due guidance and collaboration from ODOT TAC. Preliminary market feedback was used to refine concept development. As concepts became more refined a broad set of functional requirements were developed and continually refined. The following activities were designed in Task 2 of this research program:

- Review ODOT's needs and Task 1 findings to determine operational conditions.

  The goal of this activity was to determine most effective operating conditions for the alternative device's use from an analysis of Work Zone crash data. Additional comments from ODOT's Highway Technicians and Transportation Managers are distilled to understand the key preferable and not-so-preferred characteristics of dump-trucks when used as shadow vehicles in a Work Zone.

- Propose concepts for an Alternative Device, which may replace dump trucks as shadow vehicles in a Work Zone

  A functional view of the roles performed by the dump truck in a Work Zone's life-cycle allows for the conceptualization of an Alternative Device, which may replace the dump truck. The research staff focused on developing three alternative device concepts. The proposed concepts also identify a set of features that satisfy ODOT's identified needs. Strengths and weaknesses of these concepts and their fit in various operational conditions is identified.

- Perform an Interim Market Review to identify candidate vendors that may suggest technologies that enable development of this alternative device

  As concepts are developed and proposed, an Interim Market Review was performed to identify candidate vendors and technologies that may satisfy the needs outlined by ODOT. The goal of the interim market review is to inform the Request for Information phase of the research program. Additionally, the goal was to also identify if technical solutions exist that have the potential to satisfy ODOT's needs.

Task 3 – Specification Development

A set of concepts for an alternative device that may replace the dump truck in Work Zones is developed on completion of Task 2 of this research. Additionally a high-level understanding of a concept's feasibility and candidate technology solutions that enable a concept is also obtained based on Interim Market Review in Task 2. Task 3 expands that research further with the goal of developing functional requirements that are refined by market feedback. The following activities are performed in Task 3 of this research:

- Develop Functional Specifications for proposed alternative device concepts

  The research team reviewed the roles expected to be played by a shadow vehicle in a Work Zone, and ODOT's needs as researched in Task 1 of this program. Next, these needs were classified into functions to be performed by proposed concepts of the alternative device.

  Next, the team developed a set of requirements for each function to be performed by proposed alternative device concepts. In many cases these functions were nested within the role expected to be performed by the alternative device within a phase of the Work Zone life-cycle. These requirements were specified in a functional manner. A specification document was developed that detailed these requirements for both concepts proposed in the research. A functional approach towards development and specification of requirements enables for the specification of "what" needs to be done, and not the "how". This approach is designed to ensure that ODOT benefits from market competition forces, and multiple competing candidate solutions may achieve the same function using different techniques.

- Develop, host, and receive feedback via a Request for Information (RFI) mechanism.

  It is critical to ensure that functional specifications developed for the alternative device concepts benefit from market feedback. TRC Inc. developed and hosted a Request for Information to facilitate feedback and commentary on the developed functional specifications. Feedback was invited from the industry and included a broad spectrum of technology vendors, vehicle platform providers, and technology solution integrators.

- Consolidate vendor feedback received via the RFI mechanism

  The research team consolidated feedback received via the RFI mechanism. Vendor feedback was used to identify and define candidate technological solutions proposed by the industry to implement requirements stated in functional specifications. These product brochures, technical implementations, and vendor experiences were packaged into usable feedback that defined the manner in which technological solutions may be used to create an alternative device that may replace the dump truck in a Work Zone.

  Feedback from vendors was also used to identify feasibility and challenges of achieving posted functional requirements. This allows ODOT to learn from vendor experiences and market best practices when specifying the requirements of this alternative device. Finally, feedback from the RFI mechanism was also used to refine functional specifications proposed for both concepts of the alternative device.

- Inform Economic Analysis

  A few vendors also provided feedback and pricing estimates for candidate solutions proposed in their RFI response. This information was used as inputs for the Economic Analysis performed in Task 1 of this research program.

- Refine functional specifications of alternative device

  Functional specifications for concepts were refined based on feedback received via the RFI mechanism.

4. Research Findings and Conclusions

Research indicates that the choice of using a dump-truck as a shadow vehicle in a Work Zone is non-trivial in nature. While dump-trucks do offer advantages today, an Alternative Device can be designed using technology available today that may replace their use in a Work Zone as a shadow vehicle. The use of such an Alternative Device removes the safety operators from harm during a crash event, provide adequate positive protection to exposed workers and the errant motorist vehicle during rear-end and sideswipe crash event. The following sections categorically outline key research findings.

4.1. Research Highlights from Task 1 – ODOT Work Zone Analysis

4.1.1. Research Highlights from Task 1.1 – Work Zone Accident Analysis

Literature Review

A review of existing published literature revealed that the role of the shadow vehicles when used in a TMA application has not been well understood. While the role of TMAs is understood the choice of shadow vehicle and best practices that guide their placement and use are not well defined. Research revealed that organizations like AASHTO, ATSSA, and some research under the FHWA Work Zone Grant has produced some training material and best practices that can help inform the use of shadow vehicles in a Work Zone. Other literature relevant to the understanding of shadow vehicles in a Work Zone was also reviewed and summarized in Sec 9.3 of this research report. There appears to be an increasing national focus on whether additional guidance should be provided on shadow vehicle size and spacing when performing work operations on high-speed facilities. This research program expands that question further to also include the choice of shadow vehicles in a Work Zone. This research program tries to address the question of whether an alternative device can replace the dump trucks as shadow vehicles in a Work Zone, while still providing adequate protection to workers and all relevant actors in the event of a Work Zone crash scenario. Additional information about this Literature Review is presented in Sec 9. A summary of literature review is presented in Research Background Section 2.

Life-cycle of a Work Zone

A life-cycle view of the Work Zone was developed to understand the role performed by the shadow vehicles in a Work Zone. A graphical representation of the Work Zone life cycle is displayed below in Figure 5. A Work Zone's life-cycle can be broadly divided into five phases shown below.

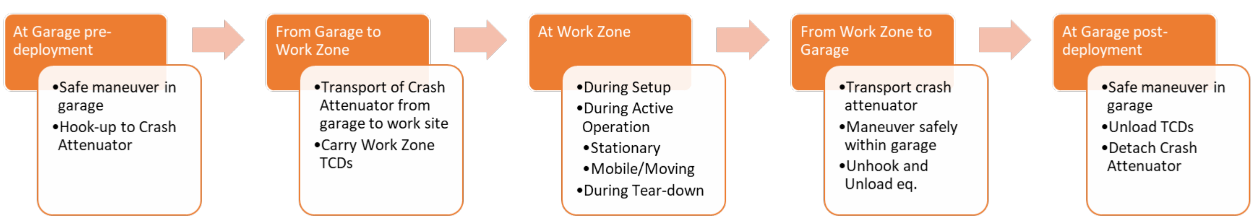

Figure 5 - Analysis of dump truck's functions through the Work Zone lifecycle

This life-cycle view of the shadow vehicle's roles enables focus on all the functions a shadow vehicle needs to perform at the garage, during travel to and from the worksite, and in active operation at the work site. Such a view allows for the development of a comprehensive understanding of the shadow vehicle's role in a Work Zone. Additional details are in Sec 10.1 - Appendix D.

Role performed by the Dump Truck in a Work Zone Life-Cycle

The role performed by the Dump Truck as a shadow vehicle was reviewed with the lens of a Work Zone life cycle. The dump truck performs the following key functional roles in a Work Zone life-cycle:

- Carry Payload – Carry equipment and Traffic Control Devices (TCDs) to work site
- Facilitate Mechanical Attachment and Interface – Interface and attach to attenuators
- Be Maneuverable – Maneuver in tight-spaces (ex. garage), at work-site, and on wide array of open roads in variety of operating conditions.
- Carry Electronics and Provide Warning – Provide electronic or sign-based warning for motorists
- Provide Positive Protection – Provide positive protection to work site from rogue traffic

An expanded analysis of dump truck's roles in various phases of Work Zone's life-cycle is in Sec 10.1 - Appendix D.

Review of O-MUTCD Work Zone Typical Applications

Agencies like FHWA or various state DOTs provide information that informs design of traffic control in Work Zones. Such information allows for Work Zones to be arranged into multiple categories depending upon the factors such as location of work, type of operations, duration of work and characteristics of the roadway. Additionally, such information also outlines if a shadow vehicle, arrow sign, crash cushion, and TMA is used in these typical applications. A review of O-MUTCD's Work Zone configurations facilitates an understanding of the role expected to be performed by the dump truck in an active Work Zone in select Typical Applications on Ohio's Work Zones.

The current research focuses on performing additional analysis on information, which pertains to the role of shadow vehicles, presented in Typical Applications of Ohio's Work Zones. There are 12 Typical Ohio Work Zone Applications where shadow vehicles are used in some capacity. These work zone scenarios can be classified into the following categories:

- Work on shoulder/median
- Intermittent / moving work
- Lane-closures
- Lane shift

Role of TMA and Shadow Vehicle in Functional Form

An analysis of the role of TMA and shadow vehicle during the active operation phase at Work Zone yields the following key requirements in each identified functional category:

- Electronics
    i. Capability to accommodate high-intensity rotating, flashing, oscillating, or strobe type lights
    ii. Attachment, mounting, and power for arrow boards
    iii. Hazard warning signals (supplementary, during active operation only)

    iv. Multiple high-intensity flashing lights (in select scenarios)
- Warning Signs
    i. Accommodate mounting of MUTCD signs like "LEFT LANE CLOSED AHEAD"
    ii. Signs should be visible and not obscured by equipment or other supplies
    iii. Easy access to cover signs or turned from view, when work is not in progress
- Positive Protection
    i. Placement guidance – position at a static, short-duration, mobile and moving operations Work Zone
    ii. Longitudinal safe distance from work vehicle
        - Adapt with rear traffic sight distance
        - Position to prevent traffic side-swipe incidents with work vehicle
        - Adaptability with respect to terrain (roadway geometry & sight-distance)
        - Adaptability to traffic conditions (high-speed roadway guidance, traffic back-up)
    iii. Lateral placement (contingent on infrastructure & roadway operation conditions)
        - Interior Lane
        - Shoulder work
        - Lane-edge straddle
- Maneuver
    i. Ability to follow work vehicle at a safe distance
    ii. Ability to adapt to infrastructure and traffic conditions
    iii. Initiate periodic pull-over maneuver to allow safe passage for following traffic

Additional information about the O-MUTCD Work Zone Typical Applications and an assessment of functions performed by TMA and Shadow Vehicle in an active work zone can be found in Sec 10.3 of Appendix C.

Work Zone Crash and Accident Data Summary

The research team performed analysis on Accident and Crash Data in Ohio's Work Zones between 2016-2020, to identify characteristics of dominant operating case for the use of shadow vehicles. This assessment was also designed to inform the development of functional specifications of the alternative device that may be used to replace the dump truck.

There were over ~26,700 crashes in Ohio's Work Zones. The research team applied appropriate filters on key parameters to enable clustering of data and development of a refined dataset. This clustering technique allowed for the generation of patterns. Application of filters led to the identification of 166 potential crashes, which could have benefited from the use of TMAs. Of the 166 crashes:

- 55% occurred on Interstates and Freeways/Expressways
- 25% occurred on Arterial Roadways

When crashes on the Interstates and Freeways were reviewed, over 85% occurred on roadways with straight roadway geometry contour. Table 1 investigates such crashes further.

Table 1 - Summary of findings from a review of the refined crash dataset

Parameter	Findings	This implies:
Type of Work Zone	Of all crashes in Work Zones on Straight roads: • 70% crashes occurred in static work zones • 30% crashes occurred in mobile/moving work zones	While both static and mobile work sites pose a separate set of risks and challenges, it appears that static operations have percentage of crashes.
Type of Work Zone Activity	Crash frequency list: • Lane closure sites (41%) • Work on shoulder/median (38%) • Intermittent / Moving Work (15%)	Static lane closure sites are most common and risky to workers. Working on shoulder and medians, is also conducive to the use of TMAs.

Additional information about findings of Work Zone Accident Crash Data analysis is reflected in Sec 10.4 of Appendix C.

4.1.2. Research Highlights from Task 1.2 – Economic Analysis

Cost Benefit Analysis method was considered to be the most appropriate method for conducting economic analysis of feasibility of the alternative device concept over the existing dump truck. In the case of alternative device concept, the objective of the analysis is determining the whether the implementation cost of the concept will provide with adequate benefits over the existing dump truck system. This approach was designed to provide ODOT with a comprehensive coverage of costs, and help establish the economic viability of market alternatives, identified in-line with the specifications vs. the traditional dump truck model.

Results for Economic Analysis in one key scenario “New Dump Truck vs. New Alternative Device” is documented here. The key outcome of the Economic Analysis is an Excel calculation program, which allows ODOT to perform their economic analysis as updated cost and benefit input parameters become available. This allows for the most up-to-date generation of insights and decision making with regards to economic feasibility assessment of the alternative device.

Cost Benefit Analysis performed for the scenario listed above suggests that the use of an Alternative Device is economically feasible. The differential costs of using the Alternative Device over the dump-trucks are dominated by purchase costs. However, an estimate of potential benefits indicates that costs are closely matched with the benefits to be accrued by the use of the Alternative Device in Scenario 1. It is recognized that a large share of potential benefits lies in the reduced costs for Workers Compensation and lower downtime and rental costs to cover for a dump truck damaged in a Work Zone. Table 2 summarizes these findings.

Table 2 - Summary of Cost-Benefit Analysis for Scenario 1.

Cost-Benefit Analysis	Differential Costs / life	Differential Benefits / life
Scenario 1 – Use of New Alternative Device over a New Dump Truck	$ 77,097	$ 77,563
Is choice feasible?	Yes	

Additional information about the method, results, and supplementary calculations for Cost-Benefit Analysis are posted in Sec 14 – Appendix H.

4.1.3. Research Highlights from Task 1.3 – ODOT Needs Assessment

ODOT's needs from an assessment of Work Zone Accident Crash data reflects that a few operating conditions dominate the most effective use case for shadow vehicles and TMA system in a Work Zone. The research team identified potential Work Zone crashes that will benefit from the use of a shadow vehicle and determined characteristics that dictate the operating conditions. There characteristics may relate to the Roadway Functional Class on which these crashes seem to frequently occur or may typify the type of Work Zones which are susceptible to crashes. Table 3 summarizes these findings and connects the information to relevant implications on the design of the alternate device.

Table 3 – Summary of needs and implications on design of an alternative device from a review of crash dataset

Category of Need	Design implication (ordered list)
Roadway Functional Class	1. Interstates and Freeways/Expressways 2. Arterial Roads These functional classes imply an use case with: Moderate to high speed travel ways Moderate to high traffic volume travel ways
Nature of Work Zone	1. Static 2. Mobile / Moving
Type of Work Zone	1. Lane Closure 2. Work on shoulder or median 3. Moving and mobile work
Crash Vehicle, type of crash, most common pre-crash action	1. Passenger vehicles, straight-ahead 2. SUVs, straight-ahead 3. Semi-tractor, straight-ahead

Additional information about the analysis of operating conditions is found in Sec 10.5

The research team performed a field visit to ODOT's District #6 Hilliard Outpost to observe operations, and understand challenges faced by ODOT's HTs using the shadow vehicle and TMA. Table 4 summarizes ODOT's needs as observed during the field visit for an alternative device in TMA operations.

Table 4 - ODOT's needs as observed during field visit, categorized into key functional areas

Category	Description of Needs
Information to design Work Zone	When considering setup of a work zone, provide staff with adequate information to make an informed choice to use an appropriate device in a work zone configuration
Interface and Attachment	Easy mechanical attachment to TTMA via a hitch mechanism
	Easy mechanical attachment to TMA via adapters
	Standardized electrical adapters to accommodate TMA and CMS power needs
Travelling (to and from worksite)	When travelling in a TTMA configuration, facilitate easy backing and maneuvers in reverse
	Enable operators to maintain safe following distance from work vehicle
	Facilitate travel in narrow shoulders that may include a drop-off and uneven terrain
	Enable operators to become spatially aware of potential impacts of TMA/TTMA or shadow vehicle with hazards like roadside crash attenuators, bridge guardrails etc.
	Enable operators to become spatially aware of encroachment of TMA/TTMA or shadow vehicle into other lanes
Maneuver (at or within work zone)	When at work zone during setup, encourage safe maneuver in tight spaces
	When at a static work zone, enable slow speed maneuvers to reposition TMAs per work site needs
	When maneuvering (in mobile operations), enable operators to become spatially aware of encroachment of TMA/TTMA or shadow vehicle into other lanes
	Enable operators to become spatially aware of potential impacts of TMA/TTMA or shadow vehicle with hazards such as work zone barrels, cones in tight spaces etc.
Positive Protection	When at a work zone, enable operators to maintain safe longitudinal distance and lateral position for crash protection from workers or (moving or static) work vehicles at the site.
	When using the alternative device, provide adequate positive crash protection during static or mobile operations
	Under an impending crash, apply full braking to reduce roll-ahead into workers
Crash Alerts	Under an impending work zone crash, alert workers via an air-horn and panic lights
	Under an impending work zone crash, provide workers visibility on the type of impacting vehicle and pre-crash action to help them react to the crash event

Discussions between the research staff, ODOT TAC and ODOT's HTs have been edited, categorized and presented in Sec 10.6.

4.2. Research Highlights from Task 2 – Market Survey

Task 1 helped in the development of an understanding of the role of dump trucks in Work Zones with TMA. A functional understanding of the roles was developed. Such an understanding allowed for the conversation to evolve and explore the possibility of whether these dump trucks could be replaced with an alternative device. The conversation was also informed by an assessment of operating conditions derived from an analysis of Work Zone Crashes in the state of Ohio. To round off this information, the role to be performed by a futuristic alternative device were also informed with needs of ODOT's Highway Technicians and Transportation Managers.

Task 2 processes this information and proposes concepts for the Alternative device, which may be able to replace the use of dump trucks as shadow vehicles in Work Zones. The concepts focus on performing functional roles identified as needs in research conducted in Task 1. These concepts were generated with a design philosophy that focused on:

- Providing maximum worker protection by enabling crash prevention, warning, and protection
- Minimize interaction of human operator with the alternative device
- Provide protection to the errant motorist crash vehicle

The research staff proposed two concepts that could be used for the alternative device. A functional description of concepts was defined in the research. These concepts are listed below:

- Concept C1 – Upgraded Mobile Vehicle
- Concept C2 – Mobile Remote Platform

The Upgraded Mobile Vehicle Concept C1 would involve replacing the dump truck with a smaller vehicle deemed fit to provide the required positive protection. The impact handling capacity of this vehicle may be enhanced by adding the required payload on the vehicle such that it provides necessary positive protection in a work zone. The operator would drive the vehicle to the worksite, and once it is stationed correctly, the device is envisioned to work without the need for a driver, in both static and mobile/moving work zones. A remote operator may need to monitor the device for safety. An implementation of this device may also incorporate Crash Protection, and Prevention technologies in order to provide safety to workers in a Work Zone.

The Mobile Remote Platform (MRP) Concept C2 can be envisioned to be a towing device, which can be utilized to carry an attenuator attached to it. The MRP device is expected to be maneuvered by a remote operator within in the work zone. It is envisioned that such a device would be driven/towed to the work zone using other vehicles and then the mounted crash attenuator would be deployed at the worksite. The platform should have the ability to have the attenuator detached, removed, and replaced. The attenuator is not a permanent piece of the platform. The minimum payload needed for appropriate positive protection of workers in case of a crash should be offered by the MRP device. An implementation of this concept may also include Crash Protection, and Prevention technologies.

Figure 6 outlines the key facets of proposed concepts of the alternative device.

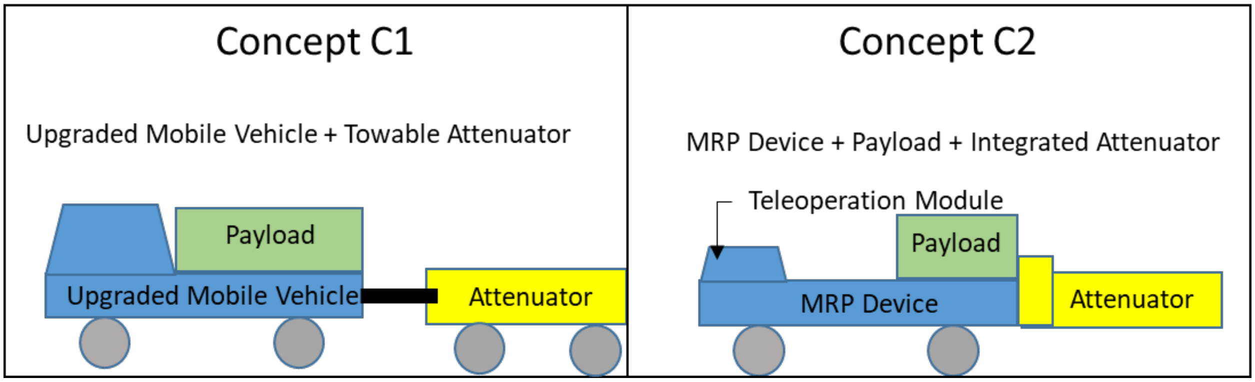

Figure 6 - An illustration of proposed concepts for the alternative device

Additional information on the proposed alternative device concepts, and their functional features is available in Sec 11.1.

The research staff also developed preliminary functional requirements for both Concepts. These functional requirements are designed to accommodate ODOT's needs and other learnings obtained from Task 1 of Market Review. The functional requirements proposed for both concepts can be broadly classified into the following categories:

- General Requirements
- Pre-Deployment and Post-Deployment functions
- Operability
- Crash Prevention
- Crash Sensing and Warning
- Crash Protection
- Post-Crash Requirements
- TMA Adapter Requirements and Other Considerations (if needed)

A host of features and technological solutions may implement these functional requirements. The research staff performed an Interim Market Review to identify potential vendors and candidate technical solutions that may enable implementation of concepts. These vendors were identified via a Market Review.

The market review identified over 25 vendors and related products from a broad spectrum of industries that may be used to satisfy the posted requirements at least partially. The market review identified full vehicle OEMs, which may have vehicle solutions that may potentially satisfy the positive protection style requirements. Also, the review identified vendors that may supply Driving Automation System, Sensing, and Warning technology systems that may improve protection in a Work Zone. Finally, vendors which specialize in technology integration, and have experience in building such alternative devices were also identified in this Interim Market Review.

The Interim Market Review helped the research team make a preliminary assessment of market's readiness towards proposing technical solutions that may satisfy ODOT's needs. Additionally, it helped the research staff identify candidate vendors that may be contacted to receive feedback during the RFI process. A more expansive commentary and findings of the Interim Market Review can be found in Sec 11.4.

4.3. Research Highlights from Task 3 – Specifications Development

The completion of Task 2 of this research program led to the development of two alternative device concepts. A preliminary set of functional requirements were developed for these concepts. An Interim Market Review was also performed to determine technical feasibility of proposed concepts. Task 3 seeks to expand this work further and develop a final set of functional specifications for an alternative device. These final sets of alternative device specifications are informed by market feedback received through the RFI mechanism. This section outlines key findings and research highlights of Task 3.

Develop Functional Specifications

The research staff developed functional specifications for both Concepts C1 and C2. The functional nature of specifications ensured that the requirements stated "what" needed to be done, and not the "how". The following paragraph outlines the kinds of requirements lumped into the functional categories developed in Task 2 above.

1. General requirements:

   The general requirements section specifies the functions, which need to be performed by the alternative device to replace the dump truck in order to satisfy the payload conditions, considerations involved in attaching the attenuator, visibility and monitoring conditions, and operating conditions for maneuvering on the roads.

2. Pre-deployment and post-deployment at the garage

   These functional specifications provide a guideline for the alternative vehicle to safely maneuver from garage to the work zone and vice versa. It also specifies the conditions for secure mounting of the adapter onto the vehicle to facilitate the attachment and detachment of the attenuator.

3. Operability

   This section describes the modes under which the alternative device is expected to operate. Three modes are proposed; human driven, stationary protection, and low-speed autonomy. The conditions under which the vehicle travel to and from the garage to the work zone is described in the maneuverability sub section. The maneuvering of the vehicle within the work zone in either stationary protection, low-speed autonomy is included in the controllability sub section. Within the work zone the vehicle operation can be controlled manually, autonomously, or semi autonomously through the teleoperation module.

4. Crash prevention

   Crash prevention section describes the requirements concerning the speed of operation, tight space maneuvers, personnel in the vicinity etc. in order to avoid the crashes.

5. Crash sensing

This section describes the different functions which the technology should meet for the vehicle sensing and work zone monitoring. It also describes the functions which the alternative device must fulfill in order to warn the workers or to mitigate the crash, one an impending crash is sensed.

6. Crash Protection

The Crash Protection section provides requirements that outline the expected behavior of an alternative device when a motor vehicle crash is imminent or in the moments just after a crash has occurred. The focus of these requirements is on outlining actions to be taken by the device in order to prevent a roll-ahead crash with workers in the work zone. Additional requirements on warning and alerts are also presented here.

7. Post-Crash requirements

The Post-Crash requirements focus on outlining the expectations on an alternative device after a crash event. These relate to the ease of cleanup and removal of the device from an active Work Zone post a crash.

These functional specifications for both concepts are presented in Sec 7 – Appendix A, and Sec 8 – Appendix B.

Develop, host, and receive feedback via a RFI

The research team developed a formal Request for Information process to invite feedback from industry on the functional specifications developed for the alternative device concepts. The TRC Team designed the data confidentiality policies, and RFI questionnaire with due regards to concerns about protection and sharing of potential confidential information. The RFI was promoted using relevant social media channels (LinkedIn, Twitter and Facebook) as well as via direct emails to TRC Inc. industry contacts. Candidate vendors identified in the Interim Market Review were targeted for outreach. The goal of the RFI was to invite feedback that will fit into the following categories:

- General Information or Brochures that outlines products that may satisfy listed functional requirements
- Feedback that outlines technological solutions and approaches that satisfy functional requirements
- Feedback that refines proposed functional requirements

TRC Inc. hosted the RFI to protect vendor supplied trade secret data from potential public release, as information marked as such by vendors will be aggregated to generate insights. TRC Inc. packaged these aggregate insights to help ODOT determine market readiness, challenges, and determine viability of proposed concepts. Additional information about the RFI document is available in Sec 12.

Consolidated vendor feedback

The research staff received responses from nine vendors on the functional specification of the alternative device via the RFI mechanism. Some vendors proposed full-system technological solutions, while others proposed products that satisfy the functional requirements partially.

Most vendor responses proposed technologies that will facilitate implementation of Concept C1 – The Upgraded Mobile Vehicle over Concept C2 – The Mobile Remote Platform. There are two key differences between Concepts C1 and C2:

- Difference in the constituent “shadow vehicle”:

The Concept C2 calls for a low speed mobile platform that carries an integrated attenuator in a Work Zone. This platform will need to be transported to and from the work site. However, Concept C1 relies more on a traditional vehicular device, which can be driven by a human operator to the work site.

- Difference in technology used to move the alternative device in a Work Zone

The Concept C1 may be implemented by a wide spectrum of technologies that emulate the Leader/Follower concept. Concept C2 primarily relies on the use of a teleoperation controlled remotely by a safety operator for movement within the Work Zone.

The ability to rely on existing vehicular platforms, ease of operation, relatability to existing Highway Workers, and ability to fit within existing Work Zone maintenance operating procedures made Concept C1 the preferred choice of implementation amongst vendors. Based on the feedback received from vendors, the Concept C1 – Upgraded Mobile Vehicle can be implemented using two broad distinctive technologies:

- Leader/Follower Autonomy with Electro-Mechanical Actuators[2]
- Leader/Follower Autonomy with a Drive-by-Wire Kit

These implementations enable the alternative device to meet fundamental requirements that allow the device to maneuver, operate, and carry a TMA in a Work Zone. Additional options and upgrades will enable the device to perform advanced Crash Sensing, Protection, Prevention, Navigation Assist, and Traffic Monitoring and Awareness features.

Table 4 summarizes the key facets of feedback received from vendors on a Leader/Follower based implementation of Concept C1 – The Upgraded Mobile Vehicle.

[2] A set of driving robots, which actuate gas, brake, and steer on a vehicle.

Table 4 - Key highlights of proposed technology implementations

Key Highlights	Leader-Follower Autonomy with Electro-Mechanical Actuators	Leader-Follower Autonomy with Drive-by-Wire Kit
What was the type of alternative device vehicle platform suggested?	Vehicle choice neutral as long as Steering, Gas, Brake available. Kratos/Royal Trucking leans towards the use of HD trucks as they offer high ballast, braking, and many optional features	Dataspeed Inc.: Proposed the use of a production Ford F-450 Chassis Cab XL
What considerations should be made for ensuring adequate and safe ballast?	Kratos/Royal Trucking: Engineer certified concrete poured into ballast chambers. This technique maintains body-balance, provides additional safety by reducing risk of projectile. Not a lot of commentary from other vendors, but an acknowledgement that choice of vehicle will determine GVW rating.	Dataspeed Inc.: Proposed the use of a flat-bed for ballast and TMA connector.
In the Autonomous Stack		
How is the leader perceived?	Kratos/Royal Trucking: Based on GPS information coupled with front and side obstacle detection. AB-Dynamics: Retrofit automated driving solution with intelligent leader-follower capability based on GNSS corrected Inertial Navigation Units. Added object detection capability. SEA: A real-time control system "Automated Test Driver" coupled with vision systems and radar, coupled with added object detection sensors. Geo-fencing achieved by dGPS, when available.	Dataspeed Inc.: Perception by the Automated Driving System using LiDAR and Cameras.
How is the navigation information communicated between leader/follower?	Kratos/Royal Trucking: Vehicle-Vehicle Communications Link	Dataspeed Inc.: Not true leader/follower, but more limited automated driving

Key Highlights	Leader-Follower Autonomy with Electro-Mechanical Actuators	Leader-Follower Autonomy with Drive-by-Wire Kit
	AB-Dynamics: Vehicle-Vehicle Meshing IP Radio communicates position data to synchronize motion to emulate platooning. SEA: Path following trained by vision detection. No navigation communication link needed.	system tuned for work zone navigation needs
How is the path of follower planned?	Kratos/Royal Trucking: Smart path planner monitors leader's motion AB-Dynamics: Intelligent leader-follower, controls spacing and headway of an emulated platoon SEA: Vision based detection drives path-planning and path-follow.	Dataspeed Inc.: Planned by the Automated Driving System and includes Object Detection.
How can some of the Advanced Crash Protection and Prevention Features be included in the proposed implementations?	Kratos/Royal Trucking – Front view RADAR and LIDAR Sensors SEA – Camera / Machine vision based forward crash detection AB-Dynamics – Sensing devices and software for the application Dataspeed Inc. – Achieved via object detection and avoidance features of the Automated Driving System Brandmotion – V2X (OBU) Based Solutions that can inform operator or AD system. Can provide an in-vehicle HMI Integration, which allows for display of warning for a Camera/Radar based Forward Collision Detection feature. VIATech – D700 A.I dashcam for forward collision warning detection. Some more products with fused camera, radar, and ultrasonic sensors.	
What are some of the ways in which Crash Sensing and Prediction features could be implemented?	Kratos / Royal Trucking: Rear facing LiDAR and RADAR Sensors SEA – Radar and accelerometers Dataspeed – Use of redundant and independent sensors – LiDAR, RADAR, GPS, IMU etc. Bosch – Radar based technology needs access to vehicle CAN Bus. MH Corbin – Camera based Connect:ITS Detection Technology VIATech – M810 Mining Kit with Camera and sensor fusion using RADAR and Ultrasonics to detect objects in proximity of vehicle. Similar M500 Forklift Safety System for lower speeds.	

Key Highlights	Leader-Follower Autonomy with Electro-Mechanical Actuators	Leader-Follower Autonomy with Drive-by-Wire Kit
How can Navigation Assist Features be incorporated?	Use of Ultrasonics, RADAR, and 360° Surround View Systems.	
What Traffic Monitoring and Awareness Features exist in the market?	Radar and Camera (Live Recording) to monitor traffic flow conditions, inform motorists, and increase awareness.	

Additional feedback from vendors on their proposed technical implementations is presented in the form of Vendor Technology Briefs and can be found in Sec 13.3.

The research staff converted this feedback received on candidate solutions into hypothetical ODOT Buyer Options to outline a full system implementation of products in an easy digestible format. The ODOT Buyer Options were structured and presented in a format similar to that experienced by car buyers. The hypothetical full stack implementations were segregated into classes like – Economy, Mid, and Premium. An alternative device implementation in a particular class had a set of features, which were enabled by a combination of products ordered in increasing levels of feature richness, robustness, and price. Figure 7 outlines the hypothetical ODOT Buyer Options designed from feedback received from the Industry.

Type of Feature	Sub Category	Economy	Midsize	Premium
Base Vehicle	Vehicle	Existing ODOT Non Dump Truck	New ODOT Non-Dump Truck	New Truck with all Options
	Leader/Follower Perception	GPS Tracking + V2V Communication	GPS Tracking + V2V Communication	GPS Tracking + V2V Communication
	Leader/Follower Actuation	BTR + Steer Robot	BTR + Steer + Trailer Brake	BTR + Steer + Parking&Trailer Brake Robot
Standard Features	Crash Prevention - Visibility	Make Truck Visible	Make Truck Visible	Make Truck Visible
	Detect Hit	Contact Sensors and Accelerometers	Contact Sensors and Accelerometers	Contact Sensors and Accelerometers
	Warn	Hazard Lights and Siren	Hazard Lights, Siren, Warn through remote operator unit	Hazard Lights, Siren, Warn through remote operator unit, and Wearable Devices
	Act	Hit Brakes - Truck only	Hit brakes - Truck + Trailer	Hit Brakes - Truck (airbrake) + Trailer
	Payload	12,000 lbs	16,000 lbs	16,000 - 20,000 lbs
	TMA	Either type	Either type	Either type
Advanced Crash Protection Features	Advanced Forward Crash Protection Features	None	Keep Object Detection and Active Braking	Keep Object Detection, Active Braking, and Avoidance Active
Crash Prediction Features	Rear Crash Sensing Feature	None	With Camera and RADAR	With Camera, Radar, Lidar, and V2X Technology
	Side-Crash Sensing Feature	None	With Just RADAR or LIDAR	With RADAR, LiDAR, and Blind-Spot Monitoring Features
Traffic Monitoring and Awareness Features	Traffic Awareness Display	None	RADAR Speed	RADAR Speed, DMS Speed Display, Live Recording
Navigation Assist Features	Operator navigation assist	None	Backup Camera, Ultrasonics	Backup, Ultrasonics, Birds-eye-view

Figure 7 - Vendor feedback turned into ODOT Buyer Options

Additional information about the choices available for ODOT in Leader/Follower Perception and Actuation are also discussed in Sec 13.2

Inform Economic Analysis

The research staff used findings from the RFI mechanism to inform the Economic Analysis. The Economic Analysis was performed using a Cost Benefit Analysis method.

It analyzed the Cost vs. Benefits of using a new alternative device with a new dump truck in Work Zones. The alternative device used in Economic Analysis used a structure similar to the hypothetical ODOT Buyer Options proposed in Task 3, which were identified from vendor feedback received via the RFI.

Refine functional specifications of the Alternative Device

Finally, the RFI mechanism was used to refine functional specifications of the alternative device proposed via the research. Vendor feedback was reviewed to assess key commentary on feasibility and challenges involved in implementation of functional requirements posted for Concepts C1 and C2 by the research team. This technical feedback on feasibility and challenges is summarized below for both Concepts C1 and C2.

For Concept C1 – The Upgraded Mobile Vehicle

- Requirements may be implemented as a Leader/Follower system either using Electro-mechanical Actuators or a Drive-by-Wire kit.
- Achieving the payload requirements, and adequate rear-ward visibility is a function of appropriate choice of the base vehicle.
- The functions expected to be performed at a Garage are feasible and depend on maneuverability of the vehicle chosen.
- The ability of an implementation to execute functions specified in the Operability Functional Requirements vary by vendor's technological readiness:
    - Some vendors appear to have a baseline system that needs to be tailored to achieve listed functional requirements
    - Other vendors indicate the need to perform engineering development using a proposed set of sensors and autonomy solutions to achieve posted requirements.
    - In many cases a need for establishment of a low-latency communications network is deemed necessary to facilitate remote monitoring or redundant operation.
    - Vendors expressed the need to have additional specifications that define the use-cases that cover mode switching between "Stationary Protection" and "Low Speed Autonomy".
- The functional requirements listed in the Crash Prevention, Crash Sensing, and Crash Protection mode will rely on the use of redundant sensors, object detection, and crash avoidance features. However, these features will need to be tuned from both a detection as well as a stopping mechanism perspective to achieve safety needs.
- Finally, the ability of any alternative device to be removed from a Work Zone depends on the severity of an accident.

For Concept C2 – The Mobile Remote Platform:

- Requirements of Concept C2 call for a custom low speed platform. However, very little feedback was received from vendors on the ability of such platforms to carry the payload needed to provide positive protection in Work Zones. The interim market review also revealed only a few potential candidate solutions.

- The use of a teleoperation module to drive such a platform remotely in a Work Zone has not been tested. Such modules are being designed by the industry and are expected to become available. However, thorough feedback was not received from vendors on enabling teleoperation for Concept C2.
- Most feedback on functional requirements posted in Crash Prevention, Crash Sensing, and Crash Protection modes of Concept C1 were also applicable to requirements listed for Concept C2.
- Finally, an implementation of Concept C2 seemed to require a rethink of Operations and Logistics of a Work Zone. This may also be a challenge.

In a few scenarios, vendors provided targeted feedback on a particular functional requirement. This feedback was used to refine the approach in-line with ODOT's expressed needs. Additional detail on feedback received about technical feasibility and challenges is available in Sec 13.4. More information about targeted feedback received that refined functional specifications is available in Sec 13.5.

A final set of Functional Requirements for both Concept C1 and Concept C2 are available for review in Sec 7 - Appendix A and Sec 8 – Appendix B.

5. Recommendations for Implementation

The research suggests that an implementation of scope-limited Driving Automation System using advanced sensors such as LiDAR, RADAR, Ultrasonic, and communication that is fine-tuned for the prescribed Work Zone Operational Design Domain has the potential to act as a dump-truck replacement device. Vendor feedback also identified key challenges such as the need for ease-of-use, low maintenance, cyber-security, system reliability, and redundancy, which need to be considered in an implementation. The presence of such favorable characteristics may encourage wide-spread use of an Alternative Device in lieu of dump-trucks.

It is likely that one of the first concepts that can be operationalized is a Leader/Follower Technology implementation of Concept C1 – The Upgraded Mobile Vehicle. Vendor feedback suggests that this concept can be implemented with a wide variety of sensing stacks, and actuation that is either performed by a Drive-by-Wire Kit or an Electro-Mechanical Actuators. Additional research and evaluation of such conceptual prototypes from an ease-of-use, robustness, and ability to perform maneuvers is suggested. Additionally, the development of such a scope limited in Work Zone autonomy solution must be complemented by its testing and evaluation to determine fit-for-use within the designated operational design domain.

The research also developed a calculation tool based on the Cost Benefit Analysis Framework to help evaluate the economic feasibility of using such an Alternative Device against a dump-truck. Such an analysis was performed for one scenario where the use of a New Alternative Device was weighted against the use of a New Dump Truck. This economic evaluation indicates that the use of an Alternative Device is marginally infeasible for the analyzed scenario. However, such an analysis is sensitive to the inputs used to determine costs and benefits, and the underlying assumptions. ODOT is encouraged to re-run the analysis with more updated inputs, and potentially expand this framework before a final determination is made. The framework may be expanded to include some intangible benefits, economies of scale, and potential benefits that may be unlocked when using the Alternative Device in a networked fashion across the state's roadway system.

In summary, the research indicates that the proposed concepts are technically feasible, identifies desirable end-user characteristics, and provides ODOT with some tools necessary to evaluate economic feasibility. The replacement of a dump-truck with a well-defined Alternative Device has the potential to; provide adequate positive protection to exposed workers, remove the safety operator from a motor vehicle crash event harm by minimizing their interaction during active operation, and provide crash protection to the errant motorist vehicle using a crash attenuator.

The research will also benefit from a further identification and evaluation of areas on ODOT's roadway network that have the potential to benefit the most from the use of such an Alternative Device that may replace the dump-trucks in a Work Zone.

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7. Appendix A – Functional Specifications for Concept C1

7.1. General Requirements

1) The device shall replace the dump truck used in work zones as a shadow vehicle, which carries an appropriate crash attenuator.
2) The device shall weigh a minimum of 12,000 lbs. and a maximum of 16,000 lbs. gross vehicle weight (GVW).
3) The weight requirement should be achieved by using a combination of vehicle weight, and a configurable payload.
4) The required payload should be achieved using any necessary ballast. Ballast should be configurable to achieve the desired gross vehicle weight.
5) The ballast should be placed in a manner to preclude movement during a high-speed impact with the rear of the device. Ballast should either be securely anchored to the device or be placed such that it minimizes shifting during a high-speed impact.
   FMCSA provides best practices, guidance, and rules that may apply to the use of cargo securement systems used to secure ballast on highways. Refer to Subpart I – Protection against Shifting and Falling Cargo, 49 C.F.R. § 393 (2021). These best practices may apply when ballast is achieved using traditional payload elements (steel plates etc.). If liquid media enclosed in a compartmentalized tank are used to maintain payload, securing the tank and reducing sloshing loads may become important.
6) The device shall offer a 12V power supply to power the hydraulic system of a crash attenuator via the adapter.
7) The device should offer a high degree of visibility through the windshield and minimal blind spots to the human operator during manual driving.
8) The shape and size profile of this device should offer increased rear-ward visibility to workers standing in the work area ahead of the device.
9) The device shall have an automatic transmission.
10) The device shall have a steering, gas, and brake pedals to enable human driving.

7.2. Pre-deployment and post-deployment: At the garage

1) The device shall provide the mechanical, electrical, and electronic interfaces needed by the adapter. More adapter's requirements are in Sec 7.10.
2) The device should enable easy attachment and detachment with the adapter, using shop tools and support equipment.
3) The device should offer an inspection method to verify mechanical interlock between the adapter and the device.
4) The adapter shall not serve as a structural weak-link in the TMA system assembly during a crash event. The device should have a secure connection to the attenuator in an event of crash.

5) The device should offer quick connect/disconnect style electrical and electronic interfaces to attach to the adapter.
6) On completion of the work zone deployment and on being driven back to the garage, the device shall:
   a) Enable easy removal of installed/configured payload
   b) Enable detachment of crash attenuator, when deemed necessary
   c) Enable detachment of adapter, when deemed necessary

7.3. Operability

1) The device shall offer the user a choice of three modes of operation:
   a) Human-driven,
   b) Stationary Protection, and
   c) Low-speed Autonomy.
2) The device should be used in "human-driven" mode:
   a) At the garage,
   b) during travel to-and-from the work site,
   c) And when setting up a work zone.

   The functional requirements for this mode are specified in Sec 7.4.

3) Once the device is correctly positioned by the human operator in a work zone, the device should:
   a) Operate in the "Stationary Protection" mode, in a stationary work zone.
   b) Operate in the "Low-speed Autonomy" mode, in a mobile or moving work zone.
4) On completion of the work zone activity, the operator shall be able to disengage the device from other modes and activate the "human-driven" mode.

7.4. Maneuverability

1) The device should enable easy maneuverability by a human operator, in tight spaces and at low speeds, inside the garage.

   One measure of ease of maneuverability is the turning radius of the device. The turning radius of the device should be lower than 30ft.

2) Driving to and from the work site will be done by the human operator at normal roadway speeds, with the attached crash attenuator.
3) At the work site when setting up a work zone, the device shall enable safe maneuvering in tight spaces. Additional requirements for this activity in the form of possible operator navigation assistance features are presented in Sec 7.6.
4) At the work site, the human operator will position the device at a rated safe following distance away from the work crew (deemed necessary for correct operation of the crash attenuator. When positioned at the work site by the operator,
   a) The device shall measure and display a read-out of the current following distance between the device and work vehicles/crew positioned in front of the device.

7.5. Controllability

1) The device shall offer the operator a method to change operational modes when positioned appropriately in a work zone.

   It is likely that the device may need to be used in all three modes – human driven, stationary protection, and low-speed autonomy in a single work zone trip. It is envisioned that once the device is position by the human operator in the work zone, the operator may not be required to enter into the device physically. It is preferred if switching of modes between the stationary protection and the Low-speed Autonomy can be executed remotely, and do not require physical entry by a human operator into the device. However, if this human operator entry is unavoidable, care shall be taken to design operational procedures safely.

2) A static work zone shall use the “Stationary Protection” mode.
3) A mobile or moving work zone shall use the “Low-speed Autonomy” mode.
4) In the “Stationary Protection” mode:
   a) The device shall not require the presence of a human operator in the driving seat or inside the device.
   b) The device shall hold its position set by the human operator by application of all brakes, including the parking and trailer brake, if necessary.
      A system set in the “Stationary Protection” mode should continue to hold brakes and respond appropriately in case of an impact. The requirements stated in Crash Sensing and Protection dictate behavior of the device in an impending crash event.
   c) The device shall maintain a straight wheel angle.
   d) The device shall tow or carry a crash attenuator in the work zone.
   e) The device shall perform the functions presented in the Crash Prevention, Crash Sensing, and Crash Protection categories.
5) In the “Low-speed Autonomy” mode:
   a) The device should not require the presence of a human operator in the driving seat or inside the device.
   b) The “Low-speed Autonomy” mode should be self-aware of its capabilities and operational limitations.
      i) The device should evaluate the feasibility to operate in low-speed autonomy mode, under the current operating conditions.

         The feasibility of operation may be determined by running a sensor health and status check. It may also involve the need to verify correctness and completeness of path information (either a-priori or in real-time).

      ii) When autonomy is deemed infeasible by the system due to the current operating conditions or other reasons, the device shall:
         (1) Warn the operator remotely.
         (2) Not allow for engagement of “Low-speed Autonomy” mode.
         (3) Enable take-over by human operator.
      iii) When low-speed autonomy mode is already engaged, but a change in operational conditions or other reasons, deem its further use infeasible:

(1) Warn the operator remotely.
(2) Stop safely.
(3) Disengage the "Low-speed Autonomy" mode. This disengagement shall be made possible locally as well as remotely.
(4) Enable take-over by human operator. Optionally, enable safe fallback to human driving for a short duration by teleoperation, if deemed feasible.

c) When operating in the "Low-speed Autonomy" mode:
   i) The device's lateral and longitudinal motion should be controlled autonomously for a maximum operating speed of 10mph.
   ii) The device shall tow or carry a crash attenuator through the work zone.
   iii) The device shall maintain appropriate following distance (longitudinal position) from a leading work vehicle to provide protection in an event of crash. The following distance shall be user-configurable, as needed.

   The following distance for a TMA system is defined by roll-ahead distance / gap recommended by crash attenuator OEMs. In "Low-speed Autonomy" mode, the device may need to adapt the following distance based on current environmental conditions, operating speed, and traffic conditions.

   iv) The device should also include technology that allows for an adaptation of the set following distance with oncoming vertical or horizontal curves.

   Successful implementation of such a feature may require awareness of oncoming roadway characteristics such as presence of horizontal and vertical curves and the ability to adapt following distance based on such information.

   v) The device shall also perform the functions presented in the Crash Prevention, Crash Sensing, and Crash Protection categories.

d) When performing functions stated in the Operability, Maneuverability, and Controllability mode:
   i) Remote monitoring the device's operation may be needed.
   ii) Some mode switching, fallback, or diagnostics commands may be needed to be sent from the remote operator to the device for safe operation.

   Remote monitoring or control of the device open up a point of attack for malicious actors. Appropriate cybersecurity hardening features should be designed and incorporated to ensure secure communications are available and protect the device from cyber-attacks.

7.6. Crash Prevention

1) The device should have crash prevention technology in order to reduce occurrence of hazardous crashes with motorists and crashes with objects in the work zone.
2) The driver should be able to maneuver the device in a compact work zone at low speeds prior to starting the desired operation in the work zone. The device should have technology that enables the driver to maneuver in tight spaces at the work site, while reducing the chance of impacts with stationary objects like guard-rails, barrels, cones and other temporary/permanent work zone and roadway features.

3) The device should be able to perceive the stationary and slow-moving objects, equipment, and personnel in its vicinity and provide such information to the driver to assist in navigation around these objects. Such features can reduce any inadvertent damage to attenuator and device during the setup of work zones.

   Short range ultrasonic sensors can be used for detection up to 10m range and short-range radar sensors may be used to detect objects in the proximity of 30 m. Backup cameras might be used to view the rear end objects. Bird's eye view technology can be used to get an overhead view of the vehicle and then plan the maneuverability in accordance with the surrounding objects.

7.7. Crash Sensing (OPTIONAL)

1) When the device is deployed in an active work zone in the "Stationary Protection" mode, the device:
   a) Should allow an operator to define an intrusion area (digitally or physically), which indicates the boundary of an active work zone.
      Technology may be used to monitor intrusion of traffic into this defined area, and such information may be used to warn workers of an impending impact.
   b) Should include technologies, which observe vehicular traffic that drives past the defined work zone and intrusion area.
   c) Should include technologies, which detect errant vehicles that may impact the device and/or crash attenuator.

      The determination of impact may be made by classifying errant motorist vehicles from regular traffic flow. One may observe a motorist vehicle's characteristics such as speed, trajectory, and relative position to the device.

   d) The deployed crash sensing technologies should enable detection of rear-end crashes of errant motorist vehicles with the crash attenuator.
   e) The deployed crash-sensing technologies should enable detection of sideswipe crashes of errant motorist vehicles with the device.
   f) On sensing and detection of an impending impact, the device should:
      i) Warn the remote operator and workers via actuation of hazard and emergency lights (if any).
      ii) Warn the remote operator and workers via actuation of horn, and/or use of wearable technology enabled with communication. The device should send appropriate warning alerts to the wearable device within 300 ms. once an impending impact is detected.
   g) The device and its crash sensing technology should be such that it provides work zone occupants visibility of the impending impact. This may help workers inform their evasive actions better.

      Information about the type of impacting vehicle, and its direction may be important. Such information may be communicated to workers digitally by the device or by offering adequate rear-ward visibility due to the inherent geometry and shape profile of alternative device.

2) Before the device is ready for deployment in the “Low-speed autonomy” mode, the device should allow an operator to define an intrusion area (digitally or physically) behind and around the shadow vehicle of an active mobile or moving work zone.
   Technology may be used to monitor intrusion of traffic into this defined area, and such information may be used to warn workers of an impending impact.
3) When the device is deployed in an active work zone in the “Low-speed autonomy” mode, the device should:
   a) Maintain the definition of the intrusion area as defined by the operator.
   b) Allow the operator to monitor the defined intrusion area.
   c) Include technologies, which observe vehicular traffic that drives past the active work zone, especially those near the intrusion area.
   d) Include technologies, which detect errant vehicles that breach the defined intrusion area and may impact the device and/or crash attenuator.
      The determination of impact may be made by observation of the errant motorist vehicle’s characteristics such as speed, trajectory, and knowledge of the device’s relative position and velocity. Such impacts may include both rear-end and side-swipe type crashes.
   e) These crash sensing technologies should enable detection of rear-end crashes of errant motorist vehicles with the crash attenuator.
   f) These crash-sensing technologies should enable detection of sideswipe crashes of errant motorist vehicles with the device.
   g) On detection of an impending impact, the device should:
      i) Warn the remote operator and workers in other moving vehicles, via actuation of hazard and emergency lights (if any).
      ii) Warn the remote operator and workers via actuation of horn and/or wearable devices.

7.8. Crash Protection

1) When the device is deployed in an active work zone in the “Stationary Protection” mode, and has sensed that a crash with an errant motorist is imminent, the device shall prepare for an imminent crash by:
   a) Holding its steering position.
   b) Engage and hold all brakes to reduce following distance and mitigate severity of crash event.
   c) Keep object detection, and steering avoidance features active. The intent of activating these features is for the device to avoid work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
      The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.
2) When the device is deployed in an active work zone in the “Stationary Protection” mode, during the subsequent crash:
   a) Continue to warn workers by actuating hazard lights, emergency lights, an air-horn, and wearable devices.

b) Provide positive protection to the workers against rear-end and side-swipe crashes.
   i) By holding steering position.
   ii) By holding brakes, including the parking brake, if necessary.

c) Absorb impact using the attached crash attenuator, which may be integrated into the device (TMA) or be towed via a hitch mechanism (TTMA). In case of a crash, the attenuator should remain attached to the device, to provide maximum protection to work crew against an impacting vehicle.

d) Act on inputs provided by the object detection, and steering avoidance features. The intent of these features is to enable the device to avoid secondary impacts with work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
   The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.

e) If the device veers into active travel lanes due to crash, warn motorists by continued flashing of hazard lights, emergency lights, and an air-horn.

3) When the device is deployed in an active work zone in the "Low-speed autonomy" mode, and has sensed that a crash with an errant motorist is imminent, the device shall prepare for an imminent crash by:
   a) Maintaining appropriate device position (as a shadow vehicle) in lateral direction to offer cover to work vehicles positioned in front of it.
   b) Maintaining appropriate device position (as a shadow vehicle) in longitudinal direction measured by following distance gap.
   c) Holding its intended direction and path.
   d) Apply all brakes or hold its intended speed, as appropriate.
      The device's response on detection of an imminent crash may need to be fine-tuned to the nature of predicted crash event, time-to-collision between detection and impact, and confidence in detection as indicated by the crash sensing technology. The device is expected to have the intelligence necessary to choose the correct course of action based on the predicted characteristics of the impending crash event.
   e) Keep object detection, and steering avoidance features active. The intent of activating these features is for the device to avoid work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
      The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.

4) When the device is deployed in an active work zone in the "Low-speed autonomy" mode, during the subsequent crash:
   a) Continue to warn workers by actuating hazard lights, emergency lights, an air-horn and/or wearable devices. Alerts continue to flash until turned off by safety operator.
   b) Absorb impact using the attached crash attenuator, which may be integrated into the device or be towed via a hitch mechanism.
   c) Just after an impact occurs:

   i) Apply all brakes to stop the device roll-ahead into work vehicles or workers, or other traffic ahead.
   ii) Warn motorists and surrounding traffic of a crash event.
d) If the device veers into active travel lanes due to crash, warn motorists by continued flashing of hazard lights, emergency lights, and an air-horn.
e) Act on inputs provided by the object detection, and steering avoidance features. The intent of these features is to enable the device to avoid secondary impacts with work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
   The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.

7.9. Post-Crash Requirements

1) When a motorist impacts with the device and the attached crash attenuator in a work zone:
   a) The design of the device shall enable its easy removal from the scene of the crash and roadway, into a safe location (ex. roadway shoulder) to ensure smooth flow of traffic operations is restored quickly.
   b) The device should be able to be transported back to the garage after a crash event has occurred. Based on the severity of crash, this transport may be performed by driving the device manually with crash attenuator attached, crash attenuator detached, or towed by a different vehicle, or on a flat-bed tow-truck, as deemed necessary.

The severity of crashes determines the ability of the device to comply with post-crash requirements. The goal of these requirements is not to design and achieve functionality for all crash conditions, but to ensure a reasonable operational condition is maintained to enable safe clean-up of crash site when using the alternative device.

7.10. TMA Adapter Functions

The adapter sits between the device and the crash attenuator to provide the right mechanical, electrical, and electronic interfaces needed for safe operation in work zones.

1) The mechanical interface of the adapter and attenuator should be generalized. This generalized interface should allow for the attachment of one attenuator at a time, which is either:
   a) A single type (make/model) of designated integrated attenuator.
   b) Or one amongst a variety of towable attenuators available in ODOT's inventory.
2) The adapter should offer a quick connect/disconnect electrical and electronic interface needed by the attenuator assembly.
3) If an arrow board sign is not mounted on an attenuator, the adapter should offer mounting points and electrical/electronic interface needed to hold and activate the arrow board sign.

8. Appendix B - Functional Specifications for Concept C2

8.1. General Requirements

1) The MRP device shall replace the dump truck used in work zones as a shadow vehicle and allow for attachment of an appropriate crash attenuator.
2) The MRP device and any attached payload shall weigh a minimum of 12,000 lbs. and a maximum of 16,000 lbs.
3) The weight requirement should be achieved by using a combination of MRP device weight, and a configurable payload.
4) The required payload should be achieved using any necessary ballast. Ballast should be configurable to achieve the desired weight range.
5) The ballast should be placed in a manner to preclude movement during a high-speed impact with the rear of the device.
   Ballast should either be attached to the MRP device or may be integrated within the chassis in an innovative fashion. Care must be taken to achieve a weight distribution as uniform as possible to provide appropriate stability from a vehicle dynamics perspective during operation. Ballast should be placed such that it minimizes shifting during a high-speed impact. FMCSA provides best practices, guidance, and rules that may apply to the use of cargo securement systems used to secure ballast on highways. Refer to Subpart I – Protection against Shifting and Falling Cargo, 49 C.F.R. § 393 (2021). These best practices may apply when ballast is achieved using traditional payload elements (steel plates etc.). If liquid media enclosed in a compartmentalized tank are used to maintain payload, securing the tank and reducing sloshing loads may become important.
6) The MRP device shall offer a 12V power supply to power the hydraulic and electrical/electronic systems of a crash attenuator if needed.
7) The shape and size profile of this MRP device should offer increased rear-ward visibility to workers standing in the work area ahead of the device.
8) The MRP device should have a powertrain configuration necessary to operate at a maximum speed of 10mph in a wide variety of work zone and roadway conditions.
9) The MRP device shall have an automatic transmission, if necessary.
10) The MRP device shall have the necessary steering, gas, and brake actuation interfaces to enable remote operation via configurable teleoperation modules.

8.2. Pre-deployment and post-deployment: At the garage

1) The MRP device shall provide the mechanical, electrical, and electronic interfaces needed by the crash attenuator, and the adapter (if needed). More details on adapter's requirements are in Sec 7.10.

2) The MRP device should offer quick connect/disconnect style electrical and electronic interfaces that enable attachment with the crash attenuator, via the adapter (if needed).
3) At the garage before deployment, the concept shall offer functionality, which enables the MRP device to be transported to the worksite. Additional requirements are in Sec 2.3.1.
4) Post-deployment, the concept shall offer functionality, which enables the MRP device to be offloaded from the transport trailer, driven remotely to a safe parking spot.

8.3. Operability

1) The MRP device shall offer the user a choice of three modes of operation:
   a) Transport,
   b) Stationary Protection, and
   c) Low-speed Travel.
2) The MRP device should be used in “Transport” mode:
   a) At the garage,
   b) During travel to-and-from the work site,
   c) When setting up a work zone.

   The functional requirements for this mode are specified in Sec 8.4.

3) Once the MRP device is correctly positioned by the teleoperator in a work zone, the device should:
   a) Operate in the “Stationary Protection” mode, in a stationary work zone.
   b) Operate in the “Low-speed Travel” mode, in a mobile or moving work zone.

   Additional requirements for operation in these modes are in Sec 8.5.

4) On completion of the work zone activity, the operator shall be able to disengage the MRP device from other modes and operate in the “Transport” mode.
5) If any system components are un-operational or become faulty during the time of operation, the system shall raise an audible alert and notify the remote operator via the teleoperation interface. After an alert is raised, the system shall default to transport mode of operation after a minimum of 1minute.
   a) The system shall not leave transport mode if faults are detected. The check for faults shall be performed autonomously by the system prior to leaving transport mode.

8.4. Maneuverability

1) At the garage, the MRP device:
   a) Should enable easy maneuverability in tight spaces and at low speeds, inside the garage, using a teleoperation module or via remote control.
   b) The MRP device should enable easy attachment with a vehicle or be loaded into an enclosed trailer or onto a flatbed truck used for transport to the worksite, at the garage.
   The MRP may need to be secured to the trailer or flatbed truck before transport to the worksite.

c) The MRP device should be powered down and allow for safe transport to the worksite.

Driving to and from the work site to transport the MRP device and the integrated crash attenuator will be done by a human operator at normal roadway speeds in appropriate transport vehicles.

2) On reaching the work-site and before work-zone is setup:
   a) The MRP device and integrated crash attenuator shall be appropriately unloaded/detached from the transport vehicle at a safe location on the worksite.
   b) The MRP device shall be maneuvered to a safe position at the worksite to enable deployment of the crash attenuator as deemed appropriate.
   c) The MRP device should offer an inspection method to verify mechanical interlock between the crash attenuator, and the MRP device.
   d) The mechanical interlock shall not serve as a structural weak-link in the TMA system during a crash event.
3) At the work site when setting up a work zone, the MRP device shall enable safe maneuvering in tight spaces with payload and the crash attenuator attached to it. Additional requirements for this activity in the form of possible remote operator navigation assistance features are presented in Sec 7.6.
4) At the work site, the human operator will position the MRP device at a rated safe following distance away from the work crew deemed necessary for correct operation of the attached crash attenuator. When positioned at the work site by the teleoperator:
   a) The MRP device shall measure and display a read-out of the current following distance between the MRP device and work vehicles positioned in front of the device.
   b) The MRP mechanical/electrical/electronic interfaces shall be tested for functionality before allowing for activation of other operating modes.
5) On completion of the work zone activity:
   a) The MRP device and crash attenuator will be maneuvered to a safe position along the roadway.
   b) The MRP device shall allow for easy electrical and electronic disconnect, and power-down of the crash attenuator.
   c) The MRP device shall be prepared for transport back to the garage. The transport can occur by towing, on a flatbed trailer, or in an enclosed trailer. The MRP device will be secured and turned off, before transport.

8.5. Controllability

1) The MRP device shall offer the teleoperator a method to change operational modes from “Transport” mode into other operational modes remotely, when positioned appropriately in a work zone. This shall only occur after system health operational checks are deemed complete and pass requirements.

It is likely that the MRP device may need to be used in both the Stationary Protection and Low-speed Travel mode in a single work zone trip. It is envisioned that the teleoperator may enable this switch remotely in a seamless manner. If physical *human interaction is needed, care shall be taken to design operational procedures that ensure safety of the worker.*

2) The TMA system when deployed in a static work zone shall use the “Stationary Protection” mode.
3) The TMA system when deployed in a mobile or moving work zone shall use the “Low-speed Travel” mode.
4) In the “Stationary Protection” mode:
    a) The MRP device shall require minimal monitoring by an operator. Such monitoring may be a check on brake status, power-levels etc., and shall be done remotely.

        A handheld device placed with a designated operator or status screens within the teleoperation module may facilitate such remote monitoring. It is likely that the remote operator or teleoperation module may be installed in a work-truck placed at the worksite at a safe distance from the TMA system.

    b) The MRP device shall hold its longitudinal position as set by the teleoperator by application of all brakes, including high-power brakes, if necessary.
        A system set in the “Stationary Protection” mode should continue to hold brakes and respond appropriately in case of an impact. The requirements stated in Crash Sensing and Protection dictate behavior of the device in an impending crash event.
    c) The MRP device shall maintain a straight wheel angle.
    d) The MRP device shall carry the crash attenuator in the work zone.
    e) The MRP device shall perform the functions presented in the Crash Prevention, Crash Sensing, and Crash Protection categories.
5) In the “Low-speed Travel” mode:
    a) The MRP device shall be operated by a teleoperation module. The teleoperation module shall provide the remote operator features used to accelerate, brake, and steer the MRP device and attached crash attenuator.

        Such a teleoperation module may be a mobile unit (remote control integrated with a tablet screen), or one integrated in a support vehicle located in the work crew. Maintaining time-sensitive, low latency, secure communications between the teleoperation module and MRP device may be essential for operation.

    b) The teleoperation module shall provide the remote operator features that enable it to monitor, act, and react to the driving environment around it.

        Monitoring of driving environment may require the strategic use of cameras and other sensors to help the remote operator navigate complex driving environments. This environment may include driving in nighttime conditions, low light areas, and in adverse weather conditions (snow and ice).

    c) The teleoperation module shall facilitate driving through on-road work zone environments, at speeds lower than 10mph.

While the operating speeds are expected to be low, the MRP device and the integrated crash attenuator may need to navigate tight spaces on roadway shoulders, and make lane changes, when deemed necessary by the remote operator. The TMA system should follow other work vehicles at a safe distance to provide positive protection in the event of a traffic crash.

d) The MRP device operating in “Low-speed Travel” mode should be self-aware of its capabilities and operational limitations.
   i) The MRP device should evaluate the feasibility to operate in “Low-speed Travel” mode, under the current operating conditions.

      The feasibility of operation in current environmental conditions may be determined by running a sensor health and status checks.

   ii) When operation in “Low-speed Travel” mode is deemed infeasible by the system due to the current operating conditions, the MRP device shall:
      (1) Warn the remote operator.
      (2) Not allow for engagement of “Low-speed Travel” mode.
      (3) Transition into other modes such as “Transport” mode.
   iii) When “Low-speed Travel” mode is already engaged, but a change in operational conditions deem its further use infeasible:
      (1) Warn the operator remotely.
      (2) Stop safely.
      (3) Disengage the “Low-speed Travel” mode.
      (4) Enable take-over by human operator using the teleoperation module.

      Refer to additional requirements in Sec 2.3 Item (5).

e) When operating in the “Low-speed Travel” mode:
   i) The MRP device’s lateral and longitudinal motion should be controlled via the teleoperation module for a maximum operating speed of 10mph.
   ii) The MRP device shall carry the crash attenuator in the work zone.
   iii) The MRP device shall provide information that allows the remote operator to maintain appropriate following distance (longitudinal direction) from a leading work vehicle to provide protection in an event of crash. The following distance shall be user-configurable, as needed.

      The following distance for a TMA system is set by following distance / gap recommended from crash attenuator testing. In low-speed travel mode the MRP device may need to adapt the roll-ahead distance based on current environmental conditions, operating speed, and traffic conditions.

   iv) The MRP device shall also perform the functions presented in the Crash Prevention, Crash Sensing, and Crash Protection categories.
f) When performing functions stated in the Operability, Maneuverability, and Controllability mode:
   i) Remote monitoring and control the device’s operation may be needed.
   ii) Some mode switching, fall-back, or diagnostics commands may be needed to be sent from the remote operator to the device for safe operation.

Remote monitoring or control of the device opens up a point of attack for malicious actors. Appropriate cybersecurity hardening features should be designed and incorporated to ensure secure communications are available and protect the device from cyber-attacks.

8.6. Crash Prevention

1) The MRP device should have crash prevention technology in order to prevent occurrence of hazardous crashes with motorists and crashes with objects in the work zone.
2) The MRP device should be able to perceive the stationary and slow-moving objects, equipment, and personnel in its vicinity and the device should provide such information to the teleoperation module to assist in navigation around these objects. Such features can reduce any inadvertent damage to attenuator and device during the setup of work zones.

   Short range ultrasonic sensors can be used for detection up to 10m range and short-range radar sensors may be used to detect objects in the proximity of 30 m. Backup cameras might be used to view the rear end objects. Bird's eye view technology can be used to get an overhead view of the vehicle and then plan the maneuverability in accordance with the surrounding objects.

8.7. Crash Sensing (OPTIONAL)

1) When the MRP device is deployed in an active work zone in the "Stationary Protection" mode, perform the following functions:
   a) Allow a remote operator to define an intrusion area (digitally or physically), which indicates the boundary of an active work zone. Technology may be used to monitor intrusion of traffic into this defined area, and such information may be used to warn workers of an impending impact.
   b) The MRP device should include technologies, which observe vehicular traffic that drives past the defined work zone and intrusion area.
   c) The MRP device should include technologies, which detect errant vehicles that may impact the device and/or crash attenuator.

      The determination of impact may be made by classifying errant motorist vehicles from regular traffic flow. One may observe a motorist vehicle's characteristics such as speed, trajectory, and relative position to the device to make such determinations.

   d) The deployed crash sensing technologies should enable detection of rear-end crashes of errant motorist vehicles with the crash attenuator.
   e) These crash-sensing technologies should enable detection of sideswipe crashes of errant motorist vehicles with the MRP device.
   f) On sensing and detection of an impending impact, the MRP device should:
      i) Warn the remote operator and workers via actuation of hazard and emergency lights.
      ii) Warn the remote operator and workers via actuation of horn, and/or use of wearable technology enabled with communication. The device should send

appropriate warning alerts to the wearable device once an impending impact is detected.

g) The MRP device and its crash sensing technology should be such that it provides work zone occupants visibility of the impending impact. This may help workers inform their evasive actions better.

   Information about the type of impacting vehicle, and its direction may be important. Such information may be communicated to workers digitally by the device and/or by offering adequate rear-ward visibility due to the inherent nature of geometry and shape profile of alternative device.

2) Before the MRP device is ready for deployment in the "Low-speed travel" mode, the device should allow an operator to define an intrusion area (digitally or physically) behind and around the shadow vehicle of an active mobile or moving work zone. Technology may be used to monitor intrusion of traffic into this defined area, and such information may be used to warn workers of an impending impact.
3) When the MRP device is deployed in an active work zone in the "Low-speed Travel" mode, perform the following functions:
   a) The MRP device should maintain the definition of the intrusion area as defined by the remote operator.
   b) The MRP device should allow the remote operator to monitor the defined intrusion area remotely.
   c) The MRP device should include technologies, which observe vehicular traffic that drives past the active work zone, especially those near the intrusion area.
   d) The MRP device should include technologies, which detect errant vehicles that breach the defined intrusion area and may impact the device and/or crash attenuator.

      The determination of impact may be made by observation of the errant motorist vehicle's characteristics such as speed, trajectory, and knowledge of the device's relative position and velocity. Such impacts may include both rear-end and side-swipe type crashes.

   e) These crash sensing technologies should enable detection of rear-end crashes of errant motorist vehicles with the crash attenuator.
   f) These crash-sensing technologies should enable detection of sideswipe crashes of errant motorist vehicles with the MRP device.
   g) On detection of an impending impact, the MRP device should:
      i) Warn the remote operator and workers in other moving vehicles, via actuation of hazard and emergency lights (if any).
      ii) Warn the remote operator and workers via actuation of horn and/or wearable devices. The device should send appropriate warning alerts to the wearable device within 300 ms once an impending impact is detected.

8.8. Crash Protection

1) When the MRP device is deployed in an active work zone in the "Stationary Protection" mode, and has sensed that a crash with an errant motorist is imminent, the device shall prepare for an imminent crash by:
   a) Holding its steering position.
   b) Engage and hold all brakes to reduce following distance and mitigate severity of crash event for workers in work zone ahead.
   c) Keep object detection, and steering avoidance features active. The intent of activating these features is for the device to avoid work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
   The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.
2) When the MRP device is deployed in an active work zone in the "Stationary Protection" mode, during the subsequent crash event:
   a) Continue to warn workers by actuating hazard lights, emergency lights, an air-horn and/or wearable devices.
   b) Provide positive protection to the workers against rear-end and side-swipe crashes.
      i) By holding steering position.
      ii) By holding high-power brakes.
   c) Absorb impact using the attached crash attenuator. In case of a crash, the attenuator shall remain attached to the device, to provide maximum protection to work crew against an impacting vehicle.
   d) Act on inputs provided by the object detection, and steering avoidance features. The intent of these features is to enable the device to avoid secondary impacts with work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
   The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.
   e) If the MRP device veers into active travel lanes due to crash, warn motorists by continued flashing of hazard lights, emergency lights, and an air-horn.
3) When the MRP device is deployed in an active work zone in the "Low-speed autonomy" mode, and has sensed that a crash with an errant motorist is imminent, the device shall prepare for an imminent crash by:
   a) Maintaining appropriate device position (as a shadow vehicle) in lateral direction to offer cover to work vehicles positioned in front of it.
   b) Maintaining appropriate device position (as a shadow vehicle) in longitudinal direction measured by roll-ahead distance gap.
   c) Holding its intended direction and path.
   d) Apply all brakes or hold its intended speed, as appropriate.
   When preparing for an impending crash, the teleoperation module should the remote operator an ability to facilitate execution of the above actions. Alternatively, an algorithm may trigger the device into a "prepare-for-crash"

mode and perform actions listed above under supervision of the operator. In such an arrangement, the remote operator should have the ability to override the algorithm, if deemed necessary. The device's response on detection of an imminent crash may need to be fine-tuned to the nature of predicted crash event, time-to-collision between detection and impact, and confidence in detection as indicated by the crash sensing technology. The device is expected to have the intelligence necessary to choose the correct course of action based on the predicted characteristics of the impending crash event.

e) Keep object detection and steering avoidance features active. The intent of activating these features is for the device to avoid work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.

4) When the MRP device is deployed in an active work zone in the "Low-speed autonomy" mode, during the subsequent crash:
   a) Continue to warn workers by actuating hazard lights, emergency lights, an air-horn and/or wearable devices. Alerts continue to flash until turned off by safety operator.
   b) Absorb impact using the attached crash attenuator.
   c) Just after an impact occurs:
      i) Apply brakes to stop roll of the device into work vehicles or workers, or other traffic ahead.
      ii) Warn motorists and surrounding traffic of a crash event.
   d) If the device veers into active travel lanes due to crash, warn motorists by continued flashing of hazard lights, emergency lights, and an air-horn.
   e) Act on inputs provided by the object detection, and steering avoidance features. The intent of these features is to enable the device to avoid secondary impacts with work zone vehicles, through traffic, or workers in path, after a crash event has occurred.
   The device should have the environmental awareness, intelligence, and decision-making ability necessary to plan and behave in a manner that minimizes crash risks for workers as well as through traffic in a Work Zone.

   The actions listed above shall be facilitated through the teleoperation module by the remote operator. Some functions such as activation of the horn etc. may occur automatically on sensing crash, under the supervision of the remote operator. When such functions are performed automatically, the remote operator shall have the ability to override.

8.9. Post-Crash Requirements

1) When a motorist impacts with the MRP device in a work zone:
   a) The design of the MRP device shall enable its easy removal from the scene of the crash and roadway, into a safe location (ex. roadway shoulder) to ensure smooth flow of traffic operations is restored quickly.

b) The MRP device should be able to be transported back to the garage after a crash event has occurred. Based on the severity of crash, this transport may be performed by towing with a different vehicle, or on a flat-bed tow-truck, as deemed necessary.
c) The attached crash attenuator may need to be transported back to the garage separately, using methods deemed suitable based on severity of damage suffered in the crash event.

The severity of a crash determines the ability of MRP *device to comply with post-crash requirements. The goal of these requirements is not to design and achieve functionality for all conditions, but to ensure a reasonable operational condition is maintained to enable safe clean-up of crash site using the aforementioned alternative device.*

8.10. TMA Adapter Functions

Based on the configuration of the proposed MRP device, and crash attenuator the concept may need an adapter. Such an adapter may sit between the MRP device and the crash attenuator to provide the right mechanical, electrical, and electronic interfaces needed for safe operation in work zones.

1) The mechanical interface of the adapter and attenuator should be generalized. This generalized interface should allow for the attachment of one attenuator at a time, which shall be a single type (make/model) of a designated crash attenuator.
2) The adapter should offer a quick connect/disconnect electrical and electronic interface needed by the crash attenuator, if needed.

9. Appendix C – Expanded Literature Review

9.1. Work Zones are challenging

Work zones are one of the most challenging areas of a roadway system. Design of the work zone has to deal with competing demands 1) To ensure minimum disruption to traffic flow, 2) To ensure safe work-space to conduct roadway maintenance operations. Oftentimes, these demands fluctuate during the course of operations. As already noted, the dynamic nature of roadways (demand on space, throughput, and travel times) is accentuated when work zones are placed. This may lead to increased risk to safety for both travelers and workers alike.

A well-designed work zone aims to satisfy these competing demands from roadway users and workers. FHWA and State DOTs have developed information that helps to solve this critical transportation problem. In summary, a three-pronged approach towards work zone safety is observed:

1. Education – Initiatives that inform, educate and train both roadway users and worker personnel on safe behavior in a work zone. ODOT's Move Over Law emphasizes that an approaching vehicle "Slow Down, Move Over for all roadside workers". Work zone worker training programs (Flagger Operation, Guidance for Work Zone Planning) already exist and are offered by DOTs across the nation.

2. Prevention – Prevention of work zone crashes by the use of advance warning signs and lights, channelizing devices, and improving worker visibility are features of this strategy.

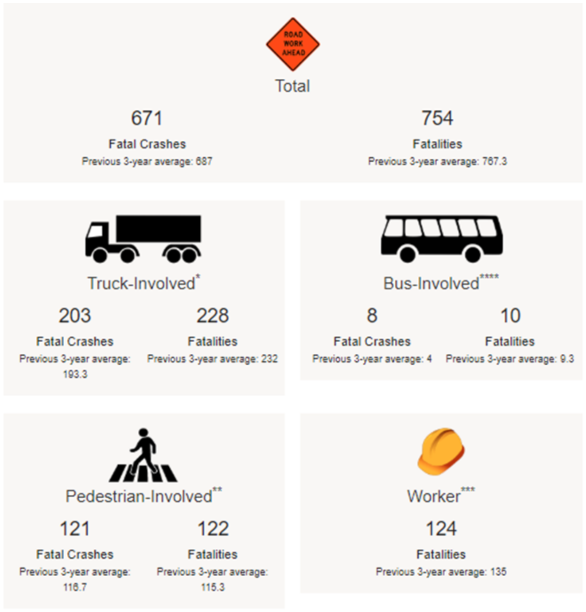
3. Protection – Attempts are made to reduce the risk for both, the occupants of an errant vehicle, and workers occupying the active work area in case of a crash. Work zone sites use MASH (AASHTO, 2016) approved lateral barriers to reduce impact of roadway departures. They also rely on the use of Mobile Attenuators to reduce impact of rear-end motor vehicle crashes.

While most of these measures directly pertain to the work zone, systemic aspects such as evaluation of work zone speed limits, use of patrol vehicles to raise driver awareness, and planning of roadway maintenance work at hours of low traffic volume also ensure safety for workers.

The nation's roads are proving to be a dangerous place for workers. Between 2016 and 2017, fatal crashes in work zones increased by 3 percent, while fatal crashes outside of work zones decreased by 1.5 percent. In 2018, 754 fatalities were recorded, amongst which 124 workers lost their lives in work zones across the nation.

The State of Ohio recorded a total of 17 fatalities in work zones, of which 6 people were workers. In ODOT's resolve "Towards Zero Deaths", even one death is far too many on Ohio's roadways.

While a record of fatalities paints the gravest picture of the importance of work zone safety, a measure of injuries and property damage is also needed. In 2017, Ohioans suffered 4,898 vehicle crashes in work zones (Figure 3). These crashes lead to 17 fatalities. Over 23% of crashes (1,159) led to injuries to either the occupants of impact vehicles or workers. A large majority of these crashes (76%) led to property damage. While not as grave as fatalities, injuries and property damage heavily impact quality of life.



National Work Zone FARS Statistics

Ohio Department of Public Safety, Crash Statistics – Work Zone

Work Zone Related	Fatal	Injury	Property Damage	Total
No	1,077	74,278	223,045	**298,400**
Yes	17	1,159	3,722	**4,898**
Total	**1,094**	**75,437**	**226,767**	**303,298**

Figure 8 - Exhibit illustrates Work Zone related Fatalities on Nation's Roads in 2018. Table indicates Work Zone Crash Statistics by Severity in Ohio for 2017.

These grave statistics point to a growing need for systemic evaluation of work zone safety.

9.2. ODOT's Assets and Scale of Winter Operations

ODOT manages one of the country's largest statewide transportation systems with over $116 billion dollar worth of assets. To paint a brief picture of its scale of operations, ODOT manages:

- Over 43,000 lane miles of roads and nation's fifth largest interstate highway network.
- More than 14,000 Bridges (Nation's 2nd largest inventory in the country)
- Nation's 5th highest number of vehicle miles travelled

Owing to its particular geographical location, Ohio's transportation system is heavily impacted by winter weather. The ODOT's Ice and Snow Information page states that a closure of Ohio's transportation system for one day due to a winter storm would cause the state to lose more than $300 million in direct and indirect productivity.

ODOT has 1,700 plow trucks, a workforce of 3,000 employees, and 650,000 tons of salt at its disposal, to ensure minimum disruption to efficient and safe roadway travel. ODOT's winter operations cost an estimated $103 million annually on labor, equipment, and materials. A critical piece of equipment ensuring the success of ODOT's winter operations is the standard dump truck.

One of the guiding principles for ODOT is their drive to be the standard to excellence for winter maintenance, while continuing to be productive, lean, efficient and effective. ODOT's critical surface factors for FY19 Q2 indicate the DOT's stellar performance in Snow and Ice Control. Critical Success Factor (CSF) metrics note that 99% of priority routes recovered speeds within two hours after a snow event.

9.3. Role of Shadow Vehicles and TMA is less understood

In work zones across the country, the use of shadow vehicles during mobile operations and the use of barrier vehicles in stationary operation is a common technique to protect workers from crashes (Theiss & Bligh, 2013). The use of an attenuator amplifies the safety of a work zone for both occupants of the errant vehicle and workers by absorbing impact energy of a target vehicle in a crash scenario. Advancements in the industry have led to an increased focus on research, design and validation of the mobile attenuators as they play a critical role in crash safety. However, the role of shadow vehicle is often less understood.

MASH Standard (AASHTO, 2016) recognizes the important role played by the shadow vehicle (referenced as support vehicle) in the performance of the TMA. The mass of the support vehicle plays an important role in the impact of an errant vehicle with the TMA. During a TMA crash, the support truck is accelerated forward due to momentum transfer, while the impact vehicle is decelerated. Hence, the total velocity change of the impact vehicle during a TMA impact and the demands placed on a TMA for energy absorption, are influenced by the mass of the support truck. The performance of TMAs is evaluated with both heaviest and lightest support vehicle in appropriate test scenarios.

Another important parameter, given lower consideration is the roll ahead distance, i.e. length of the travel of the support vehicle in case of an impact. The support trucks, which are too light, may show high roll ahead distance in the case of an impact, hence potentially endangering safety of workers in the area ahead of the support vehicle. The MASH standard gives some more guidance on these competing physics of support vehicle in Appendix A - Section A.2.2.3, of MASH, 2016.

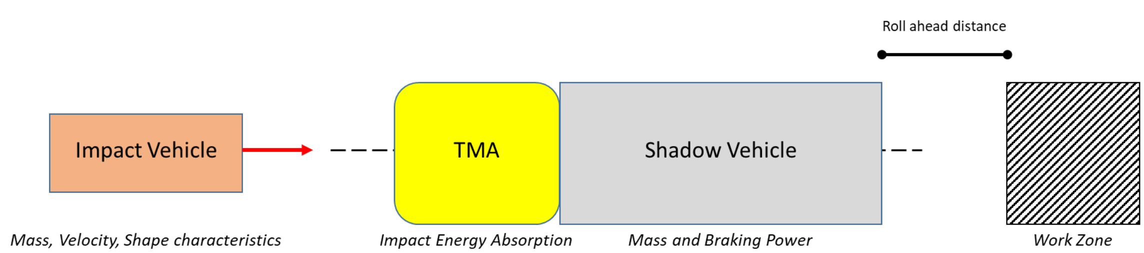


Figure 9 - Conceptual representation of the role of shadow vehicle with TMA used in a work zone.

There are three areas of concern in an impact with TMA: 1) Safety of occupants in impact vehicle, 2) Risk to workers in work zone ahead of support vehicle, 3) Risk to occupants of the support vehicle (shadow vehicle). The commentary (in Appendix A.2.2.3 of MASH, 2016) provides a good discussion on the competing nature of roles to be performed by the shadow vehicle (Figure 9).

The vehicle needs to be heavy enough and possess adequate braking power to have roll-ahead distance safe for the designed work zone. However, a heavy vehicle maybe detrimental to safety of occupants in the impact vehicle. If the vehicle is too light, while safety of occupants in the impact vehicle is better, but this may endanger the safety of workers in the work zone and occupants of the support vehicle.

MASH 2016 provides additional guidance on this potential tradeoff and allows for the evaluation of roll-ahead distance using the “conservation of momentum” principle. A few published works (Theiss & Bligh, 2013) aim to perform safety assessment for workers in a shadow vehicle by using collision dynamics principles. The authors also evaluate roll-ahead distance for stationary and mobile work zone operations using a mathematical model. An attempt is made to document risk to the driver of support vehicle. However, their approach is not comprehensive and suffers from the lack of occupant and impact safety background.

The aspects of shadow vehicle that influence occupant impact safety, roll-ahead distances are of prime concern in this research effort. Additionally, the shadow vehicle performs other roles, such as – display of signage, carrying of work zone safety material etc., which will also be given due consideration during this research.

9.4. State of Existing Literature on Shadow Vehicles and TMAs

The TRC Team reviewed key research literature available publicly with regards to the safety of Work Zones. The research team reviewed literature specifically targeted to understand the use of the Truck/Trailer Mounted Attenuators in Work Zones.

In Finley et al. 2017[3], the authors evaluated prevalent safety practices for short duration Work Zones. These included an investigation of different equipment types such as – Barriers, Work Zone Lighting Devices, and passive protection devices seen in Work Zones. The report observed current practices in ODOT’s Work Zones and provides insights on the use of TMAs and shadow vehicles, in mobile and stationary operations. The researchers observed over 15 maintenance operations, and following key observations can be made with regards to the use of shadow vehicles and TMA in Work Zones:

- O-MUTCD Work Zone Typical Application examples provide only broad information on placement of shadow vehicles and other work vehicles.
- Observations were made on behavior of traffic operating in the vicinity of the work vehicles:
    - During transport to work site
    - At work site
    - From work site and back

[3] Finley, M. D., Theiss, L., Ullman, G. L., Pickens, A., Benden, M., & Jenkins, J. M. (2017). Evaluation of Safety Practices for Short Duration Work Zones (No. FHWA/OH-2017-29).

- Appropriate placement of shadow vehicles in Work Zones is a topic of research in the community. Organizations such as AASHTO, FHWA Work Zone Grant, and ATSSA has produced material, which offers some guidance.

Operating Speed	Recommended Spacing for Vehicles Weighing 9,900–22,000 lb (ft)		Recommended Spacing for Vehicles Weighing over 22,000 lb (ft)	
	Stationary	Moving	Stationary	Moving
Greater than 55 mph	172	222	150	172
45 to 55 mph	123	172	100	150
Less than 45 mph	100	100	74	100

Figure 10 – Guidelines for spacing of shadow vehicles adapted from ATSSA (2012)[4].

- There is an increasing national focus on whether additional guidance should be provided on shadow vehicle size and spacing when performing work operations on high-speed facilities. There was also a need displayed for basic engineering analysis of kinetic energy requirements with shadow vehicles and TMAs.
- The research also identified other practices in the Work Zones.

In Finley et. al.(2015)[5], the researchers outlined the current state of practice and best practices in rural, one-lane, two-way temporary traffic control during maintenance operations. The study broadly outlined the need and importance of appropriate advance warning signs, portable traffic signals (PTS), and automated flagger assistance devices (AFAD) in these settings. The study identified a set of applicable roadway and operating conditions where traditional flagger approaches, PTS, and AFADs can be used to control traffic flow in temporary maintenance operation.

The research team also reviewed ODOT's Highway Technician Training Manual[6]. Lesson Six of the manual provides training on Temporary Traffic Control in mobile and moving operations. The manual emphasizes the need to design a traffic control plan with careful consideration to factors such as location, traffic volume, speeds and time of day. Visibility of work equipment and personnel are key factors to help reduce surprises for motorists. The manual also provides some training on the use of shadow vehicles with arrow panels and TMAs.

The research team reviewed ODOT funded research with Finley et al.[7] The report contains a wealth of information and contemporary findings in regarding the use of

[4] ATSSA (2012), Field Guide for the Use and Placement of Shadow Vehicles in Work Zones
[5] Finley, M. D., Jenkins, J. M., & Songchitruksa, P. (2015). Evaluation of alternative methods of temporary traffic control on rural one-lane, two-way highways (No. FHWA/OH-2015/9). Texas A & M Transportation Institute, The Texas A & M University System.
[6] ODOT (2018), HT.108 – Work Zone Maintenance of Traffic, Highway Technician Academy
[7] Finley M.D., Ruback L., Ye F. (2020). Evaluate the Uses and Technology for Truck-Mounted Attenuators

TMAs and shadow vehicles. The current research program has expanded on some of the work performed in the areas of traffic crash report investigation. The report provides some contemporary guidance on topics such as:

- Role of shadow vehicles and choice of TMAs
- Study and use of autonomous impact protection vehicle
- Placement of shadow vehicles and development of a prototype roll-ahead distance alarm
- A review of select state DOT shadow vehicle placement policies/guidance in a variety of work zones
- Use of full matrix truck mounted changeable message signs on shadow vehicles, which provide advance warning to the traffic flow

Finally, the American Traffic Safety Services Association (ATSSA) has published important training and research material, which highlights key considerations work crews should make during the use of shadow vehicles in Work Zones. These publications offer both policy as well as technical guidance for the correct use of shadow vehicles. In ATSSA's[8] Shadow Vehicles for Work Zones Training Module, researchers highlight the role of key parameters such as – Weight of Impacting Vehicle, Weight of TMAs in establishing the correct roll-ahead distances (based on Humphreys and Sullivan (1991)[9]). The training also accounts for the need to adapt roll-ahead distance with speed of operating traffic per AASHTO[10].

10. Appendix D – Work Zone Accident Analysis

The goal of section is to:

- Understand the role of the dump truck during the Work Zone life-cycle in selected configurations
- Develop an understanding of Work Zone configurations where truck mounted attenuators are deployed
- Develop an understanding of role performed by the TMA and Shadow Vehicle system during the active work zone

10.1. Role of the Dump Truck in a Work Zone's Life-Cycle

The dump trucks perform a diverse set of operations in Work Zones today. While most literature focuses on the role of shadow vehicles at the work site during active operation, the preparation for Work Zone deployment starts at the garage. The role executed by shadow vehicles in the Work Zone life cycle can be broadly categorized into the following functions:

- Payload – Carry equipment and Traffic Control Devices (TCDs) to work site
- Mechanical Attachment and Interface – Interface and attach to attenuators

[8] ATSSA, Shadow Vehicles for Work Zones Training Module

[9] Humphreys, J. B., & Sullivan, T. D. (1991). Guidelines for the use of truck-mounted attenuators in work zones. Transportation Research Record, (1304).

[10] AASHTO, Roadside Design Guide

- Maneuverability – Maneuver in tight-spaces (ex. garage), at work-site, and on wide array of open roads in variety of operating conditions.
- Electronics and Warning – Provide electronic or sign-based warning for motorists
- Positive Protection – Provide positive protection to work site from rogue traffic.

The shadow vehicle plays multiple roles in the Work Zone life-cycle. Currently ODOT uses dump trucks to perform the role of the shadow vehicle in designated Work Zones. Figure 11 outlines the lifecycle of the use of dump truck in the Work Zone operation. The figure outlines the various roles performed by the dump truck during the origination, setup, and tear-down of the Work Zone.

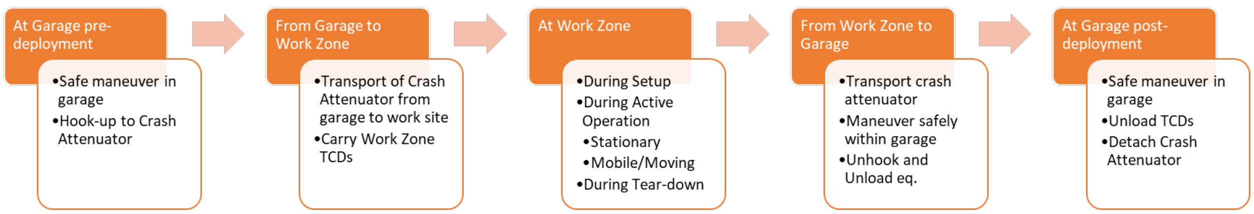


Figure 11 - Analysis of dump truck's functions through the Work Zone lifecycle

It is recognized that dump truck performs various roles throughout the various phases of the Work Zone. Analysis of these roles performed will help build the foundation for development of functional specifications. An attempt is made to categorize the roles performed by the dump truck in each phase of the Work Zone into appropriate functional categories. Table 5 outlines an assessment of these roles.

Table 5 - Functional Categorization of roles of dump truck through Work Zone lifecycle

Phase	Function / Role	Functional Category
At Garage Pre-Deployment	Safely maneuver in the garage (tight-spaces)	Maneuver
	Attach to crash attenuator	Mechanical
	Load Work Zone TCDs	Payload
From Garage to Work Zone	Transport crash attenuator to work site	Maneuver
	Carry Work Zone TCDs to work site	Payload
At Work Zone - During Setup	Enable setup of TCDs	Maneuver
	Maneuver within Work Zone	Maneuver
	Establish safe distance from work site	Positive Protection

Phase	Function / Role	Functional Category
	Deploy Crash Attenuator	Positive Protection / Mechanical
At Work Zone – During Active Operation	Turn-on warning signs	Electronics/Warning
	Maintain safe distance from work site (in mobile/moving or stationary operations)	Positive Protection
	Provide positive protection to workers from traffic	Positive Protection
At Work Zone – During Teardown	Pickup / Hook-up Crash Attenuator	Mechanical, Payload
	Turn-off warning signs	Electronics
	Enable pick-up and loading of TCDs	Payload, Maneuver
	Maneuver within Work Zone	Maneuver
From Work Zone to Garage	Transport crash attenuator to Garage	Maneuver
	Carry/Tow a payload of TCDs from work site	Payload
At Garage Post-Deployment	Unload TCDs	Payload
	Detach crash attenuator	Mechanical
	Safely maneuver in garage (tight-spaces)	Maneuver

10.2. Ohio Work Zone Configurations with Shadow Vehicles and TMA

According to the guidelines provided by FHWA and ODOT for traffic control in Work Zones, the Work Zones are arranged into multiple types based on factors such as location of work, type of operations and duration of work and characteristics of the roadway. Table 6 outlines the wide variety of Work Zones and typical applications of TCDs possible on roadways. The table also outlines if a shadow vehicle, arrow sign, crash cushion, and TMA is used in these typical applications.

This section particularly focuses on the typical applications where TMA and shadow vehicles are recommended. These configurations are analyzed to understand the expected role of the shadow vehicles at a Work Zone during Active Operation. Table 7 summarizes the types of requirements on shadow vehicles observed in practice on Work Zones. Rows highlighted in yellow indicate typical applications where use of TMAs is recommended in some capacity.

Table 6 -A survey of relevant TCDs used in O-MUTCD recommended Work Zone Typical Applications

OMUTCD TA #	Typical Application Description	Type of Work Zone	Sign	Truck mounted attenuator	Arrow Panel	Arrow Panel Trailer	Vehicle Hazard Warning Signal
TA-3	Work on the Shoulders	Work on shoulder/ Median	Yes	No	No	No	Supplementary
TA-4	Short-Duration or Mobile Operations on Shoulder	Work on shoulder/ Median	Yes	Optional	Optional	Optional	Supplementary
TA-5	Shoulder Closure on a Freeway	Work on shoulder	Yes	Crash cushion	No	No	No
TA-6	Shoulder Work with Minor Encroachment	Work on shoulder	Yes	Optional	No	No	Supplementary
TA-8	Road Closure with Off-Site Detour	Other	Yes	No	No	No	No
TA-9	Overlapping Routes with Detour	Other	Yes	No	No	No	No
TA-10	Lane Closure on Two-Lane Road	Lane closure	Yes	No	No	No	No
TA-11	Lane Closure on Low-Volume Two-Lane Road	Lane closure	Yes	No	No	No	No
TA-13	Temporary Road Closure	Other	Yes	No	No	No	No
TA-15	Work in Center of Low-Volume Road	other	Yes	No	No	No	Supplementary
TA-17	Mobile Operations on Two-Lane Road	Intermittent/ moving work	Yes	Optional	Optional	No	No
TA-18	Lane Closure on Minor Street	Lane closure	Yes	Optional	No	No	No

OMUTCD TA #	Typical Application Description	Type of Work Zone	Sign	Truck mounted attenuator	Arrow Panel	Arrow Panel Trailer	Vehicle Hazard Warning Signal
TA-20	Detour for Closed Street	Other	Yes	No	No	No	No
TA-21	Lane Closure on near side of intersection	Lane closure	Yes	Optional	No	No	Supplementary
TA-22	Right Lane Closure on Far Side of Intersection	Lane closure	Yes	No	Yes	Yes	No
TA-23	Left Lane Closure on Far Side of Intersection	Lane closure	Yes	No	Optional	Optional	No
TA-25	Multiple lane closure at intersection	Lane closure	Yes	No	No	No	No
TA-26	Closure in Center of Intersection	Other	Yes	No	No	No	Supplementary
TA-27	Closure at Side of Intersection	Other	Yes	No	No	No	Supplementary
TA-28	Sidewalk Closures and Bypass Sidewalks	Other	Yes	Crash cushion Optional	No	No	No
TA-29	Crosswalk Closures and Pedestrian Detours	Other	Yes	No	No	No	No
TA-30	Interior Lane Closure on Multilane Street	Lane closure	Yes	Optional	Optional	Yes	No
TA-31	Lane Closure on street with uneven Directional Volume	Lane closure	Yes	Optional	Optional	Yes	No
TA-32	Half Road Closure on a Multi-lane, High-Speed Highway	Lane closure	Yes	Optional	Yes	Yes	No

OMUTCD TA #	Typical Application Description	Type of Work Zone	Sign	Truck mounted attenuator	Arrow Panel	Arrow Panel Trailer	Vehicle Hazard Warning Signal
TA-33	Lane Closure on Divided Highway (Short Term)	Lane closure	Yes	Optional	Yes	Yes	No
TA-34	Lane Closure with a Temporary Traffic Barrier	Lane closure	Yes	No	Optional	Optional	No
TA-35	Mobile Operation on Multilane Road	Intermittent/ moving work	Yes	Optional	Yes	Yes	No
TA-36	Lane Shift on a Freeway	Lane shift/Crossover	Yes	Crash cushion	No	No	No
TA-37	Double Lane Closure on Freeway	Lane closure	Yes	Optional	Yes	Yes	No
TA-38	Interior Lane Closure on a Freeway	Lane closure	Yes	No	Yes	Yes	No
TA-39	Median Crossover on a Freeway	Lane shift/Crossover	Yes	Crash cushion Optional	Yes	Yes	No
TA-40	Median Crossover for an Entrance Ramp	Lane shift/Crossover	Yes	No	No	No	No
TA-41	Median Crossover for an Exit Ramp	Lane shift/Crossover	Yes	No	No	No	No
TA-42	Work in Vicinity of Exit Ramp	Other	Yes	No	Yes	Yes	No
TA-44	Work in Vicinity of Entrance Ramp	Other	Yes	No	Yes	Yes	No
TA-45	Temporary Reversible Lane Using Movable Barriers	Lane shift/Crossover	Yes	Optional	Yes	Yes	No

Table 7 - Nature of requirements on shadow vehicles when used in identified Work Zone Typical Applications

OMUTCD TA #	Typical Application Description	Types of Requirements on Shadow Vehicles
TA-4	Short-Duration or Mobile Operations on Shoulder	Electronics, Warning, Visibility of signage.
TA-6	Shoulder Work with Minor Encroachment	Electronics, Warning, Hierarchy for use of TMA, shadow vehicle, warning lights, taper and channelizing devices.
TA-17	Mobile Operations on Two-Lane Road	Electronics, Warning, Visibility of signage, Maneuver (Pull-over to allow passing), Positive Protection – Safe distance guidance and options, Use of TMA, Use of additional shadow vehicles from law-enforcement, Presence of shadow vehicle to warn motorists.
TA-18	Lane Closure on Minor Street	Positive Protection – Optional Placement Information
TA-21	Lane Closure on near side of intersection	Positive Protection – Optional Placement Information
TA-30	Interior Lane Closure on Multilane Street	Positive Protection – Optional Placement Information
TA-31	Lane Closure on street with uneven Directional Volume	Positive Protection – Optional Placement Information
TA-32	Half Road Closure on a Multi-lane, High-Speed Highway	Positive Protection – Optional Placement Information
TA-33	Lane Closure on Divided Highway (Short Term)	Positive Protection – Optional placement information, Short duration Work Zones
TA-35	Mobile Operation on Multilane Road	Electronics, Warning, Signage Visibility, Use of TMAs, Use of Signage, Positive Protection – Guidance on Placement, Safe Distance based on Sight Distance, Placement guidance to prevent road users driving between shadow vehicle and work vehicle, Guidance on Interior Lane Operation, High Speed Roadway Adaptability, Rules to allow straddle edge line driving.
TA-37	Double Lane Closure on Freeway	Positive Protection – Optional Placement Information
TA-45	Temporary Reversible Lane Using Movable Barriers	Positive Protection – Optional Placement Information

10.3. An assessment of TMA and Shadow Vehicle System's functions in an Active Work Zone

The TMA and shadow vehicle system is designed to play two key roles in active operation during the identified Work Zone typical traffic configuration scenarios:

- Provide motorists and traffic with warning in-advance of work-site
- Provide positive protection to workers and traffic during a traffic vehicle crash accident

An analysis of the role of TMA and shadow vehicle during the active operation phase at a Work Zone yields the following key requirements in each identified functional category:

- Electronics
    i. Capability to accommodate high-intensity rotating, flashing, oscillating, or strobe type lights
    ii. Attachment, mounting, and power for arrow boards
    iii. Hazard warning signals (supplementary, during active operation only)
    iv. Multiple high-intensity flashing lights (in select scenarios)
- Warning Signs
    i. Accommodate mounting of MUTCD signs like "LEFT LANE CLOSED AHEAD"
    ii. Signs should be visible and not obscured by equipment or other supplies
    iii. Easy access to cover signs or turned from view, when work is not in progress
- Positive Protection
    i. Placement guidance – position at a static, short-duration, mobile and moving operations Work Zone
    ii. Longitudinal safe distance from work vehicle
        - Adapt with rear traffic sight distance
        - Position to prevent traffic side-swipe incidents with work vehicle
        - Adaptability with respect to terrain (roadway geometry & sight-distance)
        - Adaptability to traffic conditions (high-speed roadway guidance, traffic back-up)
    iii. Lateral placement (contingent on infrastructure & roadway operation conditions)
        - Interior Lane
        - Shoulder work
        - Lane-edge straddle
- Maneuver
    i. Ability to follow work vehicle at a safe distance
    ii. Ability to adapt to infrastructure and traffic conditions
    iii. Initiate periodic pull-over maneuver to allow safe passage for following traffic

10.4. Work Zone Accident Analysis

The goal of section is to:

- Evaluate Work Zone Accident Data to inform requirements of the alternative device

This section's Work Zone accident data analysis is a process that compiles the existing data of the Work Zone accident for last 5 years. A thorough study was conducted on the current Work Zone configurations with TMA to extract various factors necessary to develop insights into the role of truck (shadow vehicles) and TMA system.

10.4.1. Method

Data analysis was conducted using the data workflow described below. For this analysis, the researchers used the Work Zone accident data provided by ODOT. During analysis, various trends, and patterns were explored which indicate with substantial evidence that the TMA and shadow vehicle play a positive role in Work Zone.

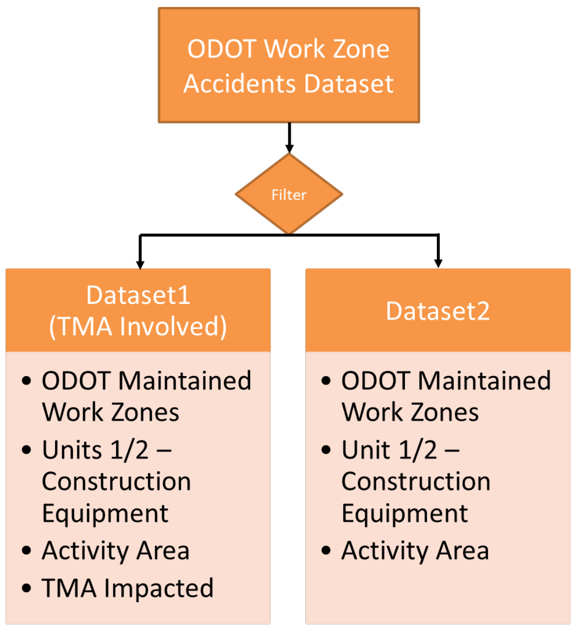


Figure 12 - Filtering and classification of ODOT Work Zone Traffic Crash Report datasets.

ODOT TAC provided TRC's researchers with a list of all reported traffic crash accidents in Ohio's Work Zones during the years 2016-2020. This dataset included traffic crash reports for over 26,700 traffic incidents in Ohio's Work Zones. The research team applied filters to reduce the set of traffic crash reports to identify traffic incidents of interest to the scope of this research.

Filters used:

- Were Work Zones ODOT maintained?
- Did accidents involve construction equipment?
- Were there accidents in the activity area of the Work Zone?
- Was a Truck Mounted Crash Attenuator involved in the accidents?

Application of these filters led to the generation of two data subsets from the original data.

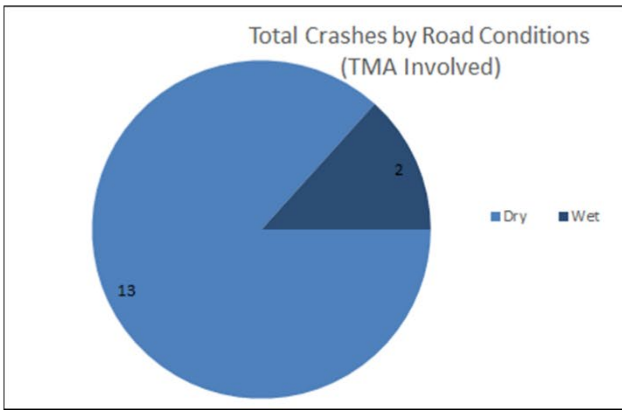
i. **Dataset1 (TMA Involved)** – Identified 15 reports on ODOT maintained roadways, where one of the two units involved in a crash was construction equipment (single unit/ heavy equipment), and that a TMA was impacted.
ii. **Dataset2** – Identified 166 reports on ODOT maintained roadways, where construction equipment was hit, and the crashes occurred in an activity area.

The researchers performed additional analysis on these data subsets in a compare-and-contrast fashion to understand the nature and characteristics of select set of traffic incidents. The researchers used both subjective and objective methods to glean insights from these datasets.

10.4.2. Analysis Results

Analysis of Work Zone Crashes – Road conditions, Weather, and Roadway Geometry

To analyze any aspect of accident data it is important to look into the primary conditions such as the weather conditions, road conditions and structure of road. The following plots that provide details regarding these factors.



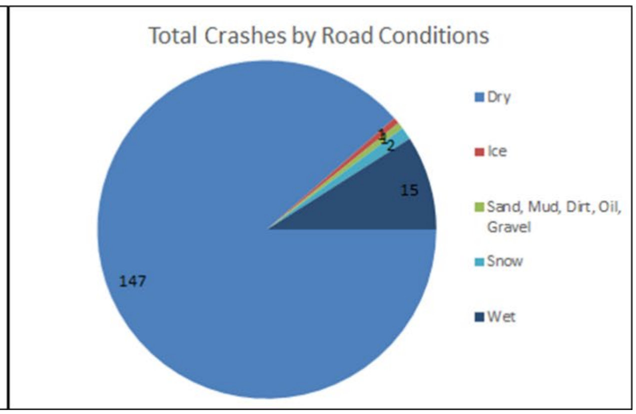


Figure 13 – Influence of road-weather on crashes in Work Zones. Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2.

By visualization of the above plots, it is clear that the maximum accidents occurred on dry roads. Quantitatively for Figure 13 on the left; total of 15 accidents occurred, 13 of these accidents were on dry road while only 2 accidents on wet road. Around 86% accidents occurred on dry road. For Figure 13 on the right, out of 165 total accidents 147 accidents were on dry road, which accounts to around 88.5%.

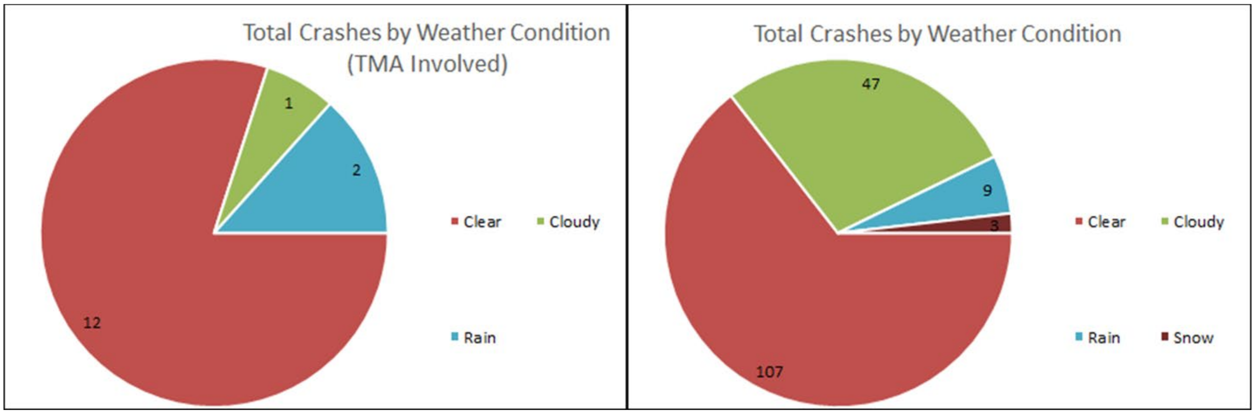


Figure 14 - Influence of weather conditions on crashes in Work Zones. Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

Similar to the above plots here maximum accidents occurred in clear weather conditions for both scenarios. For Figure 14 on left shows 12 out of 15 accidents occurred in clear weather conditions and for Figure 14 on right shows 147 out of 165 occurred in clear or cloudy weather conditions, accounting to 80% and 92% respectively

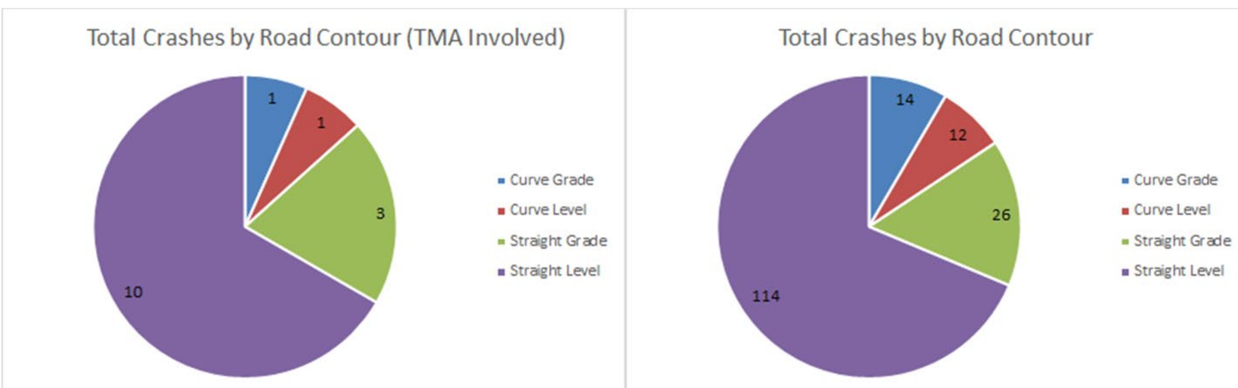


Figure 15 - Influence of road-contour on crashes in Work Zones. Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

Here both the plots show maximum roads were of straight level contour at the place of accidents. In left of Figure 15, 10 of 15 i.e. around 66% accidents occurred on roads with straight level, and 3 of 15 on straight grade. Similarly, in right of Figure 15, 114 of 165 on straight level i.e. approximately 68%. While curve grade and curve level comprised of only 13%-15%.

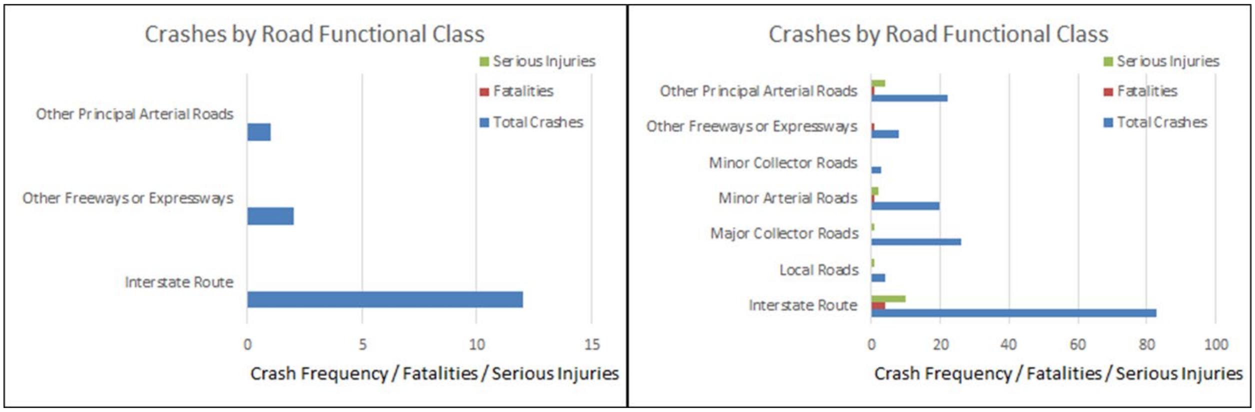


Figure 16 - Crashes by road functional class. Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

Figure 16 outlines that a majority of Work Zone crashes occur on Interstate Routes and on Major Collectors. This observation allows for the development of requirements tailor-made for that operational domain.

Therefore, by analyzing all the above plots, it is conclusive that the road conditions, weather conditions, and Road contour have trivial role in these accidents and are not major factors that influence accidents. However, the dominance of Work Zone crashes on interstate routes provides an opportunity to tailor the alternate device's specifications to meet the needs of the identified operational domain.

Crash severity analysis

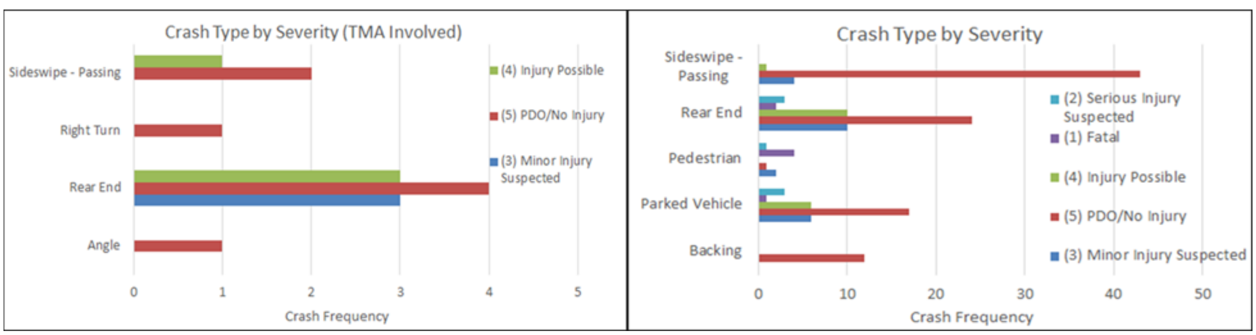


Figure 17 - Crash type by severity. Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

Figure 17 on left represents the plot of crash types and the injuries caused by each type of crash as analyzed from Dataset1. The observation here is there are no fatal or serious injuries caused in any type of crash, when a TMA was involved. Maximum number of crashes with TMAs are of the rear-end kind.

Similar to above Figure 17 on right shows analysis conducted on Dataset2, in this case there are fatalities and serious injuries caused by crashes; relatively a greater number of crashes appear in Sideswipe-passing, rear end and parked vehicles.

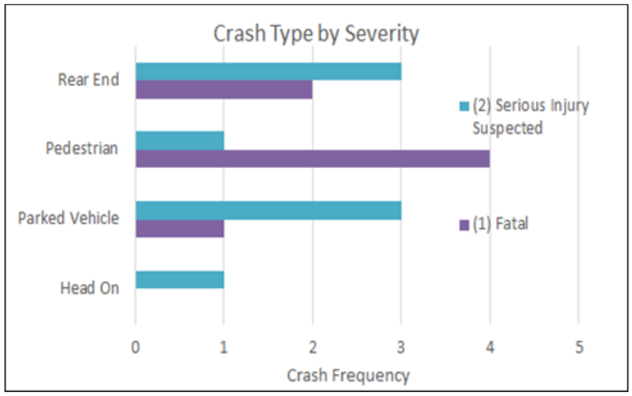


Figure 18 - Fatalities and serious injuries observed in Dataset2

Figure 18 shows serious and fatal injuries observed in Dataset2. It should be noted that this data contains Work Zones such as lane closure, intermittent or moving work etc., where TMAs are recommended. The crash data did not indicate presence of a TMA or impact with a TMA. Although maximum crashes occurred were of the Sideswipe-passing kind, the number of fatalities and serious injuries caused to pedestrians are higher. These are followed closely by parked vehicle, rear end and head on crashes in a descending order.

While injuries have been recorded, the damage caused to ODOT equipment may also have been high, which needs to be paid for by ODOT. When compared to Dataset1 it shows that presence and proper placement of TMA and shadow vehicle could have prevented this along with reducing fatalities and serious injuries.

Crashes by Work Zone type

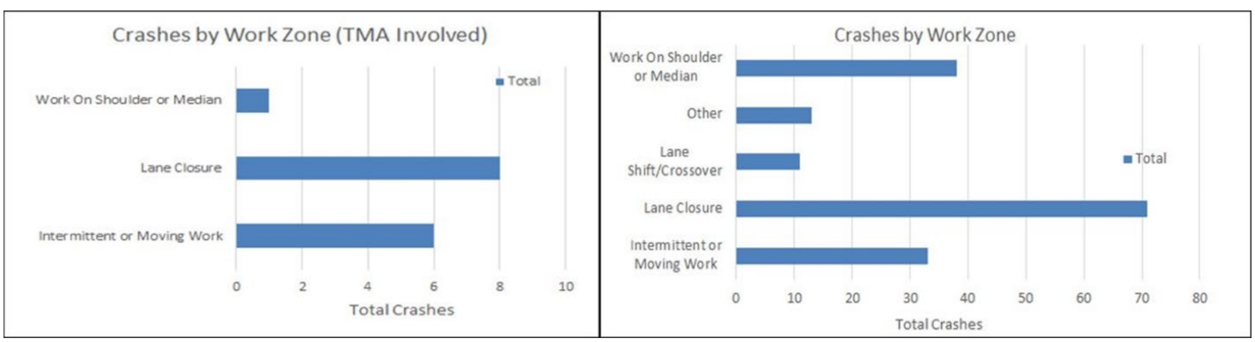


Figure 19 - Crashes by type of Work Zone. Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

There are numerous types of Work Zones as defined by FHWA in MUTCD with their desired configuration. But after data analysis we observe only certain types of Work Zones are more susceptible to crashes. For instance, Figure 19 left shows lane closures and intermittent/moving type of Work Zones have maximum number of crashes accounting for 14 of 15 i.e. 93% of total crashes in these two types of Work Zones.

Similarly, as per Figure 19 on right although the number of crashes are highest in lane closure and intermittent/ moving work scenarios - 103 of 165 crashes, there is a significant increase in number of crashes in work on shoulder/median. It is likely that number crashes may be reduced if TMA and shadow vehicle are used in work on shoulder/ median, as it could force motorists to become more aware of the Work Zone ahead.

Analysis of Pre-Crash Actions in Work Zone Accidents

Table 8 - Pre-crash action of vehicles in Dataset1

Pre-Crash Action	Total Crashes
Changing Lanes	1
Making Right Turn	1
Slowing Or Stopped In Traffic	1
Straight Ahead	10
Other	2
Grand Total	15

Table 9 - Type of impactor vehicle in Dataset1 accidents with straight ahead pre-crash action.

Type of Unit	Total Crashes
Pickup	1
Passenger Car	6
Passenger Van (Minivan)	1
Cargo Van	1
Single Unit Truck	1
Grand Total	10

Table 10 - Pre-crash action of vehicles in Dataset2.

Pre-Crash Action	Total Crashes	Fatalities	Serious Injuries
Backing	12	0	0
Changing Lanes	18	0	4
Leaving Traffic Lane	3	0	1

Making Left Turn	4	0	0
Making Right Turn	4	0	0
Negotiating A Curve	4	0	0
Overtaking/Passing	7	0	1
Slowing or Stopped In Traffic	6	0	0
Standing	1	0	0
Straight Ahead	103	7	12
Other	4	0	0
Grand Total	166	7	18

Table 11 - Type of impactor vehicle in Dataset2 accidents with straight ahead pre-crash action.

Type of Unit	Total Crashes	Fatalities	Serious Injuries
Pickup	14	0	2
Sport Utility Vehicle	11	2	1
Unknown or Hit/Skip	2	0	0
Semi-Tractor	14	3	4
Passenger Car	45	2	5
Passenger Van (Minivan)	3	0	0
Cargo Van	4	0	0
Single Unit Truck	8	0	0
Heavy Equipment	1	0	0
Bus (16+ Passengers)	1	0	0
Grand Total	103	7	12

Table 8 gives information about the pre-crash actions of impacting vehicles in Dataset1. Most common pre-crash action was straight ahead motion. This could mean that the drivers of these vehicles did not notice the Work Zone ahead and did not attempt to change the lanes as directed.

Table 9 provides details about the type of vehicle were involved in straight ahead pre-crash action. From the numbers in the table, it is evident that majority of the vehicles were passenger car/van. This is consistent even with Dataset2 as shown in Table 10 majority of accidents happened in straight ahead pre-crash action with maximum of passenger car involvement as per Table 11.

Spatial distribution of Work Zone Crashes in state of Ohio

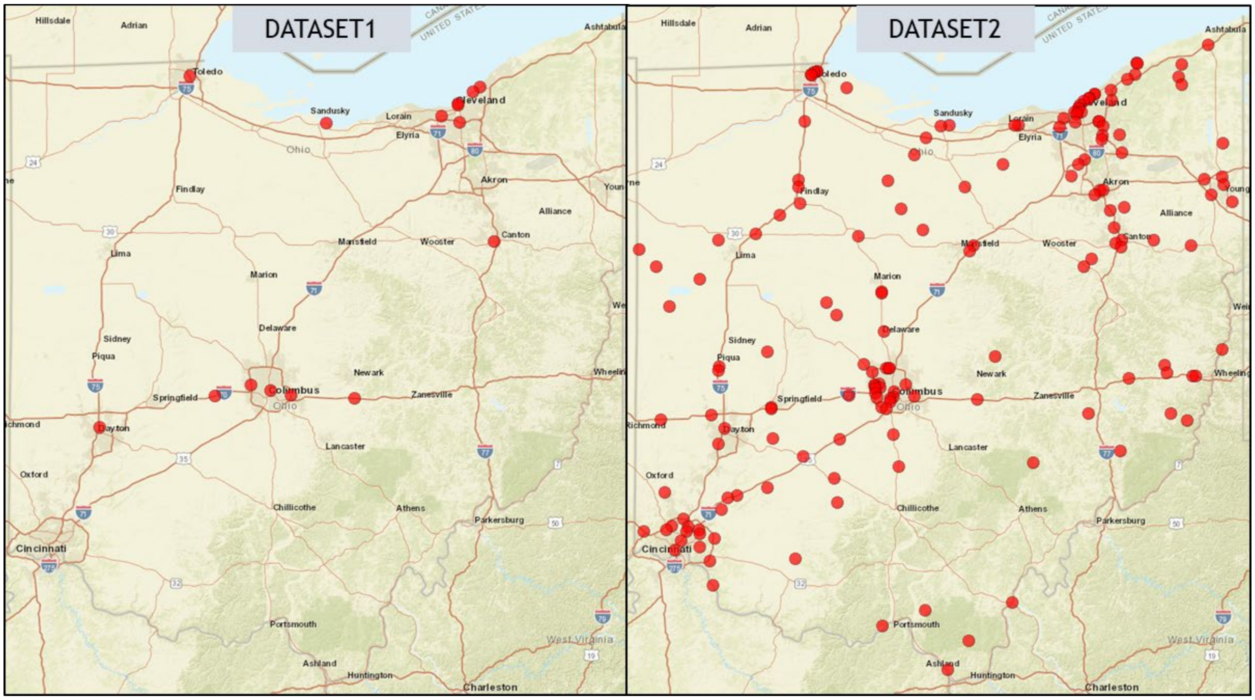


Figure 20 - Spatial distribution of Work Zone crashes in the state of Ohio (Map-View). Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

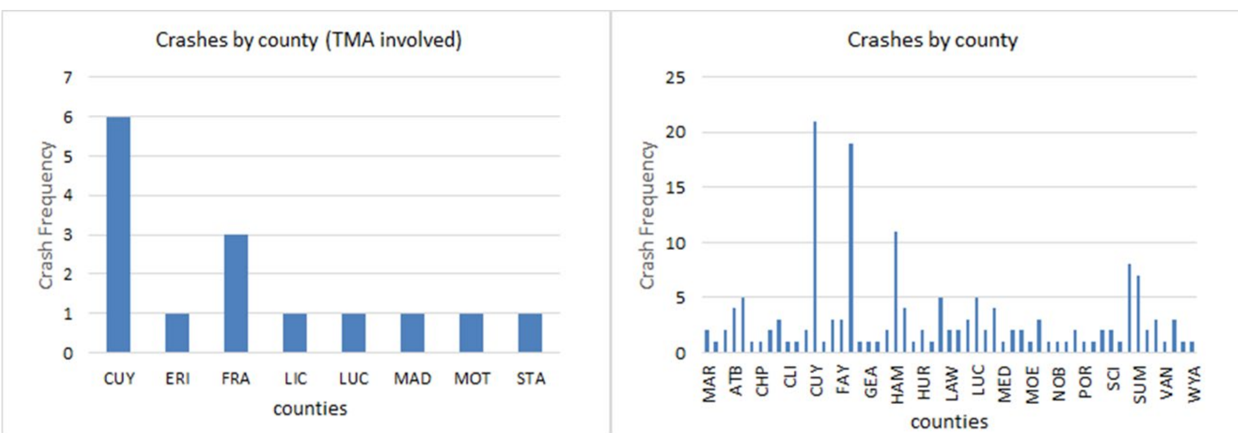


Figure 21 - Spatial distribution of Work Zone crashes in the state of Ohio (county-view). Left shows results for Dataset1, where TMA was involved. Right shows results for Dataset2

Figure 20 on left-The red points indicate the site at which the accidents occurred as referred in Dataset1. These accidents are concentrated to highly populated counties as show in Figure 21 left. Moreover, all the accidents in Cuyahoga County occurred at

Dark - Lighted Roadway. Of accidents from Dataset1 occurring in major counties (Cuyahoga, Franklin, Lucas, Montgomery and Stark) around 66% were in Dark - Lighted Roadway. While deriving specifications this should be considered and steps should be taken to improve visibility particularly of TMA and shadow vehicle.

Figure 21 on right shows the accidents occurrence as per Dataset2, 61 of 165 accidents occurred in 5 most densely populated counties while 104 accidents were distributed in other 50 counties. Unlike Dataset1 here the accidents in daylight vs dark were around equal for 5 most densely populated counties.

Crash Analysis by Time-of-Day and Seasons.

Table 12 - Analysis of crash distribution by time-of-day in Dataset1 and Dataset2

Time of Day	Dataset1 (TMA Involved)	Dataset2
Dawn (06:00 – 08:59)	0	28
Day (09:00 – 17:59)	6	87
Dusk (18:00 – 20:59)	1	8
Night (21:00 – 05:59)	8	43
Total	15	166

Table 13 - Analysis of crash distribution by seasons in Dataset1 and Dataset2

Seasons	Dataset1 (TMA Involved)	Dataset2
Spring (Mar.-May)	7	31
Summer (Jun.-Aug.)	7	70
Fall (Sep. – Nov.)	0	51
Winter (Dec. - Feb.)	1	14
Total	15	166

An assessment of distribution of traffic crash incidents against time-of-day is performed in Table 12. In Dataset1, a higher number of crash incidents with TMAs are reported in night-time conditions. The causal factors for these accidents (driver distraction, impairment, fatigue, low-visibility of Work Zone equipment) may need to be reviewed. Dataset2 indicates a higher number of crashes in the day-time conditions. However, night-time visibility may still be a challenge. These findings will benefit from a review of time-of-day distribution of average traffic volume on Ohio's. It is likely that higher crashes during the day-time in Dataset2 are due to higher traffic volumes, typically observed in day-time conditions.

Table 13 reviews the seasonal distribution of Work Zone crashes as observed in ODOT monitored Work Zones. These findings will also benefit from a review of seasonal distribution of traffic on Ohio's roadways. It is also likely that a low number of Work Zone repair activities are conducted during the months of winter, which leads to traffic crash accidents overall.

10.5. Key Operating Conditions for the use of Shadow Vehicle in Ohio's Work Zones

The goal of this section is to answer the following key questions:

1. Do key operating conditions emerge from an analysis of crash data?

The research team performed analysis on Accident and Crash Data in Ohio's Work Zones between 2016-2020, to identify characteristics of dominant operating case for the use of shadow vehicles. This assessment was also designed to inform the development of functional specifications of the alternative device that may be used to replace the dump truck.

There were over ~26,700 crashes in Ohio's Work Zones. The research team applied appropriate filters on key parameters to enable clustering of data and development of a refined dataset. This clustering technique allowed for the generation of patterns. Application of filters led to the identification of 166 potential crashes, which could have benefited from the use of TMAs. Of the 166 crashes:

- 55% occurred on Interstates and Freeways/Expressways
- 25% occurred on Arterial Roadways

When crashes on the Interstates and Freeways were reviewed, over 85% occurred on roadways with straight roadway geometry contour. Table 14 investigates such crashes further.

Table 14 - Summary of findings from a review of the refined crash dataset

Parameter	Findings	This implies:
Type of Work Zone	Of all crashes in Work Zones on Straight roads: • 70% crashes occurred in static work zones • 30% crashes occurred in mobile/moving work zones	While both static and mobile work sites pose a separate set of risks and challenges, it appears that static operations have higher number of crashes.
Type of Work Zone Activity	Crash frequency list: • Lane closure sites (41%) • Work on shoulder/median (38%)	Static lane closure sites are most common and risky to workers. Working on shoulder and medians, is also conducive to the use of TMAs.

	• Intermittent / Moving Work (15%)	

A majority of fatalities and serious injuries occur on static work zones that include the lane closure and shoulder/median work (Figure 22). While, moving/mobile work sites are more dynamic it appears that these work sites have lower fatality risk as ODOT's workers have reduced and intermittent exposure to live traffic. Workers may be in an enclosed truck during a variety of mobile/moving operations (sweeping, lane marking repair etc.).

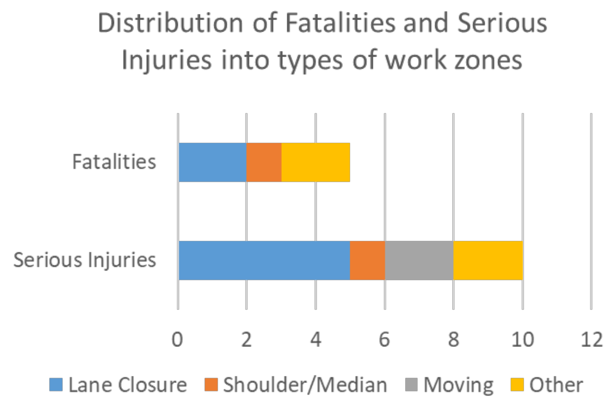


Figure 22 - Distribution of fatalities and serious injuries across types of work zones on interstates and freeways.

The high-speed, high-volume travel-way could become the controlling case for design. Arterials are also important, but involve lower speeds and may provide more flexibility for the use of an alternative device. Additionally, most crashes occurred in non-adverse weather conditions under clear weather (~89% of crashes) and dry roadways (~86% of the crashes). Therefore, weather was not deemed as a controlling factor for the design.

Rear-end and side-swipe type of crashes dominated the dataset. Most often, the impacting vehicle was a passenger vehicle, but pickup-trucks, SUVs, and Semi-Tractors were also involved in crash incidents. The most common pre-crash action regardless of vehicle type was "straight-ahead", which indicates that there is an element of surprise when vehicles encounter work zones on public roads. It is important that the alternative device accommodate countermeasures to reduce this element of surprise. Table 3Table 15 summarizes these findings with regards to their implications on the design of the alternate device.

Table 15 - Summary of needs and implications on design of an alternative device from a review of crash dataset

Category of Need	Design implication (ordered list)
Roadway Functional Class	1. Interstates and Freeways/Expressways 2. Arterial Roads These functional classes imply an use case with: Moderate to high speed travel ways Moderate to high traffic volume travel ways
Nature of Work Zone	1. Static 2. Mobile / Moving
Type of Work Zone	1. Lane Closure 2. Work on shoulder or median 3. Moving and mobile work

Crash Vehicle, type of crash, most common pre-crash action	1. Passenger vehicles, straight-ahead 2. SUVs, straight-ahead 3. Semi-tractor, straight-ahead

10.6. ODOT Needs Assessment

The goal of this section is to answer the following key questions:

1. Can a more widespread use of TMAs reduce crash risk in the identified operating conditions (Sec 10.5)?
2. If yes, understand the impediments to a more widespread use of TMAs. What factors of shadow vehicles contribute to these impediments?

While the TMA system is effective at protecting against fatalities and serious injuries in crashes, there may be key challenges that impede a more wide-spread use of the system. The challenges may be categorized into four broad issues (Table 16), which plague both the TMA as well as shadow vehicles in work zones.

Table 16 - Possible impediments to a more widespread use of TMAs.

Category of Impediment	Shadow Vehicle	Crash attenuator
Choice of equipment	What shadow vehicles can be used with the attenuator?	Type of crash attenuator appropriate for site – truck-mounted or trailer-mounted?
Availability of equipment	Is the shadow vehicle available?	Is the crash attenuator available?
Ease-of-use	Does the shadow vehicle facilitate easy setup and safe-use in a work zone?	Is the crash attenuator easy to deploy and use in a work zone?
Clear direction	Is right information and guidance available to help ODOT's staff make an appropriate choice of TMA system?	

The research team performed a field visit to ODOT's District #6 Hilliard Outpost to observe operations, and understand challenges faced by ODOT's HTs using the shadow vehicle and TMA. Discussions between the research staff, ODOT TAC and ODOT's HTs have been edited, categorized and presented in following sections. Table 17 summarizes ODOT's needs as observed during the field visit for an alternative device in TMA operations.

Table 17 - ODOT's needs as observed during field visit, categorized into key functional areas

Category	Description of Needs
Information to design Work Zone	When considering setup of a work zone, provide staff with adequate information to make an informed choice to use an appropriate device in a work zone configuration
	Easy mechanical attachment to TTMA via a hitch mechanism

Interface and Attachment	Easy mechanical attachment to TMA via adapters
	Standardized electrical adapters to accommodate TMA and CMS power needs
Travelling (to and from worksite)	When travelling in a TTMA configuration, facilitate easy backing and maneuvers in reverse
	Enable operators to maintain safe following distance from work vehicle
	Facilitate travel in narrow shoulders that may include a drop-off and uneven terrain
	Enable operators to become spatially aware of potential impacts of TMA/TTMA or shadow vehicle with hazards like roadside crash attenuators, bridge guardrails etc.
	Enable operators to become spatially aware of encroachment of TMA/TTMA or shadow vehicle into other lanes
Maneuver (at or within a work zone)	When at work zone during setup, encourage safe maneuver in tight spaces
	When at a static work zone, enable slow speed maneuvers to reposition TMAs per work site needs
	When maneuvering (in mobile operations), enable operators to become spatially aware of encroachment of TMA/TTMA or shadow vehicle into other lanes
	Enable operators to become spatially aware of potential impacts of TMA/TTMA or shadow vehicle with hazards such as work zone barrels, cones in tight spaces etc.
Positive Protection	When at a work zone, enable operators to maintain safe longitudinal distance and lateral position for crash protection from workers or (moving or static) work vehicles at the site.
	When using the alternative device, provide adequate positive crash protection during static or mobile operations
	Under an impending crash, apply full braking to reduce roll-ahead into workers
Crash Alerts	Under an impending work zone crash, alert workers via an air-horn and panic lights
	Under an impending work zone crash, provide workers visibility on the type of impacting vehicle and pre-crash action to help them react to the crash event

What are the challenges in current use of TMA system(s)?

Challenges during setup at the garage

The research team observed both TTMA and integrated TMA configurations, which seemed to offer unique set of challenges during setup at the garage.

Figure 23 –TMA systems of different kinds installed on dump-trucks

Figure 24 - TTMA ready for attachment to a dump truck (not in picture).

For integrated TMAs, two types of systems were observed (Figure 24). The TMAs were attached to single axle dump trucks, which were dedicated for use as shadow vehicles in work zones. Both types of integrated TMAs required modifications to the chassis of the dump truck and body. The modifications include attachment of a weld-plate to the chassis, and the need to run of power cables from the truck to the CMS sign and hydraulics of the TMA system were noted. Once the TMAs were integrated to the truck, the Hilliard garage intended to keep these TMAs installed to it. The turn-around time for installation of integrated TMA to a dump truck (with ready mechanical and electrical adapters) was estimated to be around 1hr.

For trailer towed TMAs, the setup time is lower because it requires the installation of a hitch (Figure 24). When using dump truck as the shadow vehicle, the ease of connecting to the trailer mounted TMAs could be improved by the use of rear-view or backup cameras.

However, in both cases ODOT's HTs at this garage indicated that the pre-deployment (in-garage) phase is not very challenging with regards to either the skills needed or equipment turn-around time.

Deployment to work-site

Visibility and maneuverability limitations of the dump truck were noted as impediments but the ODOT HTs are comfortable working around these issues.

With TTMAs:

- Maneuvering in traffic produces challenges similar to driving a long trailer, with limited rearward visibility. This includes wider-turning radii, the need for awareness when changing lanes etc.

With an integrated TMA:

- Maneuvering to the worksite in a folded position is easier than the TTMA.

At work-site

The research team observed a moving operation on right-shoulder of I-270 between Roberts Rd. and Cemetery Rd. The sweeper truck was followed by a dump truck, acting as a shadow vehicle with a TTMA attached to it. The following observations were made with regards to the shadow vehicle and TTMA operation:

- Narrow shoulder width along certain sections of the work site was a challenge for maneuvering the dump truck.
- On certain occasions when the dump truck was operating in the shoulder, traffic flow in travel lane adjacent to the shoulder was impacted.
    - Most travelers changed lanes and moved over to give the work crew a lane width clearance. This was not required by the work zone operation or by the type of sign displayed on the changeable message sign (CMS).
    - On a few occasions, the shadow vehicle veered into the travel lane, due to narrow shoulder features on bridge decks. This increased traffic risk.
- The work crew encountered a highway patrol cruiser making a traffic stop along the route, in the right shoulder. This meant the work crew had to safely navigate this situation by:
    - Executing a maneuver into the adjacent travel lane, with a trailer type attenuator
    - Perform wide turns to avoid encroachment of trailer into traffic lanes.
    - Correctly use CMS signs during this short transition event.
- While the work crew safely navigated the situation, changing of CMS signs could be made better to provide traffic with adequate warning and information.

Figure 25 - TTMA in a shoulder sweeping operation on I-270. Left - Operating on a narrow on-ramp, TTMA occupies travel lane restricting flow of traffic. Right - TTMA passed by a tractor-trailer on the left when travelling on the on-ramp. In both situations, the TTMA displayed a caution sign

- Following the work vehicle in narrow shoulder along ramps of the interstate was a challenge (Figure 25). The width of the shadow vehicle and the need to take wider turns when travelling on ramps may occlude traffic flow. This may increase risks for the work crew due to impatient backed-up traffic.
- The shadow vehicle trailed the work vehicle at a near idle speed of 5-7mph.
- On certain occasions, the shadow vehicle appeared to get too close to the work vehicle. The operator had to stop and reverse the shadow vehicle to maintain a safe roll ahead distance from the work vehicle. Backing the shadow vehicle with a TTMA attached to it was noted to be challenging as keeping the trailer straight to avoid veering into the travel lane is a difficult task.

Work-site to Garage

- Challenges during this operation were similar to those observed during the travel to work-site.

What are the impediments against a more widespread use of TMA system(s)?

The availability of a crash attenuator was not noted to be an impediment to the more widespread use of the TMA system. If an ODOT HT deems that a TMA is needed, all effort is made to acquire one for the work zone, or work is scheduled at a different time to reduce risk for the workers.

In summer months, the availability of a spare dump truck was not a challenge. In winter months, when dump trucks are busy in snow and ice operations, spare truck availability and the resources to outfit the TMAs to this new truck may be an impediment for use of a TMA system.

Operational challenges and having the information to make the right judgement calls for correct choice and use of TMAs were key impediments to the operation. ODOT HTs indicated the difficulty in using a dump truck and TMA system in work zones with space limitations (ex. narrow shoulder work, left shoulder of interstates, sign-work, ramps). With the COVID-19 pandemic, and the guidance to travel to work sites in separate vehicles (to help encourage social distancing) work sites have become crowded. There may be limited space to park work vehicles, shadow vehicles and accommodate TMAs on select work sites. This makes maneuvering the TMA system in the work site an increased challenge.

Thoughts around the use of alternative shadow vehicles for TMAs in work zones

The ODOT's Hilliard Garage staff has built-up extensive experience and expertise in using dump trucks (either single axle or tandem axle) as shadow vehicles for work zone operations with TMAs. ODOT's HTs were interested to investigate the use of flat-bed dump trucks or box-trucks to attach to the TMA. However, they were unsure if these trucks met the weight rating needed for safe operation as shadow vehicles.

When asked if HTs would feel comfortable with the use of pick-up trucks as shadow vehicles, they stated:

1) The need to review vehicle weight ratings needed for TMAs,

2) Need for a review of adequate safety offered by pick-up trucks in rear-end crashes,
3) Choice of appropriate work sites with desirable characteristics (moderate speed and moderate traffic volume).

However, if both pickup trucks and dump trucks are available for use as shadow vehicles, most HTs and TMs would encourage the use of heavier vehicle for increased safety.

ODOT staff also indicated that an alternative device may be useful in stationary operations on moderate traffic volume conditions in winter months. Additionally, the vast prevalence of high-speed and high-volume roadways under the oversight of the Hilliard outpost may not be conducive to an alternative shadow vehicle. However, an alternative to the dump truck may be useful for a different demographic within the state's vast operations.

What characteristics of the dump trucks do HTs like or dislike, when being used as a shadow vehicle in TMA operation?

<u>Likeable characteristics</u>

- Experience and familiarity with the equipment.
- Versatility of the dump truck to perform multiple roles within a work zone.
- Protection offered by the heavy weight and high-power braking characteristics during the event of a crash.
- Ability to install panic-lights and emergency air-horn to alert workers.

<u>Areas of improvement</u>

- Blind spots and low rear-ward visibility for the driver.
- Maneuvering within a tightly spaced work zone with the TMA is a challenge.
- Backing the dump truck with a TMA within a work zone is a challenge.
- Backing to attach to a TTMA is difficult with no rear cameras on dump trucks.

- In the event of an impending crash, the presence of the dump truck bed occludes vision and offers limited rearward visibility to workers. This makes determining an appropriate crash response difficult for the workers.

What are the parameters that decide the decision on whether a TMA should be used in a selected work site?

The O-MUTCD Work Zone manual provides broad guidance on the use of TMAs within a typical work zone application. ODOT's HTs and TMs apply the guidance to work zones with due consideration to factors such as:

- Location of work site
- Knowledge of current traffic conditions (AADT, Vehicle Speeds etc.)
- Experience gathered during previous work conducted on selected site
- Duration of work zone
- Nature of operation – Emergency maintenance, planned maintenance etc.

Is adequate guidance and information available to position (lateral and longitudinal) the shadow vehicle safely in a work zone?

In moving operations, ODOT's HTs do not face challenges in laterally positioning the shadow vehicle in appropriate lane behind the work vehicle. Longitudinal position is performed based on visual estimates of adherence to safe following gap (based on roll-ahead distance) of TMA system. ODOT HTs make best possible effort to maintain the safe following gap, while adapting to roadway features such as vertical curves or horizontal curves. In static work zones the challenges to positioning the shadow vehicle are lower and are primarily based on lack of space for maneuvers.

Other notes and considerations for the use of a replacement shadow vehicle

Some specific work zone use cases and operating conditions may be more conducive to the use of a replacement shadow vehicle:

- Use cases
    - Static work zones
    - Work zones with width limitations (narrow shoulders, bridge decks, ramps)
    - Work zones with lack of space to safely maneuver dump trucks
- Operating Conditions –
    - Medium traffic speed and moderate traffic volume operations
    - Winter months when dump trucks are busy with snow and ice operations
    - Summer months in counties with lack of spare/dedicated dump trucks

The alternate device should be designed to provide appropriate positive impact protection. Additionally, enough information needs to be provided to enable HTs and TMs make correct choice for their use in applicable work zones.

11. Appendix E – Market Review

11.1. Proposed Concepts for the Alternative Device

11.1.1. Concept C1 – Upgraded Mobile Vehicle

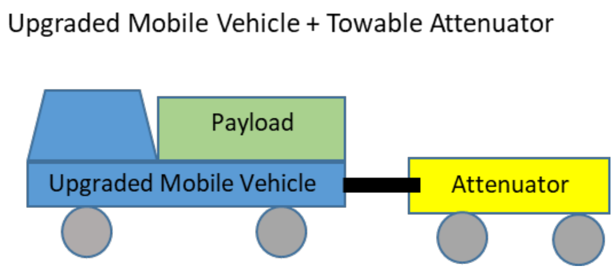


Figure 26 - Concept C1 sketch

The upgraded mobile vehicle concept (Figure 26) would involve replacing the dump truck with a smaller vehicle (alternative device or just "*device*") deemed fit to provide the required positive protection. The impact handling capacity of this vehicle may be enhanced by adding the required payload on the vehicle such that it provides necessary positive protection in a work zone. The operator would drive the vehicle to the worksite, and once it is stationed correctly, the device is imagined to work without the need for a driver, in both static and mobile/moving work zones. A remote operator may need to monitor the device for safety.

The existing market technologies like leader-follower concepts, maneuvering or steering and driving robots, can be utilized to enable the upgraded mobile vehicle to maneuver with partial autonomy. The safety of the vehicle could be enhanced by using sensing and actuation technologies that emulate features similar to automatic emergency braking, blind spot warning, rear impact warnings. These technologies can help the vehicle to perceive the environment, decide, and perform necessary control actions and mitigate any impending impacts. The visual and audible warnings provided by these sensors may be used to warn the workers in the work zone as well as the motorists of any potential harm.

11.1.2. Introduction to Concept C2 – Mobile Remote Platform

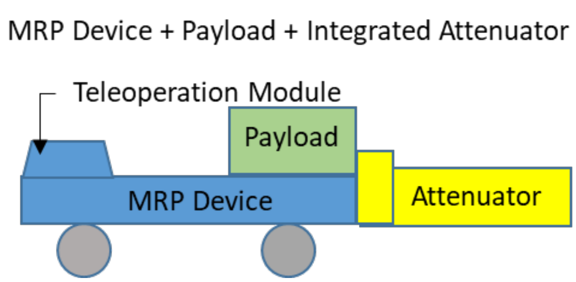


Figure 27 - Concept C2 sketch

The Mobile Remote Platform (MRP) (Figure 27) can be envisioned to be a towing device, which can be utilized to carry an attenuator attached to it. The MRP device is expected to be maneuvered by a remote operator within in the work zone. It is envisioned that such a device would be driven/towed to the work zone using other vehicles and then the mounted crash attenuator would be deployed at the worksite. The platform should have the ability to have the attenuator detached, removed, and replaced. The attenuator is not a permanent piece of the platform. The minimum payload needed for appropriate positive protection of workers in case of a crash should be offered by the MRP device.

The MRP device is envisioned to maneuver at the work zone through remote operation. It is likely that such a concept may need an operator who would interact with the MRP device by the means of a teleoperation module. This module would have the user interface, which would give the operator the ability to obtain the current position of the platform and options to control the maneuvering of the platform. The software and hardware required to achieve remote maneuvering may be customized to achieve the operability and controllability requirements listed in this document.

11.2. Intended functionality of the alternative vehicle

The shadow vehicle plays multiple roles in the Work Zone life-cycle. Currently ODOT uses dump trucks to perform the role of the shadow vehicle in designated Work Zones. Figure 3 outlines the lifecycle of the use of dump truck in the Work Zone operation. The figure outlines the various roles performed by the dump truck during the origination, setup, and tear-down of the Work Zone.

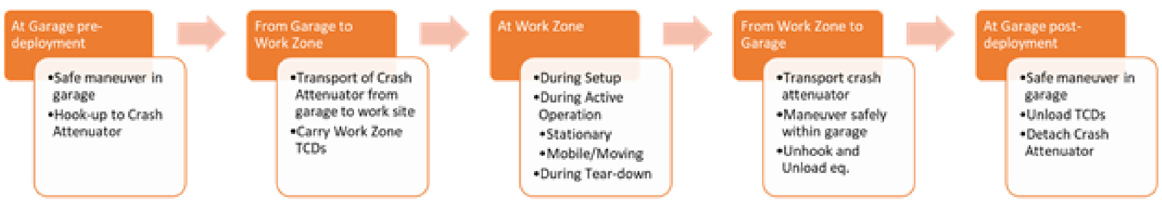


Figure 28 - Analysis of dump truck's functions through the Work Zone lifecycle

It is recognized that dump truck performs various roles throughout the various phases of the Work Zone. Analysis of these roles performed will help build the foundation for development of functional specifications. An attempt is made to categorize the roles performed by the dump truck in each phase of the Work Zone into appropriate functional categories. Table 18 outlines an assessment of these roles.

Table 18 - Functional Categorization of roles of dump truck through Work Zone lifecycle

Phase	Function / Role	Functional Category
At Garage Pre-Deployment	Safely maneuver in the garage (tight-spaces)	Maneuver
	Attach to crash attenuator	Mechanical
	Load Work Zone TCDs	Payload
From Garage to Work Zone	Transport crash attenuator to work site	Maneuver
	Carry Work Zone TCDs to work site	Payload

At Work Zone – During Setup	Enable setup of TCDs	Maneuver
	Maneuver within Work Zone	Maneuver
	Establish safe distance from work site	Positive Protection
	Deploy Crash Attenuator	Positive Protection / Mechanical
At Work Zone – During Active Operation	Turn-on warning signs	Electronics/Warning
	Maintain safe distance from work site (in mobile/moving or stationary operations)	Positive Protection
	Provide positive protection to workers from traffic	Positive Protection
At Work Zone - During Teardown	Pickup / Hook-up Crash Attenuator	Mechanical, Payload
	Turn-off warning signs	Electronics
	Enable pick-up and loading of TCDs	Payload, Maneuver
	Maneuver within Work Zone	Maneuver
From Work Zone to Garage	Transport crash attenuator to Garage	Maneuver
	Carry/Tow a payload of TCDs from work site	Payload
At Garage Post-Deployment	Unload TCDs	Payload
	Detach crash attenuator	Mechanical
	Safely maneuver in garage (tight-spaces)	Maneuver

11.3. An Overview of Categories of Functional Requirements

The functional specifications can be broadly classified into following categories:

1. General requirements:

The general requirements section specifies the functions, which need to be performed by the alternative device to replace the dump truck in order to satisfy the payload conditions, attaching and working conditions for attenuator, visibility and monitoring conditions, operating conditions for maneuvering on the roads.

2. Pre-deployment and post-deployment at the garage

These functional specifications provide a guideline for the alternative vehicle to safely maneuver from garage to the work zone and vice versa. It also specifies the conditions for secure mounting of the adapter onto the vehicle to facilitate the attachment and detachment of the attenuator.

3. Operability

This section describes the modes under which the alternative device is expected to operate. Three modes are proposed; human driven, stationary protection, and low-speed autonomy. The conditions under which the vehicle travel to and from the garage to the work zone is described in the maneuverability sub section. The maneuvering of the vehicle within the work zone in either stationary protection, low-speed autonomy is included in the controllability sub section. Within the work zone the vehicle operation can be controlled manually, autonomously, or semi autonomously through the teleoperation module.

4. Crash prevention

Crash prevention section describes the requirements concerning the speed of operation, tight space maneuvers, personnel in the vicinity etc. in order to avoid the crashes.

5. Crash sensing

This section describes the different functions, which the technology should meet for the vehicle sensing and work zone monitoring. It also describes the functions, which the alternative device must fulfill in order to warn the workers or to mitigate the crash, one an impending crash is sensed.

6. Crash Protection

The Crash Protection section provides requirements that outline the expected behavior of an alternative device when a motor vehicle crash is imminent or in the moments just after a crash has occurred. The focus of these requirements is on outlining actions to be taken by the device in order to prevent a roll-ahead crash with workers in the work zone. Additional requirements on warning and alerts are also presented here.

7. Post-Crash requirements

The Post-Crash requirements focus on outlining the expectations on an alternative device after a crash event. These relate to the ease of cleanup and removal of the device from an active Work Zone post a crash.

11.4. Interim Market Review Findings

TRC Inc. performed preliminary market review to identify vendors and candidate solutions that may satisfy ODOT's needs. This review was performed for both Concepts C1 – The Upgraded Mobile Vehicle, and Concept C2 – The Mobile Remote Platform.

The findings from this review and types of technologies, which may satisfy ODOT's needs are listed in tables below.

Table 19 - Interim Market Review for technologies that may enable implementation of Concept C1

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	**Product / Ref**	**Vendor**	**Description**
Crash Sensing and Warning, Crash Protection	Sense impacts	Radar Sensors	-	Volvo	3 radar sensors in rear bumper. Integrated to sense crashes. Available on select Volvo cars and has some limitations.
		Rear facing Camera	VIATech Mobile360 ADAS	VIATech	Watches the scene, informs driver of collision (how?). Unclear if this needs more inputs from vehicle CAN bus.
		Radar Sensors	-	Mercedes Benz Pre-Safe Plus	Similar to Volvo's operation.
		Ultrasonics	TailGUARD	WABCO	Rear-backing technology. Not directly related
	Sense intrusion into a work-zone	Rear facing Camera	Work Zone Intrusion Alarm System	Bosch	Rear facing camera mounted on a trailer. Calibrated to provide knowledge of work zone boundaries. Detects intrusion by vehicles using machine vision technology.
			WANCO ITS Collaboration	WANCO Trailers	More products possible in the ITS Domain that can help
			Portable Camera Systems	QLynxCam	They may have some camera-based monitoring systems.
	Blind spot detection system	Blind spot detection system	Radar Blind Spot System with Cross	BrandMotion	Brandmotion's radar-based system works with any

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	Product / Ref	Vendor	Description
			Traffic Detection RDBS-1500		vehicle with plastic fascia and offers the only system based on automaker-validated original equipment components
		Blind spot detection system	Dual Camera Blind Spot Monitoring System with Smart Switcher for Display Radios 9002-2904V2	BrandMotion	This system uses two cameras, mounted under your outside rearview mirrors, to watch your vehicle's blind spot areas. When you turn on your turn signal, the image from the camera on that side of your vehicle activates your display screen, and you get an instant picture of what's in your blind spot
	Roll-ahead crash prevention	Automatic emergency braking	-	Bosch, Bendix, Detroit Assurance, Continental AG, Delphi, ZF-TRW, Autoliv, Mobileye	These denote typical AEB suppliers for both passenger vehicles and commercial motor vehicles. These may be reached out to develop a camera and radar based AEB systems if the host vehicle does not have in-built capabilities.
Operability – Maneuverability and Controllability	Maneuverability Control	Steering robots	SSP3000	Stahle	High - dynamic steering system for computer controlled steering of vehicles. Application for steer dynamic and vehicle

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	Product / Ref	Vendor	Description
					dynamic tests and legal handling tests
		-	Nav	ASI	NAV is a system of robotic components that installs easily into any vehicle platform, converting it from manual to robotic control, by using by-wire, mechanical, and hydraulic modules to accommodate for different vehicle types
		-	-	SEA Limited	ATD Automated Test Driver product may provide insights
		Brake robots/driving robots	CBAR, BR, AR Pedal robots	AB Dynamics	AB Dynamics products may facilitate throttle, brake, and steering.
	Shadow vehicle should follow vehicles in front/GPS autonomously	Multi-Platform Appliqué Kit (M-PAK).	Multi-Platform Appliqué Kit (M-PAK).	Kratos	The ATMA system features component redundancy, an active safety system, high accuracy GPS/GPS-Denied navigation, encrypted V2V communications, multi-modal front and side-view obstacle detection, and a robust User Interface providing system feedback, situational awareness, multi-camera views, and operator controls

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	Product / Ref	Vendor	Description
		Implementation	ATMA	Royal Trucking	Implementation of Kratos Technology with Royal Trucking
Crash Prevention	Smart Dynamic Messaging Signs	GPS, Pedestrian 2 Infrastructure	Wearable GPS Receivers	MnDOT Research Project	Wearable GPS sensor communicates position to Dynamic Message Sign to alert motorists
	Low-speed Nuisance Hits	Blind Spot, AEB, Ultrasonic Sensor, Radar based technologies	Various Products	Various Suppliers	Various suppliers discussed in the Crash Protection and Crash Sensing section above
	Arrow Boards	Electrical/Electronic Interface	Arrow Boards	WANCO	ODOT Work Zone Best Practices
General Vehicle, Payload, Ballast and Other Requirements	General Vehicle	-	-	-	To be determined by device supplier
	Ballast	-	-	-	To be determined by device supplier
	Secure Attachment Requirements	-	-	-	As recommended by FMCSA and/or FHWA, or ODOT's best practices

Table 20 - Interim Market Review for additional technologies that may enable implementation of Concept C2

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	**Product / Ref**	**Vendor**	**Description**
Operability	Platform	Electric, Tow-Tractor, 24v system, 18mile range	E-451	Polaris (Taylor-Dunn)	10000 lbs. payload capacity
		Electric, Tow-Tractor, 36v system, 18mile range	E-457	-	15000 lbs. payload capacity
		Electric, Tow-Tractor, 48v system, 30mile range	C-425	-	15000 lbs. payload capacity
		Electric, Tow-Tractor, 36v system, 18mile range	TT-316	-	16000 lbs. payload capacity
		Gas/LPG powered vehicles	TC-50E, TC-30/50C, TC-30/60, TC-80/120	-	Higher Payload Gas Options Exist
		Electric, Warehouse, Camera/Lidar	P-MATIC	Linde	11000 lbs. payload capacity
		Autonomous Tractor, Logistics, Factories, Full-sized wheels;	TractEasy	EasyMile	-
		Platform maybe used and adapted to our needs	Core Tow Tractor Automated Forklift	Toyota Forklisfts	10000 lbs. payload capacity
		Warehouse logistics, Mapped environments	Palion Tow Tractor	Seegrid	10000 lbs. payload capacity

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	Product / Ref	Vendor	Description
		Logistics industry	Tugger	Vecna Robotics	10000 lbs. payload capacity
	Teleoperation	Vehicle agnostic, integrable, teleoperation platform, 4G/LTE Network	-	Phantom Auto	Uses your existing network infrastructure—4G LTE, WiFi, 5G, and more—to securely stream between widely-distributed nodes using reliable, secure protocols and enterprise-friendly APIs Vehicle-agnostic software integrates with all types of vehicles to drive multi-fleet efficiencies
		Integrate with vehicle, High resolution cameras, sensor, control units	Driver Station Hardware and Software Kit	Designated driver from Autonomous Stuff	The hardware includes a sensor suite, compute platform, communication platform and passenger compartment for teleoperation. The in-vehicle software connects with the remote Driver Station.
		Steer Remote Control Product, GPS, Radar, Monitoring Screens.	-	Steer	N/A
		Competitive technology	-	Ottopia	N/A
		Vendor for Teleoperation Platform. Works on cellular networks.	-	DriveU.auto	Connectivity platform provides 4k video, audio, data and control commands with very low latency and

Functional Category	Technical Function	Candidate Solution Information			
		Technology Keywords	Product / Ref	Vendor	Description
					ultra-high reliability, using cellular bonding and dynamic encoding. Dynamic video encoding and cellular bonding, and supports 4G and 5G technologies. This includes the ability to switch between the network technologies, preferring the better performing network in different locations.

12. Appendix F - Request for Information (RFI)

A RFI was used to obtain feedback from candidate vendors on proposed concepts and their functional requirements. The RFI document is copied here as-is for reference.

Introduction

The Ohio Department of Transportation (ODOT) has sponsored a research project PID 111462, SJN 136137 *"Design of an Alternative Work Zone Attenuator Device"* to investigate if dump trucks can be substituted with an alternative device, while still maintaining the necessary crash protection in Work Zones.

Transportation Research Center Inc. (TRC Inc.) is the sole contractor for this research project. TRC Inc. is North America's most advanced, independent mobility testing service provider, fulfilling the complex engineering, research, evaluation and testing needs of the world's leading transportation companies for over 45 years.

This document is a Request for Information (RFI) regarding the project, and does not constitute a commitment, implied or otherwise, that the Ohio Department of Transportation or TRC Inc. will take procurement action in this matter. This RFI will not be used to make a vendor selection. Participation in the RFI is not a prerequisite for bidding on a Request for Proposals (RFP) solicitations, which may arise in the future.

The purpose of this Request for Information (RFI) is to solicit feedback and input from consultants, vendors, and technology integrators, on the feasibility of developing solutions that can meet ODOT's identified needs. The RFI is hosted by TRC Inc. to protect vendor supplied trade secret data from public release, as information marked as such by vendors will be aggregated to generate insights. TRC Inc. will package these aggregate insights to help ODOT determine market readiness, challenges, and determine viability of proposed concepts.

The public comment period is for three weeks between 08/11/2021 – 09/01/2021. Responses are due by 5:00 PM EST on 09/01/2021.

Project Background

The Alternative Device will be designed to perform the role of a dump truck when used as a shadow vehicle in work zone operations. In focus are those operational scenarios in which a crash attenuator is attached to an existing dump truck to offer positive protection to work crew.

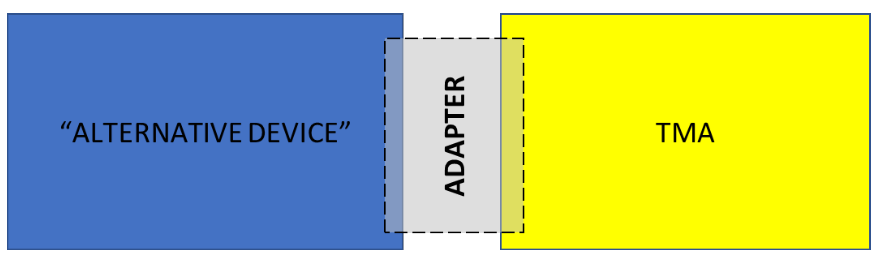


Figure 29 - Concept sketch of Alternative Work Zone Attenuator Device

Figure 29 outlines the envisioned Truck Mounted Attenuator (TMA) system. The term TMA system is used to refer to the combined alternative device, adapter (if needed), and crash attenuator assembly that will be deployed in work zones.

The research project thus far, has investigated ODOT's needs, evaluated use-cases, and developed a preliminary understanding of the Concept of Operations for such an alternative device. Furthermore, the research team has identified and developed two concepts for the alternative device, which perform functions that replace dump trucks in Work Zones. Functional requirements for both concepts were developed.

- Concept C1 – Upgraded Mobile Vehicle
- Concept C2 – Mobile Remote Platform

The prime focus of the developed concepts is to improve work zone safety by implementing technologies that:

- Remove the human operator from shadow vehicles
- Maintain safety for errant vehicle occupants that crash into shadow vehicles
- Maintain crash protection for workers in the work zone
- Provide workers advance warning of likely crash events
- Reduce dump-truck maintenance and repair costs and maintain high uptime to support mission critical snow-and-ice operations.

Target Audience for the RFI

The research team recognizes that a wide array of technologies may be used to satisfy the functional requirements developed for concepts C1 and C2. While some off-the-shelf products may exist, it is likely that these individual products and technologies may need to be customized and adapted. It is also likely that significant features are achieved by integration of individual technologies (ex. sensors, intelligence) to meet ODOT's needs.

TRC Inc. welcomes interest and responses from a broad set of vendors and technology integrators that can provide solutions that may satisfy listed needs. The goal of such feedback is to understand market's capabilities, direction, interest, and refine listed needs with market-driven technical capabilities that are available today and may become available in the near future (1-3 years).

The functional requirements touch on many technology domains, and may interest vendors and technology integrators in broad areas, including but not limited to:

- Vehicle manufacturers
- Movable platform manufacturers in logistics, warehouse, and those operating in other controlled environments like factories for specialized tasks
- Tier 1 suppliers interested in development of integrated and aftermarket ADAS features
- Integrators involved in enabling teleoperation, and driverless operation using custom sensing, communication, and control devices and technologies
- OEMs involved in Work Zone ITS and crash prevention domain
- OEMs involved in crash sensing and warning technology development
- OEMs involved in development of motorist crash protection devices such as, Truck or Trailer Mounted Attenuators

It is not expected that a sole vendor shall provide a solution that satisfies all functional requirements listed in the concepts. Feedback and information from sources or vendors whose solutions may satisfy requirements in a single domain area (for ex. crash sensing) either fully or partially, is also welcomed.

RFI Confidentiality and Use of Information

By submitting a response, each Respondent agrees that it will not bring any claim or have any cause of action against TRC Inc., its employees, subsidiaries, successors, and assigns based on any misunderstanding concerning the information provided or concerning TRC Inc.'s failure, negligent or otherwise, to provide the Respondent with pertinent information as intended by this RFI. Information submitted in response to this RFI will become property of TRC Inc. and will be managed based on policies listed below. TRC Inc. will not pay for any information herein requested nor is it liable for any cost incurred by the respondent.

Policies that govern management of "Trade Secret" information:

All Respondents must judiciously consider the sharing of any information that the Respondent considers to be a "trade secret", according to how that term is defined in Section 1333.61(D) of the Ohio Revised Code. If any information in the RFI is to be treated as a trade secret, the respondent must:

- Identify each and every occurrence of the information within the RFI with an asterisk before and after each line containing trade secret information and underline the trade secret information itself.
- Check the "This RFI response DOES include information considered a 'trade secret'" box on the Cover Page of your Response in the appropriate format specified in instructions below.
- Include a page immediately after the Respondent Information Page that lists each page in the RFI that includes trade secret information and the number of occurrences of trade secret information on that page.

Who will manage this information and how?

All data shall be submitted by the Respondents per instructions in the RFI. TRC Inc.'s research project Principal Investigator (PI) and a designated research team will handle submitted data and any correspondence with vendors. Any electronic data submitted will be stored on TRC Inc.'s servers during the duration of the research project. The data will be accessed in a controlled manner by the designated research team for data analysis, market review, and generation of aggregate insights.

How will the shared information be used?

Qualitative and quantitative data from respondents will be used to generate market insights. For information NOT marked "trade-secret" per instructions listed above:

- TRC Inc. reserves the right to share information as-is or after appropriate data analysis and categorization is performed to meet market review goals.
- Product name, technology information, and company identifier information will be retained and shared as-is in the market review, if appropriate.

- Any feedback about listed specifications and concepts will also be shared as-is, if appropriate.

For information marked "trade-secret":

- Qualitative and quantitative data will be reviewed, and aggregated. Product, technology, and solution information will be generalized to develop an understanding of the market's readiness.
- Before data aggregation, contact information may be used to gather clarifications about a response, or to solicit additional feedback if deemed necessary.
- When aggregate insights are shared, all identifier information (contact information, organization name etc.) will be removed.
- Any feedback about listed specifications that is marked "trade-secret", will also be de-identified and aggregated to the extent possible.

The TRC Inc. research team will package both non "trade-secret" information (as-is) and "trade-secret" information (in aggregate form) as insights to help ODOT assess market readiness, challenges, and determine viability of proposed concepts. This information will be packaged as a part of the final report for the ODOT sponsored research program. This report, and the market review information will be publicly available. The final research report is planned to be published by 03/05/2022.

What will happen to respondent data on completion of research program?

TRC Inc. will erase all raw data, and contact information submitted by respondents on completion of the research program.

Instructions for Responses and Feedback

12.1. RFI Procedure

Responses to this RFI should utilize the template in the RFI Questionnaire section. All responses must be emailed as a single PDF document with an attachment size lower than 20 MB) to:

"RFI - TRC Inc."

requestforinfo@trcpg.com

The subject of a response email shall be titled "RFI-Response".

The public comment period is for three weeks between 08/11/2021 – 09/01/2021. Responses are due by 5:00 PM EST on 09/01/2021.

12.2. RFI Questionnaire

Interested parties are requested to complete a review of the RFI and attached functional specifications for Concept C1 and Concept C2. Please respond to both questions A and B, and one or more questions C through E, in formats described below.

A. Respondent Information: Please fill out the information on page 1 of this RFI.

B. Notification of presence of trade secret information on cover page of response per question listed on page 1 of this RFI, and instructions listed in Sec 4.0

C. Response that outlines general product/technology information
    a. Name of the proposed solution (Product/Technology/Feature)
    b. Which domain(s) of functional requirement(s) is the proposed solution designed to serve?
    c. How does the proposed solution address functional requirements identified in domain(s) listed above?
    d. Pricing information (if available)

D. Response outlining solutions that satisfy specific functional requirements
    a. Reference to specific requirement(s)
        i. Concept: (C1/C2/Both)
        ii. Section No.: (Ex. Sec 2.3)
        iii. Requirement and Sub-part No.: (Ex. Item 1 Subpart a.1)
    b. Name of the proposed solution (Product/Technology/Feature)
    c. Relevant information that describes the proposed solution's capability and methods used to satisfy requirement(s) identified above.
    d. Product Maturity and Readiness.
    e. Challenges
        i. Development of features to satisfy requirements
        ii. Operational challenges for end-users in diverse environments
    f. Pricing Information (if available)

E. Response targeted to refine proposed functional requirements:
    a. Reference to specific Requirement(s)
        i. Concept: (C1/C2/Both)
        ii. Section No.: (Ex. Sec 2.3)
        iii. Requirement and Sub-part No.: (Ex. Item 1 Subpart a.1)
    b. Descriptive feedback on proposed requirements, can be of the type:
        i. Scope/Coverage
        ii. Degree of specificity
        iii. Feasibility of implementation

A response may contain multiple instances of items C, D, and E. Additionally, targeted product information brochures may be submitted if deemed relevant. All information shall be packaged into one PDF file before submission.

Based on the level of trade-secret information shared or that, which is planned to be shared in response to the RFI, a respondent may choose to contact TRC Inc. to request additional accommodations. TRC Inc. staff will review these requests in collaboration with ODOT, to offer the respondent an information exchange path that may satisfy the RFI's broad goals, and market readiness assessment needs. One potential accommodation that could be offered to select respondents may be a teleconference.

12.3. Questions about the RFI

Questions about this RFI can be emailed to:

"RFI - TRC Inc."

requestforinfo@trcpg.com

The subject of a question email shall be titled "RFI-Questions".

13. Appendix G - Market Feedback via the RFI Mechanism

13.1. Market, Vendor, and Technical Solution Overview

The RFI received nine responses from vendors. Most vendors proposed technology that operationalized Concept C1. The responses explored a variety of technological solutions that can be potentially used to meet ODOT's posted functional requirements. Based on the feedback received from vendors, the Concept C1 – Upgraded Mobile Vehicle can be implemented using two broad distinctive technologies:

- Leader/Follower Autonomy with Electro-Mechanical Actuators
- Leader/Follower Autonomy with a Drive-by-Wire Kit

These implementations enable the alternative device to meet fundamental requirements that allow the device to maneuver, operate, and carry a TMA in a Work Zone. Additional options and upgrades will enable the device to perform advanced Crash Sensing, Protection, Prevention, Navigation Assist, and Traffic Monitoring and Awareness features. Key highlights of the proposed implementations are presented in Table 21 to answer some fundamental questions about the concepts.

Table 21 - Key highlights of proposed technology implementations

Key Highlights	Leader-Follower Autonomy with Electro-Mechanical Actuators	Leader-Follower Autonomy with Drive-by-Wire Kit
What was the type of alternative device vehicle platform suggested?	Vehicle choice neutral as long as Steering, Gas, Brake available. Kratos/Royal Trucking leans towards the use of HD trucks as they offer high ballast, braking, and many optional features	Dataspeed Inc.: Proposed the use of a production Ford F-450 Chassis Cab XL
What considerations should be made for ensuring adequate and safe ballast?	Kratos/Royal Trucking: Engineer certified concrete poured into ballast chambers. This technique maintains body-	Dataspeed Inc.: Proposed the use of a flat-bed for ballast and TMA connector.

Key Highlights	Leader-Follower Autonomy with Electro-Mechanical Actuators	Leader-Follower Autonomy with Drive-by-Wire Kit
	balance, provides additional safety by reducing risk of projectile. Not a lot of commentary from other vendors, but an acknowledgement that choice of vehicle will determine GVW rating.	
In the Autonomous Stack		
How is the leader perceived?	Kratos/Royal Trucking: Based on GPS information coupled with front and side obstacle detection. AB-Dynamics: Bespoke retrofittable automated driving solution with intelligent leader-follower capability based on GNSS corrected Inertial Navigation Units. Added object detection capability. SEA: A real-time control system “Automated Test Driver” coupled with vision systems and radar, coupled with added object detection sensors. Geo-fencing achieved by dGPS, when available.	Dataspeed Inc.: Perceived by the Automated Driving System using LiDAR and Cameras.
How is the navigation information communicated between leader/follower?	Kratos/Royal Trucking: Vehicle-Vehicle Communications Link AB-Dynamics: Vehicle-Vehicle Meshing IP Radio communicates position data to synchronize motion to emulate platooning. SEA: Path following trained by vision detection. No navigation communication link needed.	Dataspeed Inc.: Not true leader/follower, but more limited automated driving system tuned for work zone navigation needs
How is the path of follower planned?	Kratos/Royal Trucking: Smart path planner monitors leader’s motion. AB-Dynamics: Intelligent leader-follower, controls spacing and headway of an emulated platoon	Dataspeed Inc.: Planned by the Automated Driving System and includes Object Detection.

Key Highlights	Leader-Follower Autonomy with Electro-Mechanical Actuators	Leader-Follower Autonomy with Drive-by-Wire Kit
	SEA: Vision based detection drives path-planning and path-follow.	
How can some of the Advanced Crash Protection and Prevention Features be included in the proposed implementations?	Kratos/Royal Trucking - Front view RADAR and LIDAR Sensors SEA - Camera / Machine vision based forward crash detection AB-Dynamics - Bespoke sensing devices and software for the application Dataspeed Inc. - Achieved via object detection and avoidance features of the Automated Driving System Brandmotion - V2X (OBU) Based Solutions that can inform operator or AD system. Can provide an in-vehicle HMI Integration, which allows for display of warning for a Camera/Radar based Forward Collision Detection feature. VIATech - D700 A.I dashcam for forward collision warning detection. Some more products with fused camera, radar, and ultrasonic sensors.	
What are some of the ways in which Crash Sensing and Prediction features could be implemented?	Kratos / Royal Trucking: Rear facing LiDAR and RADAR Sensors SEA - Radar and accelerometers Dataspeed - Use of redundant and independent sensors - LiDAR, RADAR, GPS, IMU etc. Bosch - Radar based technology needs access to vehicle CAN Bus. MH Corbin - Camera based Connect:ITS Detection Technology VIATech - M810 Mining Kit with Camera and sensor fusion using RADAR and Ultrasonics to detect objects in proximity of vehicle. Similar M500 Forklift Safety System for lower speeds.	
How can Navigation Assist Features be incorporated?	Use of Ultrasonics, RADAR, and 360° Surround View Systems.	
What Traffic Monitoring and Awareness Features exist in the market?	Radar and Camera (Live Recording) to monitor traffic flow conditions, inform motorists, and increase awareness.	

13.2. Packaging Vendor Technology into ODOT Options

The goal of this section is to present a set of easily digestible alternative device options that may be proposed to meet ODOT's needs. To satisfy this goal, an attempt is made to package feedback received from vendors into simple to digest options for ODOT's use. These options are presented in a "Buyer's Options" format, similar to a car-buying experience. The options presented below in many cases are a hypothetical fusion of technology solutions integrated from multiple vendors.

Type of Feature	Sub Category	Economy	Midsize	Premium
Base Vehicle	Vehicle	Existing ODOT Non Dump Truck	New ODOT Non-Dump Truck	New Truck with all Options
	Leader/Follower Perception	GPS Tracking + V2V Communication	GPS Tracking + V2V Communication	GPS Tracking + V2V Communication
	Leader/Follower Actuation	BTR + Steer Robot	BTR + Steer + Trailer Brake	BTR + Steer + Parking&Trailer Brake Robot
Standard Features	Crash Prevention - Visibility	Make Truck Visible	Make Truck Visible	Make Truck Visible
	Detect Hit	Contact Sensors and Accelerometers	Contact Sensors and Accelerometers	Contact Sensors and Accelerometers
	Warn	Hazard Lights and Siren	Hazard Lights, Siren, Warn through remote operator unit	Hazard Lights, Siren, Warn through remote operator unit, and Wearable Devices
	Act	Hit Brakes - Truck only	Hit brakes - Truck + Trailer	Hit Brakes - Truck (airbrake) + Trailer
	Payload	12,000 lbs	16,000 lbs	16,000 - 20,000 lbs
	TMA	Either type	Either type	Either type
Advanced Crash Protection Features	Advanced Forward Crash Protection Features	None	Keep Object Detection and Active Braking	Keep Object Detection, Active Braking, and Avoidance Active
Crash Prediction Features	Rear Crash Sensing Feature	None	With Camera and RADAR	With Camera, Radar, Lidar, and V2X Technology
	Side-Crash Sensing Feature	None	With Just RADAR or LIDAR	With RADAR, LiDAR, and Blind-Spot Monitoring Features
Traffic Monitoring and Awareness Features	Traffic Awareness Display	None	RADAR Speed	RADAR Speed, DMS Speed Display, Live Recording
Navigation Assist Features	Operator navigation assist	None	Backup Camera, Ultrasonics	Backup, Ultrasonics, Birds-eye-view

Figure 30 - Vendor proposed technologies for Concept C1 packaged into implementations presented as hypothetical ODOT Buyer Options

While the information above is presented using one type of leader/follower system of the base vehicle, the following alternatives are available

Table 22 - Leader/Follower Technology Options based on vendor feedback

Leader/Follower Perception	GPS Tracking + V2V Communication	GPS Tracking + V2V Communication	Camera/Vision based follower	Camera/Vision based follower	Limited In-Work Zone Automated Driving System
Leader/Follower Actuation	BTR + Steer Robot	BTR + Steer Robot + Parking & Trailer Brake Robot	BTR + Steer Robot	BTR + Steer Robot + Parking & Trailer Brake Robot	Drive-by-Wire Kit

13.3. Vendor Technology Briefs and Implementation Feedback

13.3.1. Kratos and Royal Trucking

Technology Brief

Proposed product:	Autonomous Truck Mounted Attenuator (ATMA)

Kratos and Royal Trucking appear to have the most field proven technology for enabling Concept C1 and its functional requirements. The product offered to satisfy ODOT's listed requirements is an Autonomous Truck Mounted Attenuator (ATMA) retrofit kit solution.

There have been nine ATMA systems deployed across US and England on a wide variety of platforms. Kratos/Royal Trucking appears to be flexible in adapting to ODOT's platform needs. It appears that the system has been refined using a significant amount of feedback from multiple State DOTs, industry stakeholders, and highway maintenance contractors from around the world. Advanced features include system redundancy, cybersecurity hardening, user interfaces, and multi-modal safety systems.

Figure 31 - ATMA Systems under Operation

The retrofit kit can be integrated on existing Ohio DOT fleet vehicles and is a vehicle agnostic system. The focus of an existing ATMA system is on enabling maneuverability, additional Crash Sensing and Warning elements can also be developed in collaboration with ODOT's needs.

Figure 32 - ATMA User Interface and V2V Communications between Leader/Follower.

Proposed Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Section 2.1 – General Requirements

Kratos outlined that functional requirements listed in Sec 2.1 can be listed by adapting their leader/follower retrofit kit to a wide variety of host vehicles, deemed suitable by ODOT. Following specific comments were made:

- For a vehicle chosen by ODOT, the Minimum Total Gross Vehicle Weight (GVW) of a vehicle in this configuration to include; truck chassis, body, ballast, arrow board, attenuator, and all other equipment is 20,000lbs.
- The GVW can be adjusted up/down accordingly with ballast and/or equipment addition/removal.
- The Royal Truck's Heavy-Duty truck body design includes engineer-certified ballast chambers for embedding concrete counterweight. This ballasting technique reduces liability by eliminating the possibility of a dangerous projectile in an impact, as opposed to deck-mounted counterweights.
- The trucks provided by Royal offer high visibility through the windshield and minimal blind spots to the human operator during manual driving.
- Typically, the visibility of truck solution is outfitted for high visibility size, paint, and lighting systems.
- The installation of a Kratos Leader/Follower kit does not impair a human driver's ability to operate in manual driving-mode.

Section 2.2 – Pre-Deployment and Post-Deployment Functions

Kratos and Royal Trucking notes that their Leader/Follower kit is routinely used in conjunction with Royal TMA's vehicles. This combination has offered:

- The ability to connect with MASH approved attenuators – TrafFix Devices Inc. Scorpion or Verdegro Blade.
- The trucks come equipped with all the mechanical, electrical, and electronic interfaces needed to attach the TMA mechanically and electrically.
- For attachment with TrafFix Devices attenuators a "TMA Fast-Track SwiftConnect" mechanism is used.
- Visual inspection methods are used to verify mechanical interlocks.

Section 2.3 -Operability

The ATMA product proposed by Kratos and Royal Trucking offers capabilities that satisfy requirements listed in the operability mode:

- The ATMA offers three operational modes that include:
    - Human-Driven Manual Mode
    - Stationary Mode
    - Low-Speed Autonomy Mode capable of driving up to 20mph.
- The speed limit (20mph) of the "Low-speed Autonomy" mode can be adjusted up or down as a factory setting per ODOT's needs. This limit is not user adjustable but defined by Kratos staff in a factory setting.

Section 2.3.1 - Maneuverability

The requirements listed in maneuverability section of the concept can be satisfied using the ATMA. Following specific comments were made:

- The ATMA device is integrated on trucks that are easily maneuverable in tight spaces by a human driver.
- The system is fully disengaged in human-driven mode and offers no resistance to the human driver. This allows for transport to/from the worksite at roadway speeds.
- The feature, which allows for measurement of gap distance between the leader and follower vehicle has been integrated in the ATMA system and its user interface:
    - The feature operates on GPS positioning.
    - The user interface is typically located in the cab of leader vehicle.
    - Both actual gap distance and commanded gap distance are visible to the operator.

Section 2.3.2 - Controllability

The ATMA device satisfies most functional requirements listed in the Sec 2.3. Specific comments are listed below:

- A human operator can easily switch the device from human-driven mode to autonomous operation using the designed Operator Control Unit. Four switching conditions are offered:
  - GO – Use in autonomous mode
  - IDLE – Operator takes on temporary manual control
  - OFF – Turns off the system
  - A-STOP Mode
- When in stationary mode the system will:
  - Maintain a straight wheel angle at any time
  - Continue to perform functions listed in Crash Prevention, Crash Protection, and Crash Sensing, if the option is exercised.
- When in the “Low-speed Autonomy” mode the system:
  - Does not require the presence of a human operator in the driving seat or inside the device at any time.
  - However, if desired, a person can ride along in the ATMA while in autonomous mode and take over manual driving control at any time.
  - Speed is limited to 20mph when operating in autonomous mode. However, this limit can be adjusted per ODOT’s needs in a factory setting by Kratos.
  - Can carry a TMA through the work zone in both attached and trailer towed fashion
  - Offers user adjustable vehicle-to-vehicle gap and lateral left/right offset control
  - Will have all obstacle detection and safety features active during operation
  - Will continue to perform functions presented in the Crash Prevention, Crash Protection, as well as Crash Sensing if the option is exercised.
- A wide variety of monitoring functions are enabled on the ATMA:
  - Monitor system performance, health, and status
  - Monitor environment around the ATMA, with front and side-view obstacle detection
  - A rear-facing camera on back of the leader vehicle to “watch” the ATMA
  - An optional front facing camera to provide POV display from the ATMA looking forward can be installed
- The ATMA system incorporates multiple layers of system status monitoring and redundancy:
  - System health status verifications run in the background
  - Software also monitors operational performance – precision navigation, following gap distance, and leader behavior.
  - Hardware redundancy due to the presence of redundant sensors, obstacle detection, and communication systems:
  - These systems operate simultaneously to offer more robust operation
  - Maintains human-in-the-loop capability and enables the operator to stop the ATMA at any time based on real-time video and status information reported to the leader vehicle.

    - Warnings and notifications are provided to the user interface monitored by the human safety operator.
    - When faults are detected, the system will not enter autonomous mode.
    - When operating in autonomous mode, but a fault arises, or operational conditions change:
        - The default function of system is to bring the ATMA to a safe stop by automatically engaging the brakes.
        - The human operator monitoring the system will be able to issue override commands at any time.
        - If a human operator rides along in the follower vehicle as a safety rider, they can take over control and resume human driving at any time.

<u>Section 2.4 – Crash Prevention</u>

The vendor notes that for a system like the alternative device:

- Maintaining high visibility of the device is a key component to reducing occurrence of motorist crashes into the device. On the ATMA this is achieved by:
    - Use of high visibility TMA Device Impact Face, Arrow Board, Message Boards, Strobe Lights.
    - Use of optional speed radars to measure speed of traveling public and display on sign boards.
    - Use of live recording systems to capture 360° video, internal cab video, and radar speed to motivate the traffic to slow down in a work zone.
- Maintaining appropriate situational awareness of the autonomous system is a key component to reducing occurrence of crashes with objects in the work zone. On the ATMA this is achieved by:
    - Front view obstacle detection system – A multi-modal system that uses Radar and LiDAR sensors with software control algorithms:
        - Work in a variety of work zone environments to detect workers, pedestrians, equipment, cones/barrels etc.
        - When detection is triggered, the ATMA system comes to a stop. The remote operator can restart the ATMA remotely when the obstacle is cleared path.
    - Side view obstacle detection system – LiDAR on both left and right side of vehicle
        - This can be used to detect objects in blind spots and notify the human operator via the User Interface.
        - The operator can then determine if ATMA needs to pause before making a safe lane change.
    - Optionally connected vehicle technology can be integrated if needed to provide additional situational awareness.

    - Use of 360° cameras to monitor traffic, a real-time Human-in-the-loop video to “watch” the path of the ATMA, and back-up cameras to facilitate easy reverse manual driving.

Section 2.5 – Crash Sensing

In order to facilitate the requirements listed in Crash Sensing section the ATMA device:

- Can be integrated with an optional rear-facing obstacle detection system.
    - The system can be factory tuned/calibrated for a specific coverage zone to be monitored.
    - An audio and visual alert systems based on detection in the coverage zone can be added to alert the workers.
    - A rear facing camera mounted on the follower will enable the operator to visualize threats via the User Interface and provide warning to workers ahead in the work zone
- Optional speed radar warning systems integrated with camera systems for monitoring and recording vehicular traffic past the defined work zone can also be integrated.
- The ATMA system includes a method for detecting rear-end crashes of errant motorists with the crash attenuator:
    - Upon detection of such events, brakes are fully engaged and warnings are displayed on the user interface
    - Optional 3rd party sensors can be added, which can allow interface with TMA vehicle airbrake systems.
- Detection of side-swipe crashes with the attenuator is a feature that may need some more development
- On detection of these crashes, the ATMA can be configured to:
    - Provide visual alerts to warn the remote operator and workers via actuation of hazard and emergency lights
    - Audio alerts using the ATMA horn
    - Possibly interface with 3rd party wearable devices with described interfacing details

Section 2.6 – Crash Protection

The requirements listed in the crash protection section when the alternative device is in “Stationary Protection” mode can be satisfied by the ATMA device. The following specific comments were made:

- The steering wheel position is maintained using electro-mechanical actuators.
- The brake pedal is fully engaged to reduce post-impact roll-ahead distance and mitigate severity of crash event. Royal vehicles are equipped with air-brakes to maximize braking capacity. Use of hydraulic brakes is discouraged.

- A variety of hazard, emergency lighting, and audible systems can be installed on the ATMA to warn workers of the impact:
  - These devices will continue to function during a subsequent crash depending on the severity of the crash and overall condition of the TMA, Truck.

After a crash has occurred when operating in “Low-speed Autonomy” mode, the functional requirements can be satisfied by the ATMA device. The following specific comments were made:

- The steering position is maintained using electro-mechanical actuators, and the ATMA will maintain its lateral position to shield workers and equipment ahead in the work zone.
  - The severity of the crash, crash vehicle speed, and crash vehicle weight decide:
    - The effectiveness of shield offered by the ATMA
    - The ability of the ATMA to maintain longitudinal position
    - The ability of ATMA to hold its intended direction, path, and speed
- The brake pedal is fully engaged to reduce device roll-ahead distance such that it does not roll into workers, equipment, or vehicles ahead in the work zone.

Section 2.7 – Post-Crash Requirements

The ATMA device will enable to the greatest extent possible its easy removal from the scene to ensure smooth flow of traffic operations. However, the ease/quickness of removal is highly dependent on the severity of crash.

Also, the ATMA vehicle can be removed from the scene of an accident the same way as a normal human-driven TMA vehicle, either by; human-driving, towing, or removal on a flatbed truck.

Section 3.0 – TMA Adapter

The ATMA system uses Royal’s Trucks. The standard practice on these trucks is to use MASH approved attenuators. The TMA device manufacturer approved adapters are added to the vehicles per recommended procedures.

Royal’s Trucks can also be configured to work with other TMA devices, including existing trailer mount devices that exist in Ohio DOT inventory.

All electrical and mechanical interfaces needed to run with or without an Arrow Board can be configured.

13.3.2. SEA

Technology Brief

Proposed product:	Automated Test Driver integrated with Machine Vision

SEA has suggested that an integration of their off-the-shelf products, with a camera-based perception technology can accommodate most maneuverability and operability requirements of Concepts C1, and Concept C2. SEA's Automated Test Driver, a real-time control system that actuates appropriate brake, throttle, and steering robots lies at the heart of the proposed technological solution.

Figure 33 - Brake throttle and steering robot controllers

The technical solution's main design components can be categorized into the following buckets: Controllers, Hardware Interfaces, GPS/IMU, Sensors for perception, Wireless network and remote monitor & control devices. A technical solution designed with the above sub-systems will achieve the needed functionality by:

- Tracking and following a lead-vehicle using a vision-based perception system
- Obtain and operate on real-time information received from a camera to maintain safe distances
- Operate at speeds lower than 10mph

Proposed Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
✓	-	✓	✓	✓	✓	✓	✓	-	-

Section 2.1 – General Requirements

The proposed solution is neutral regarding the choice of base vehicle selected as the Upgraded Mobile Vehicle. SEA's solution can be implemented as long as steering, gas, and brake pedal interfaces are available.

Section 2.3 - Operability

SEA indicated that some of the functional requirements listed in Sec 2.3 can be achieved as stated below:

- Mode switch can be made available by a designed GUI for the operator
- Unmanned operation of the Upgraded Mobile Vehicle will require a low-latency wireless network

Section 2.3.1 - Maneuverability

SEA's proposed solution will be designed to achieve functional requirements posted in the maneuverability category. The following comments were specifically made:

- Use of Radar / Ultrasonic sensors to display real-time following distance information to the operator.
- To adjust the start position of the vehicle, the BTR and Steering Robots will be disengaged and will allow for the human operator to maneuver the vehicle.

Section 2.3.2 - Controllability

The proposed technical solution in the stationary protection mode will:

- Allow the remote operator to monitor the status of the Upgraded Mobile Vehicle through a host program in real-time.
- The actuation of parking brake could be a technical challenge

The "Low-speed Autonomy" mode will be implemented by the proposed technical solution by:

- The use stereo vision will enable UMV to keep correct orientation relative to the lead-vehicle.
- This vision-based technique can be configured to accommodate for effects of horizontal and vertical curves.
- The solution will not need advance information about the road or the intended path of the lead vehicle.
  - The vision detection will be trained to look for a specific feature on the back of a lead-vehicle.
  - Information in a camera FOV will be used to train a vision detection system and calculate steering inputs.
- A geo-fencing feature using a map-tool can be used to define abort conditions by the operator.

- The technical solution will use the ATD control architecture. A preliminary version of object detection has been incorporated in the architecture. The controller is designed to make decisions such as, whether to abort the test, based on detection distance.

<u>Section 2.4 – Crash Prevention</u>

The technical solution proposed by SEA will achieve functionality listed in Crash Prevention domain by:

- Use of short-range distance sensors (ultrasonic or short-range-radar) to detect objects such as people, guardrails, barrels etc.
- This information is fed back in real-time to the controller. The controller can actuate the steering, brake, and throttle robots to achieve object avoidance as needed.
- Additional features can be designed to handle this information in manner needed to satisfy ODOT's requirements.

<u>Section 2.5 – Crash Sensing</u>

The functional requirements of the Crash Sensing domain can be satisfied by:

- The use of a radar sensor to detect imminent crashes.
- The use of accelerometers to detect actual crashes.
- Appropriate filtering algorithms need to be used to fine-tune crash detection.

<u>Section 2.6 – Crash Protection</u>

SEA indicates that functional requirements for the Crash Protection:

- In "Low-speed Autonomy" mode, the response of the device can be modulated to the type of crash event to offer necessary protection to the lead vehicle. The technical solution can:
    - Hold steering, stop, apply brakes, or continue normal path
- The operator will be notified that a crash is imminent. However, no response will be needed from the operator to protect workers or a lead vehicle from the crash
- Crash protection is an additional abort condition.

13.3.3. AB Dynamics

<u>Technology Brief</u>

Proposed product:	Retrofittable Automated Driving Solution (RADS)

ABD Solutions can provide technology to support elements of both Concept C1 and Concept C2 with their Retrofittable Automated Driving System (RADS) solution. The RADS solution can be used in conjunction with current Work Zone Attenuator (WZA) vehicles or can be incorporated into any newly designed products that ODOT are looking to purchase. The RADS solution is easily operated via remote (teleoperation) means and can be used in autonomous mode, remote (teleoperated) mode by using the “Ground Traffic Control” software, or can be easily operated at any time by a human operator. The technology is proven to be capable of controlling multiple vehicles in coordination and even with the robot installed, the vehicle may be manually driven.

The RADS solution achieves automation by using steer and pedal robots, controller unit, telemetry and control software. The installation of robots is quick, and the vehicle can be driven manually with the robot installed. Position guidance is provided by GNSS inertial navigation sensor. In addition, camera remote control, path following, autonomous following in convoy, waypoint navigation may be provided by RADS.

Figure 34 - Applications of RADS Solution

<u>Proposed Implementation of stated requirements</u>

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
✓	-	✓	-	✓	✓	✓	✓	-	-

<u>Section 2.1 – General</u>

The proposed solution is neutral regarding the base vehicle selected as the Upgraded Mobile Vehicle. The solution can be implemented as long as steering, gas, and brake pedal interfaces are available.

Section 2.3 – Operability

The proposed solution can operate in two modes:

- Human-driven from the garage, to-and-from the work site, and in the work-zone as required
- Low-speed Autonomy mode in the work zone when used in driverless operation

Section 2.3.2 – Controllability

Creation of an automated Leader-Follower solution for retrofit into the fleet of existing WZA vehicles using drop in Driving Robots with the addition of object detection / reaction capabilities. The solution can provide the ability to offer teleoperation of a vehicle using our existing technology that will allow the vehicle to be operated from a remote location up to 2km (1.1 miles) away. Position guidance is provided via GNSS inertial navigation sensors and allows for accurate path following and speed control in a variety of environments including road, off road and low friction surfaces. AB Dynamics Driving Robots are capable of vehicle-to-vehicle communication using meshing IP radio technology. Through communication of position data, vehicles can coordinate and synchronize their motion allowing the possibility of platooning. AB Dynamics existing capabilities support a theoretical limit of 16 vehicles with practical examples of operation with 8 vehicles in convoy. The automated scenario testing was successfully completed at highway speeds of up to 130km/h (80mph). For steady state conditions AB Dynamics Driving Robots are capable of tracking paths to with +/-2cm (+/- 0.8 inch) on asphalt tracks with ground truth corrected GNSS position feedback. Longitudinal positioning can be within +/-10cm (+/- 4 inches). The driving robots are capable of providing precision control including forward and reverse control, controlled braking, precision stopping at a point and cornering at high levels of lateral acceleration. Demonstrated capabilities in such maneuvers confirms the solutions ability to operate in the simple low-speed autonomy design domain needed by ODOT.

Vehicles can be operated to follow a defined path, in-follow me convoy mode or by remote control from a base station. AB Dynamics designed and developed a 'Ground Traffic Control' software environment specifically for its automotive customers. A handheld device placed with a designated operator or status screens within the teleoperation module will facilitate teleoperations and remote monitoring. The teleoperation module enables the remote operator to monitor, act, and react to the driving environment around it. Integration of cameras and other sensors allows navigation in complex driving environments including driving in night-time conditions, low light areas, and in adverse weather conditions. Further, the max speeds is 16km/h (10 mph).

Section 2.4 – Crash Prevention

The addition of object detection and reaction capabilities can enable achievement of Crash Prevention features. Bespoke sensing locations and sensing systems will be tuned and integrated into the solution in addition to the RADS system and driving robots. These bespoke sensing solutions will allow for the detection of objects at a range of 15-25m (50-82 feet) from front of vehicle, within path of vehicle. On detection of such objects, the driving robots can be tuned to perform controlled brake to 0km/hr.

Section 2.5 – Crash Sensing

Bespoke sensing locations and sensing systems can be tuned and integrated into the solution in addition to the RADS system and driving robots.

Section 2.6 – Crash Protection

The presence of independent and redundant safety control systems in the driving robots will allow for implementation of crash protection features. These devices are designed to either stop or perform pre-programmed maneuvers in response to detected traffic and pedestrians. The driving robots have been used to control vehicles on a variety of surfaces including asphalt, gravel, rough and undulating roads. They have been used in a variety of environmental conditions including wet and snow-covered surfaces, low light, and adverse weather conditions.

13.3.4. Dataspeed Inc.

Technology Brief

Proposed product:	Autonomous Conversion of F-450 Chassis Cab Vehicle

Dataspeed's response is primarily targeted towards operationalizing Concept C1. Their central theme of their technology solution is based on – "Autonomous Conversion of F-450 Chassis Cab Vehicle". Their proposal involves conversion of a Ford F-450 Vehicle into an Alternative Device that meets proposed requirements. The device will offer a flat-bed, which can be used for ballast and accommodates a method to connect to the crash attenuator. The vehicle will be retrofitted with Dataspeed's By-wire Kit (control system) and Autonomous Driving System.

The technology "By-Wire" Control System Kit and the Autonomous Driving System have been deployed for a variety of industry customers. Both of these solutions come with varying degree of maturity. A conversation about maturity and technological challenges is encouraged with the vendor. Product details were marked proprietary.

Proposed Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
✓	✓		✓	✓	✓	✓			

Section 2.1 – General

Dataspeed recommends that the functional requirements listed in Sec 2.1 can be satisfied by a Ford F-450 vehicle retrofitted with their Drive-by-wire control system kit. More specifically comments about the following items are noted:

- The power to the crash attenuator will be provided by the Dataspeed Power Distribution System.
- The profile of the F-450 Chassis Cab with flat-bed will dictate the amount of rear-ward visibility offered by the device to workers.

Section 2.2 – Pre-Deployment and Post-Deployment Functions

Dataspeed notes that verification of mechanical interlock with the crash attenuator is an important requirement. However, the process of mechanical interlock and it's inspection will be governed by existing procedures applicable for the selected TMA.

Section 2.3.1 – Maneuverability

Following items were noted with regards to measuring the maneuverability of the vehicle in a garage setting:

- The use of an F-450 Chassis Cab 145in wide-body device has a turning radius of 24ft.

Sec 2.3.2 – Controllability

Dataspeed notes that in the "Low-speed Autonomy" mode, the solution can be made self-aware of its operating limitations by introducing geo-fencing capabilities, or by restricting operation on a route defined by the operator. Also, a sign (or signal) from the leader / guiding vehicle may help achieve this response.

The adaptation of following distance in "Low-speed Autonomy" mode to vertical or horizontal curves in a roadway may be achievable by the use of their Automated Driving system using data from LiDAR, Cameras, IMU, and GPS sensors.

Sec 2.4 – Crash Prevention

Dataspeed notes that broadly the functional requirements of the crash prevention section can be achieved by object detection and avoidance of the AD system. In order to assist the human driver to maneuver in a work zone, a production level surround view system may be appropriate.

Sec 2.5 – Crash Sensing

The detection of side-swipe and rear-end crashes can be achieved by the use of redundant and independent sensors, such as, IMU, GPS, wheel-speed, LiDAR and RADAR. The AD system under design will help achieve features like vehicle detection, pre-impact warning, actual impact detection, and warning achievable with AD system.

13.3.5. Brandmotion

Technology Brief

Proposed product:	Wide spectrum of HMI and OBU based products best suited for the Crash Sensing and Alerts domain.

Brandmotion is recognized as a lead integrator for connected vehicles deployments and fleet provides solutions which can be retrofitted to the concepts C1 and C2. Brandmotion offers a variety of technological solutions which predominantly satisfy the general requirements, crash prevention and sensing functional requirements. The vendor provides electrical interfaces and installations solutions for the attenuator applicable to general requirements and post-crash requirements. For the crash prevention and sensing sections the vendor, proposes various sensing technologies, their installation and testing as well as data acquisition and telematics solutions. These technologies can be deployed to achieve for environment perception and operator response in accordance to that.

One of the products offered by Brandmotion is an On-Board Unit (OBU) retrofitted on the vehicle as per the requirements of the system. The OBU is capable of employing applications like Wrong Way entry, End of Ramp Declaration Warning, Vehicle Turning Right in front of transit Vehicle (VTRFTV), Pedestrian Crash Warning (PCW), Intersection Movement Assist (IMA), Transit Signal Priority (TSP), Forward Collision Warning (FCW), Emergency Electronic Brake Light (EEBL), Radar and Blind spot detection, Heads up display.

Figure 35 - Brandmotion HMI for different types of warnings

<u>Proposed Implementation of stated requirements</u>

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
✓	✓	✓		✓	✓	✓			

<u>Sec 2.1 – General Requirements</u>

The products proposed by Brandmotion may offer and operate on a 12V power supply. This plays well with the desire to power the hydraulic system of the TMA.

<u>Sec 2.2 – Pre-Deployment and Post-Deployment Functions</u>

Brandmotion suggests that they can offer quick connect and disconnect interface for the adapter for concept C1 and C2. They can also offer mechanical, electrical, and electronic interfaces needed by the crash attenuator, and the adapter for concept C2.

<u>Sec 2.3 – Operability</u>

Brandmotion has suggested that its technology can raise audible alerts and notify operator via the teleoperation interface, in case the system components are not operational. The alerts can be used to set the system in default transport mode till all the conditions for safe operation are met.

<u>Sec 2.3.2 – Controllability</u>

The technology provided by Brandmotion can be used to provide the operator a means to access the vehicle and change its mode from “Transport” to any other required mode after the operational checks are completed and safe operation requirements are met.

Sec 2.4 – Crash Prevention

Brandmotion has suggested that its technology can be used to prevent crashes and reduce the occurrence of crashes with motorists and with objects in the work zone. This is especially true if advanced V2X and connectivity technology is employed by the alternative device.

Sec 2.5 – Crash Sensing

Brandmotion propose the use of camera, radar sensing for object detection, accelerometer integration for crash sensing (severity of crash) and automatic crash notification (telematics integration). Data acquisition/logging to record potential intrusion vehicles, near-misses and crashes can be implemented. In addition, the vendor can provide vehicle electrical interfaces to support the above, power, horn/lights, vehicle network (CAN) and user interfaces for downstream signage and displaying alert messages to road crew and emergency responders. The On Board Unit (OBU) technology provided by the vendor can be used to implement different scenarios for warning workers. It can be used for applications such as Front Collision Warning, Radar and Blindspot detection, Wrong Way Entry etc.

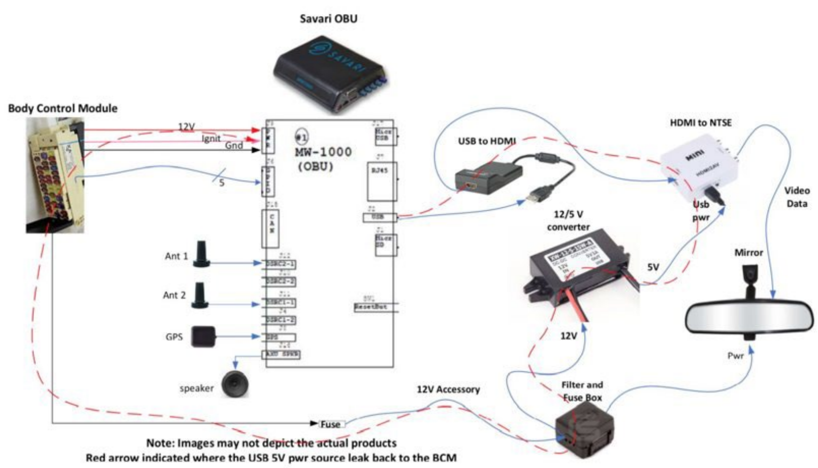


Figure 36 - OBU Architecture employed for Crash Sensing

13.3.6. MHCorbin

Technology Brief

Proposed product:	Connect: WZ

The product Connect: WZ will satisfy the Crash Sensing requirement of both the concepts. The Connect: WZ system was tested by TRC in conjunction with DriveOhio.

A portable trailer was outfitted with a Connect: ITS, Bosch Thermal 8000i CCTV, Audible horn and DSRC based Roadside Unit. The detection zones were created using the Bosch CCTV GUI. Once a vehicle entered this detection zone the Connect: ITS generated a signal to engage the horn while simultaneously generating a Traveler Information Message (TIM) for Connected Vehicles.

Proposed Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
-	-	-	-	-	-	✓	-	-	-

Section 2.5 – Crash Sensing

The product Connect: WZ will satisfy the Crash Sensing requirement of both the concepts. The Connect: WZ will utilize camera technology that allows for zones to be identified. These zones are “drawn” using the cameras GUI. If a vehicle enters one of these zones a signal is generated and the Connect will alert the workers via the horn as well as activate any other devise (RSU, flashing lights etc.)

13.3.7. ViaTech

Technology Brief

Proposed product:	ViaTech D700 A.I. Dashcam, M500 Forklift System, M810 Mining Kit

VIA has been a pioneer in Embedded Systems from motherboards to edge devices. Along with their standard products, they have the ability to create custom solutions to meet client's needs by incorporating different technologies and sensors into their design and using A.I. algorithms to create intelligent functionality. ViaTech offers three products as follows:

D700 A.I. Dashcam for Facial Recognition, Forward Collision Detection, Lane Departure warning, Driver Monitoring.

Figure 37 - ViaTech D700 A.I. Dashcam

M810 Mining Kit with Surround View and Dynamic Object Detection provides operator a bird's eye view of the vehicle and radar coupled sensors for visual alerts when objects are detected in proximity.

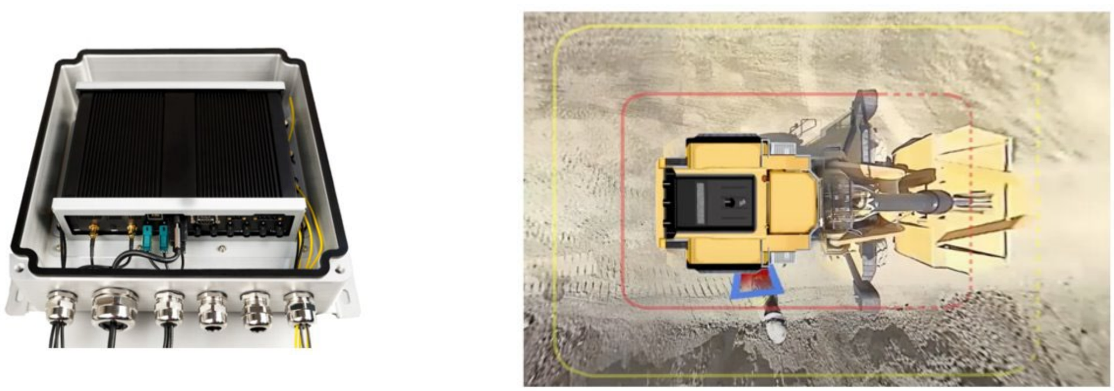


Figure 38 - M810 Mining Kit and Surround Sound System

M500 Forklift Safety System offers all the DMS and Facial Recognition characteristics of the D700 with the proximity detection of the M810.

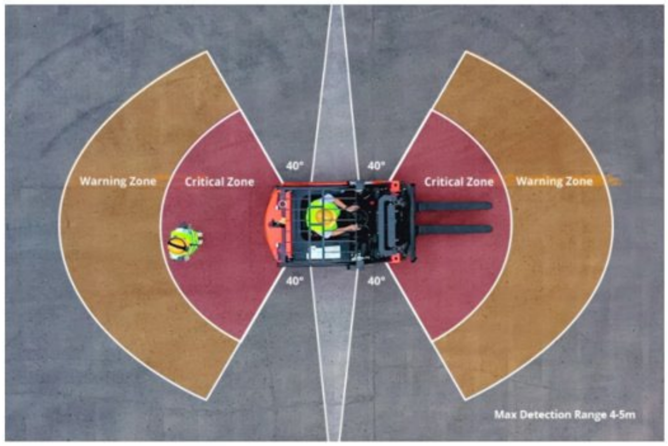


Figure 39 - M500 Forklift Safety System

Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
-	-	-	-	✓	-	✓	-	-	-

Sec 2.3.2 – Controllability

The vendor offers the M810 Mining Kit with Surround View and Dynamic Object Detection which leverages 360-degree image stitching to allow the operator to see completely around the vehicle from a bird's eye view and also Radar coupled with Ultrasonic Sensors to provide audio and visual alerts when objects come within range of the vehicle. The combination of all this data lets us accomplish a robust sensor fusion.

Sec 2.5 – Crash Sensing

The vendor offers two products, which can potentially implement crash sensing:

The D700 A.I. Dashcam provides fleet managers and operators an easy and cost-effective way to increase vehicle safety. The camera features comprise of AWS integration, GPS, CANBUS connectivity, Facial Recognition, Forward Collision Detection, Lane Departure warning, Driver Monitoring.

M500 Forklift Safety System is designed for lower speeds and offers all the DMS and Facial Recognition characteristics of the D700 with the proximity detection of the M810. For added safety, seatbelt alert is added. The vendor suggests use of GPS and radars to outline an intrusion area and detect vehicles coming into the area. The

Speed and direction of the intruding vehicle can be used to calculate the Time to Collision (TTC) and alert the operator, workers, and bystanders of the danger using many different alert methods.

13.3.8. Toyota

Technology Brief

Proposed product:	Toyota Material Handling Solutions, Forklift, AGV and Tuggers for Concept C2

Toyota Forklift has mentioned its products which are typically used in the warehouse applications and can be potentially used for concept C2 implementation. These products provide various tracking and navigation capabilities which can be used for the concept C2. The question to what extent these products can be retrofitted remains unanswered. The products can be potentially modified to meet maneuverability, controllability and crash sensing requirements for concept C2.

The products listed in the RFI response include Two AGVs: Tunnel type and Bi-directional tunnel type (Figure 40) which have max load capacity of 2000kg and 1500 kg respectively

Figure 40 - Tunnel Type AGV and Bidirectional tunnel type AGV

Forklift Tugger (Figure 41) with a capacity of 10000 lbs. and max speed of 4.7 mph.

Figure 41 - Forklift Tugger

Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
✓				✓					

Section 2.1 – General Requirements

The vendor proposed a few platforms to potentially implement general requirements listed for Concept C2. However, the payload and maximum load capacity of these proposed solutions is below listed requirements. The typical operating domain of these tugger solutions are warehouses, and their usage on public roads has not been attempted.

Section 2.3.2 – Controllability

All the products are suitable for warehouse application. There are two types of AGVs: Tunnel type and Bi-directional tunnel type having max load capacity of 2000kg and 1500 kg respectively. The navigation for the AGVs is done through magnetic tape guidance, magnetic guide bar, RFID technology. Various safety systems incorporated include adjustable travel speed, lights, audible warnings, laser bumpers, light curtains, interlocks. The AGV traffic is controlled through LIAISON Traffic and PLC control software.

Another product is Tugger with a capacity of 10000 lbs. and max speed of 4.7 mph. The navigation for this product is through Lidar, more suitable for the concept C2. In addition to the LIAISON Traffic and PLC control software, this product uses ANT lab and ANT Server navigation software which controls natural features navigation, drag and drop route planning, advanced vehicle and traffic simulation, real time vehicle tracking.

13.3.9. Bosch Engineering Group

Technology Brief

Proposed product:	Radar OHW Solution

Bosch Engineering Group proposed the use of their off-the-shelf radar solutions, “Radar OHW” to satisfy some of the functional requirements presented in the Crash Sensing domain. The Radar OHW (Figure 42) is designed to offer functionality of detecting objects in its field of view.

Figure 42 - Radar OHW product proposed to partially meet crash sensing requirements

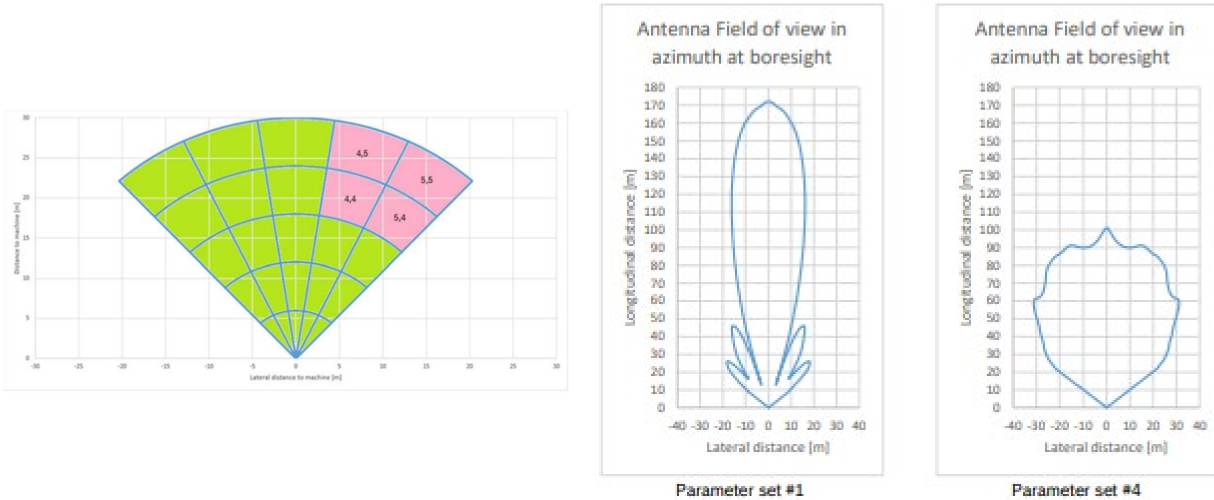


Figure 43 - Characteristics of Bosch's Radar OHW Solution. Left shows configurable detection zones. Center and Right shows configurable parameter sets that influence detection performance

Following salient features of Radar OHW are noted:

- Detect and measure object’s characteristics such as, longitudinal distances, relative velocity, reflection strength etc.
- Device offers five installer configurable parameter sets (Figure 43) that allow the radar to focus on detection zones deemed important for the use-case. These detection zones and performance of radar within it can be broadly measured by three parameters:
    - Field of View – Broad vs. Narrow
    - Range – Short, Medium, and Long.
    - Accuracy – Low, Medium, and High.
- Device offers access to processed outputs such as, object detection, clustering, and tracking, on an object layer.

Implementation of stated requirements

Feedback received on Functional Specifications listed in Section(s)									
2.1	2.2	2.3	2.3.1	2.3.2	2.4	2.5	2.6	2.7	3.0
-	-	-	-	-	-	✓	-	-	-

Section 2.5 – Crash Sensing

Bosch notes that the following important considerations may be needed, when using the Radar OHW for Crash Sensing in Concepts C1 and C2:

- Device requires access to host vehicle's data signals like yaw rate, velocity over CAN to function correctly.
- Mounting and correct configuration of radar is critical to ensure reliable detection. In particular, the choice of parameters that determine range, accuracy, and physical of the device are critical orientation

13.4. Feasibility and Challenges of achieving posted functional requirements

This section summarizes vendor feedback on feasibility and challenges of achieving posted functional requirements.

Table 23 - Feasibility and Challenges of posted General Requirements

Requirements	Feasibility	Challenges
General Requirements	Feasibility depends on choice of vehicle platform Ballast allows for achievement of GVW needed	Rear-ward visibility requirements depends on the choice of vehicle platform Secure ballast methods need to be chosen

Expanded Commentary on feasibility and challenges of General Requirements:

Dataspeed Inc.

Dataspeed noted that the rear-ward visibility functional requirements are dependent on the choice of upgraded mobile vehicle platform.

Kratos & Royal Trucking:

The following comments were made by the vendor:

- Using an existing implementation may offer larger choices of optional features and components such as:
- Man-Bucket Installations, Racks, Swing Gates, Arrow Boards, Charging Systems etc.
- The Kratos retrofit kit can be installed on an existing ODOT fleet vehicle.
- While visibility of the truck, and through the truck for a human driver were discussed, the facet of offering enhanced rear-ward visibility for workers during an impending impact needs to be elaborated further.

Toyota:

Toyota has proposed three products, which can potentially be applied to concept C2. However, the payload capacity requirement listed by the Concept C2 cannot be satisfied. It remains to be seen if alternative attachments can be added to the product to satisfy payload condition.

Table 24 - Feasibility and Challenges of posted Pre-Deployment and Post-Deployment Requirements

Requirements	Feasibility	Challenges
Pre-Deployment and Post-Deployment Functions	Quick connect electronic/electrical interfaces are feasible Method of mechanical interlock and its inspection depends on choice of TMA	N/A

No additional comments were made on feasibility and challenges of requirements posted in Pre-Deployment and Post-Deployment Functions.

Table 25 - Feasibility and Challenges of Operability Requirements

Requirements	Feasibility	Challenges
Operability	Some vendors have a baseline system setup, which may need to be tailored in a factory setting to match ODOT's specific needs For some vendors, implementation needs to be developed and tuned to ODOT's needs. Some vendors have expressed that there are unknowns like – Number of redundant sensors needed, development time, and fidelity of sensor that may pose functional challenges.	More requirement definition needed for stationary protection mode and mode switching use=cases Is speed governed/limited to 10mph or operated at 10mph? A low-latency communications network will be needed to transfer information between leader-follower vehicles.

Expanded Commentary on feasibility and challenges of Operability requirements:

SEA:

SEA noted that a path to operationalizing a technological solution is likely to require proof-of-concept design, design and acceptance of operating criteria, and then an integration with vehicle's actuators. Some system level challenges to operationalizing this concept are:

- The time duration needed to develop a limited autonomy system is unknown.
- The number and fidelity of sensors needed to achieve the redundancy necessary is unknown

Table 26 - Feasibility and Challenges of Maneuverability Requirements

Requirements	Feasibility	Challenges
Maneuverability	Generally, functional requirements that govern maneuverability by a human driver are not a challenge. Choice of vehicle platform and adept use of sensors will achieve the goals listed here.	The use of radar/ultrasonic sensors for measurement of safe following distance needs to be vetted for accuracy, reliability, and latency.

Expanded Commentary on feasibility and challenges of Maneuverability requirements:

<u>SEA</u>

When using Radar / Ultrasonic sensors for measurement of safe following distance:

- Reliability of the sensors will need to be investigated
- Accuracy of the sensor may affect estimate of safe following distance.
- Latency issues may affect the communication of the information from the sensor to the operator

Table 27 - Feasibility and Challenges of Controllability Requirements

Requirements	Feasibility	Challenges
Controllability	The controllability requirements in Stationary Protection mode are feasible. However, implementation mechanism of the parking brake needs to be investigated further.	In the stationary protection mode, actuation of parking brake requires a study of the mechanism, design of an actuator, or an ability to access vehicle level ECU brake commands.

	Low speed autonomy mode may be feasible contingent on the operating design domain of the leader-follower or limited work zone autonomy system. For a few vendors, performance of control system and actuators in inclement weather and on harsh roadway surfaces is not a problem.	It is recommended that to achieve maximum protection in stationary protection mode, the device applies brakes and holds them before, during, and after impact. In Low-Speed Autonomy mode, adaptation of following distance with roadway features is a new requirement that will need development. The device's motion may be based on GPS/IMU, which may rely on differential GPS signals. More clarity is desired on modes and switching between modes to design a robust system. While not explicit, the expected redundancy, safety, reliability parameters of the functions executed by the device need more consideration.

Expanded Commentary on feasibility and challenges of controllability requirements:

<u>SEA:</u>

Some functional requirements in Sec 2.3.2 pose technical challenges as noted below. In the stationary protection mode:

- Actuation of parking brake may need the use of a separate actuator.
- The parking brake mechanism needs to be understood to make appropriate design choices.
- Alternatively, a method to send command to the vehicle level ECU to actuate the parking brake may be explored.

<u>Kratos and Royal Trucking:</u>

The existing ATMA Leader/Follower system does not have an ability to automatically manipulate the follow distance based on upcoming roadway features. However, this feature can be developed in conjunction with the ODOT Team. Development costs may be incurred.

Toyota:

The products Tunnel type and Bi-directional tunnel type AGV require, magnetic tape guidance, magnetic guide bar, RFID technology for navigation. This type of navigation is applicable in warehouse industry where there is a set path for the robot to follow. Whether this technology can be implemented for on road application remains a question. Also, there might be effectivity and feasibility challenges if this technology was to be implemented on the public roads.

AB Dynamics:

AB Dynamics customers have successfully proven that up to eight vehicles can be synchronized and controlled in pack formation. The automated scenario testing was successfully completed at highway speeds of up to 130km/h (80mph). AB Dynamics robots have been used to control a wide range of vehicles on a variety of surfaces including asphalt, gravel, rough and undulating roads. The robots have been used in a variety of conditions including on wet and snow-covered surfaces. AB Dynamics' existing Driving Robots are currently designed to either stop or can perform pre-programmed maneuvers in response to an unexpected event or fault. AB Dynamics is aware of a variety of technologies through its testing work with automotive clients that could be used to detect traffic and pedestrians.

Table 28 - Feasibility and Challenges of Crash Prevention Requirements

Requirements	Feasibility	Challenges
Crash Prevention	Broadly, the functional requirements listed in the Crash Prevention section are achievable by an object detection and crash avoidance systems tuned for the operating domain of the work zone. Some connected vehicle technology may also be integrated in the future.	The use of radar and ultrasonic sensors to detect objects and inform crash avoidance will need to be tuned to the use-case of a work zone. This integration of new sensor sets may need additional engineering and development.

Expanded Commentary on feasibility and challenges of crash prevention requirements:

SEA

- Object detection and avoidance features will rely on the use of RADAR and Ultrasonics. These sensors, and their configurations need to be tailored to meet needs of this use-case correctly.

Kratos and Royal Trucking:

The ATMA system offers optional add-on components such as ultrasonics, which may further the execution of functionality deemed necessary per requirements listed in Crash Prevention section.

Table 29 - Feasibility and Challenges of Crash Sensing Requirements

Requirements	Feasibility	Challenges
Crash Sensing	Sensing of rear-end crashes and potentially side-swipe crashes has relied on accelerometers and contact sensors. Effectiveness of rear-end crash sensing is dependent on choice of sensors, mounting, and configuration.	The choice of an appropriate radar sensor, it's mounting at appropriate locations, and correct configuration is important. Highway speeds 60mph (88ft/sec) offer limited time-window for prediction and detection of an impending crash, and time to inform upstream systems and end-users to act on a predicted crash. While some existing systems have been tuned to detect rear-end impacts using accelerometers, the system's effectiveness to detect side swipe impacts needs to be tested. Very few systems are engineered to enable the end-user to define a digital work zone intrusion area behind the follower vehicle.

Expanded Commentary on feasibility and challenges of crash sensing requirements:

Bosch Engineering Group

The application of a radar sensor like the OHW to Concept C2 may prove to be challenging. This is because:

- For the detection to work reliably, the sensor would need to be mounted at the back of a towed attenuator.
- In this mounting position, the sensor will not work correctly if access to host platform's motion signals is unavailable over CAN.

In other general challenges to Crash Detection using sensors like the radar are:

- Highway speeds offer a limited time window to reliably detect an impending crash and inform upstream user/systems to act on the information.
    - Engineering for specific use-cases is necessary
- It is unclear, if the sensor being used for Crash Sensing functionality requires an ISO-26262 type Functional Safety development approach. Many off the shelf radars can follow alternate best practices to capture functionality, which are not designed to enable on-road driving.

<u>AB Dynamics:</u>

The driving robots have been used in number of vehicles and are readily available. This technology is proven to be capable of controlling multiple vehicles in coordination and even with the robot installed, the vehicle may be manually driven. There are over 1,000 of our robots in service worldwide, which all the top 20 vehicle manufacturers rely on, and the technology is readily adaptable to suit heavy industry applications also.

<u>MH Corbin:</u>

Individual components are readily deployed around the country. The proposed system has been tested by TRC in conjunction with DriveOhio. Warning the workers via wearable devices will require some development as this has never been tested before. Configuring the detection zones will require a detailed training course to streamline the process.

<u>SEA:</u>

An accelerometer is already used in the ATD control system architecture. The sensor will need to be tuned for an application, where G-Forces are high.

Highway speeds offer a challenging environment to successfully detect impending crashes. At highway speeds, traffic may flow at 60mph (88ft/sec). This offers a narrow time-window to detect and predict imminent crashes.

<u>Dataspeed Inc.:</u>

While features of crash sensing can be implemented using the AD system, their effectiveness is dependent on sensor mounting and ensuring visibility past the attenuator and flashing sign.

Kratos and Royal Trucking:

The ATMA includes a rear-end crash detection system to detect crashes of errant motorists impact the crash attenuator. While this system may work to detect aggressive side swipe impacts, this feature and scenario has not been previously tested.

The existing ATMA system does not have a feature that enables an operator to define a digital intrusion area to describe the work zone. The system has worked in situations where cones have been deployed to describe a physical intrusion area. The ATMA has been operated in narrow cone lanes before. Such a digital intrusion area technique can be developed to suit ODOT's needs, if needed.

Table 30 - Feasibility and Challenges of Crash Protection Requirements

Requirements	Feasibility	Challenges
Crash Protection	The crash protection should be achieved by keeping worker and object detection active and allow steering to avoid worker in path. Crash protection in stationary mode depends on effective detection, limits of electro-mechanical actuators, and ability to hold steering and brake. In Low-speed autonomy the system can be designed to maintain path, speed, and apply brakes if needed.	Under an errant motorist crash event at highway speeds in stationary protection mode it is critical to hold brakes on the device and trailer if applicable. Hydraulic brakes may offer low braking power and added safety risks during impact events. Air-brakes recommended instead. The mechanism of parking brake, the actuator, and the systems reliability in a crash event needs to be investigated. Efficacy of the electro-mechanical actuators during a crash event may be at the limits of the system. When under crash events, it is best to prepare for post-impact where the goal is to reduce roll-ahead distance ahead of the device. Any

		intermediate states may compromise crash protection.

Expanded Commentary on feasibility and challenges of requirements in Sec 2.6:

<u>SEA</u>

The following technical feasibility issues are noted during the Crash Protection phase of the upgraded mobile vehicle's operation:

- Actuators for controlling the brakes and steering are well developed. But their efficacy during a crash may be at the limits of vehicle platform's brakes and steering system.
- Preparing for imminent impact may be challenging where vehicles are traveling at highway speed
    - Under ideal conditions where short range radar is employed (30m maximum detection), and a vehicle is traveling at 60mph (26.8 m/s) the system will have approximately 1s to respond. This could be too short of a time window to perceive, detect, prepare, and respond.
    - Under these conditions, it is best to prepare for post impact where goal is to reduce roll-ahead of the UMV or MRP after impact. Any intermediate states may compromise crash protection.

<u>Kratos and Royal Trucking:</u>

While the visual and audible warning devices can be designed to continue to function post a crash event, their reliability is dependent on the severity of crash and overall condition of the truck and TMA assembly. Extreme events such as roll-over, fire etc. may pose challenges to the continued operation of these installed devices.

The ATMA system does not currently control the parking brake in automated mode, but a parking brake actuator can be designed as an optional addition.

The effectiveness of the ATMA acting as a shield to workers in a work-zone is dependent on the severity of the crash, crash vehicle speed, and crash vehicle weight.

A review of Crash Protection functional requirements has brought to the fore some implementation best practices learned by the Kratos team. They are summarized below:

- It is recommended that the trucks/alternative device use air brakes as opposed to hydraulic brakes to maximize braking capacity.
- Impact can cause hydraulic brakes to fail, which may cause the truck to freewheel into the work zone.
- The parking brake mechanism and its reliability in a crash event needs to be assessed.

Table 31 - Feasibility and Challenges of Post-Crash Requirements

Requirements	Feasibility	Challenges
Post-Crash Requirements	The device can be designed to be of equal difficulty than a current vehicle to remove from the crash-site after an impact has occurred.	The severity of accidents defines the ability of an alternative device to be easily removed from the scene.

Expanded Commentary on feasibility and challenges of post-crash requirements:

<u>Kratos and Royal Trucking:</u>

In case of severe accidents, it is not always guaranteed that the TMA vehicle/device is quickly/easily removed from the accident scene.

Table 32 - Feasibility and Challenges of Functional Requirements listed in Sec 3.0

Requirements	Feasibility	Challenges
TMA Adapter	Requirements are feasible and dependent on TMA device chosen for the application. Mechanical, Electrical, and Electronic Interfaces can be designed for the TMA and Arrow Board.	N/A

No additional commentary was received for TMA Adapter requirements

13.5. Feedback to Improve Functional Requirements

13.5.1. General Feedback

Vendor Name	Applicable to
Kratos and Royal Trucking	C1

The Kratos/Royal team has indicated that some additional considerations be made by ODOT when developing specifications for the alternative device:

- **Design for low worker burden:** The alternative device should be designed for simplicity of operation. The primary objective of the worker is to get the job done. Any additional features may increase complexity for the workers.
    - A remote-control system / teleoperation may add burden to the workers. Hence Concept C1 with a leader/follower operation may be better suited to a DOT's needs.
- **Design for system redundancy:** To include safe operation, system redundancy must be included to reduce single point of failure. Redundancies may be baked in the: navigation methods, communications link, obstacle detection, braking systems, and E-stop methods.
- **Communications hardening:** The communications link is a critical access point to the driverless system. This system must be hardened to reduce risk of malicious hacking or RF interference. Techniques such as encryption, frequency hopping, and dual-communications links are recommended.
- **Cybersecurity Protections:** Requirements and techniques that reduce risk of malicious hacking must be included in the design. Cybersecurity best practices that govern design of software, hardware, and operations must be developed and followed.
- **Winterization:** If the alternative device is going to be used in cold-weather operations, heating devices for the LiDAR, camera sensors may be required to prevent frosted lenses. If the vehicle is used for other operations, critical external components should be removed and covered to prevent damage. A winterization guide should be developed and provided to remove, and store various system items.

Vendor Name	Applicable to
AB Dynamics	C1 and C2

Due consideration should be made for enabling operation in complex environments that include harsh weather, unpaved roads, and low light. Additionally, safety and redundancy aspects of the design should also be investigated further. The dependency of operation on external information (ex. GNSS signals) needs to be considered. The impact on a device’s capabilities when such information is unavailable should be assessed. Finally, considerations for cybersecurity hardening must be given at both the communications, hardware (chip), and software levels.

13.5.2. General Requirements

Vendor Name	Applicable to
Kratos and Royal Trucking	C1

The vendor:

- Introduced the concept of using engineer-certified ballast chambers for embedding concrete counterweight. Use of this technique may reduce liability by eliminating the possibility of a loose projectile during impact.
- Suggested that choice of vehicle be made judiciously. It is recommended that those vehicles for which ODOT maintenance procedures and skillsets are available be given preference. This will reduce the need for additional system training and the chance for “one-off” fleet vehicles.

13.5.3. Pre-deployment and Post-Deployment at Garage

No feedback to improve requirements was obtained via the RFI.

13.5.4. Operability

Vendor Name	Applicable to
Kratos and Royal Trucking	C1

The vendor has requested that ODOT provide additional detail on functional specifications of the “Stationary Protection” mode. These details can help Kratos and Royal Trucking implement stationary protection in one of two methods offered by the ATMA:

- By pausing “Low-Speed Autonomy” mode – The operator can “pause” the mode as long as needed and manually park the follower vehicle in stationary position, as long as needed. The operator can realign with the leader, “un-pause”, and continue in Leader/Follower mode.

- By operating like a normal vehicle – The vehicle can be parked like a normal vehicle, and vehicle can be left in this location. Once highway operation becomes mobile the leader/follower technology can be turned on.

The "Stationary Protection" mode can be actuated using the "pause" method, using the ASTOP button on the Operator Control Unit. This enables the ATMA to be held in a stationary position, while still keeping the ATMA system operational in the background. Such a method will allow the ATMA system to transition out of the "Stationary Protection" mode without the need for anyone to enter the follower vehicle. The use of "IDLE" switch or powering off the ATMA to achieve stationary mode will require a human operator to enter the ATMA Follower to physically turn-on the system.

- Does an operating speed of 10mph on the Low-Speed Autonomy mode, mean it is limited/governed to 10mph, or is a 20mph governed limit acceptable?

13.5.5. Maneuverability

Vendor Name	Applicable to
Dataspeed Inc.	C1 and C2

Item 2 - "When maneuvering inside the garage, the device may be attached to the adapter and a crash attenuator. The crash attenuator may be of an integrated style (TMA) or a trailer towed attenuator (TTMA)". Dataspeed notes that it reads like the requirement is incomplete, or possibly a statement.

13.5.6. Controllability

Vendor Name	Applicable to
Dataspeed Inc.	C1 and C2

Dataspeed recommends that requirement 4.(b) that relates to Controllability in the Stationary Protection mode be amended to apply all brakes and hold them before, during, and after impact.

Vendor Name	Applicable to
Dataspeed Inc.	C1

When operating in "Low-speed Autonomy" mode, and a change in operating conditions makes the device's operation infeasible, a teleoperation mode will allow for further flexibility in use of the system.

Vendor Name	Applicable to
Kratos and Royal Trucking	C1 and C2

The vendor believes that there needs to be a cleaner description of ODOT's expectations when the alternative device needs to switch between modes such as, human-driven, stationary protection, and low-speed autonomy mode. A wide variety of operational protocols are feasible, and implementation methods may need to be tailored to meet specific needs.

13.5.7. Crash Prevention

Vendor Name	Applicable to
Dataspeed Inc.	C1 and C2

Dataspeed Inc. notes requirement 4.2 is not applicable to the vehicle but is more applicable to the TMA or Arrow Board Sign.

13.5.8. Crash Sensing

Vendor Name	Applicable to
Dataspeed Inc.	C1 and C2

Dataspeed recommends that on detection of an impending impact, the device should apply all brakes.

Vendor Name	Applicable to
SEA	C1 and C2

SEA recommends that when an imminent crash is detected, the requirements be switched up to:

- Warning sounds and lights will be activated,
- Brakes are applied in low-speed autonomy mode, rather than holding speed / steer,
- Lights continue to flash until manually turned off by the safety operator

13.5.9. Crash Protection

Vendor Name	Applicable to
Dataspeed Inc.	C1 and C2

When the device is deployed in "Stationary Protection" mode and a crash is imminent, in addition to the functional specifications listed the following requirements may help the device prepare for the crash:

- Keeping object/worker detection feature active and allow steering to avoid worker in path.
- While the brakes of the device are held, include the ability to apply brakes (if applicable) on the TMA trailer axles.

When the device is deployed in "Low-speed Autonomy" mode and a crash is imminent, in addition to the functional specifications listed the following requirements may help the device prepare for the crash:

- Keeping object/worker detection feature active and allow steering to avoid worker in path.

13.5.10. Post-Crash Requirements

No feedback to improve requirements was obtained via the RFI.

13.5.11. TMA Adapter

No feedback to improve requirements was obtained via the RFI.

14. Appendix H - Economic Analysis

The RFI mechanism provided feedback on the technical feasibility of alternative device concept, and TRC Inc. packaged the obtained information into three hypothetical buying options providing ODOT a range of technological upgrades for each option. The feasibility of the alternative device concept over the existing dump truck attenuators can be studied in the most effective way by economic analysis for the alternative device concept. Cost Benefit Analysis method was considered to be the most appropriate for economic analysis.

In Cost Benefit Analysis cost of the option is weighed against the benefits offered by the option, to determine its feasibility. In this analysis, the total projected cost and the benefits of the choosing the alternative device over the dump truck are calculated. If the benefits outweigh the cost, the choice is considered to be feasible. In the case of alternative device concept, the objective of the analysis is determining the whether the implementation cost of the concept will provide with adequate benefits over a dump truck system.

14.1. Cost Benefit Analysis Considerations

14.1.1. Types of Costs

The costs incurred for the implementation of alternative device concepts as well as a dump truck can be broadly classified into three categories:

- Cost of purchase (One Time Purchase)

With regards the Alternative Device, the cost of purchase may include cost for buying a new vehicle, vendor proposed technology, integration and customization cost, training of labor, and cost of modifications needed to ODOT's existing equipment like the attenuator, adaptors, or other tools as deemed necessary. With regards to the Dump Trucks, the cost of purchase may reflect the final purchase price for dump trucks paid by ODOT.

- Cost of Use (Recurring Costs per Use)

For both the Dump Truck and the Alternative Device such costs may include labor cost for setting up the work zone, labor costs for using the device, costs for providing technical support (either onsite or remotely), costs for fuel, and costs for insurance.

- Cost of maintenance (Periodic Costs)

The cost of maintenance constitutes the cost of software and hardware upgrades cost over the device's life, vehicle maintenance cost, periodic training of labor when upgrades are made, costs of extra inventory for replacing failed components.

14.1.2. Types of Benefits accrued by use of Alternative Device over the Dump Truck

For the purpose of quantifying benefits, TRC Inc. proposes that we consider the benefits gained by using the alternative device in lieu of the dump truck. Such a differential assessment of benefits will help inform the Cost Benefit Analysis in the scenarios of interest to ODOT. Such benefits can be categorized into two groups:

- Benefits to Workers

The main quantifiable benefit to workers using the alternative device is reduced chances of fatalities and serious injuries.

- Benefits to ODOT

<u>Increased Operational Efficiency</u>

The alternative device technology may provide ODOT with an increased operational efficiency in a work zone operation. The device may enable ODOT's Maintenance Crew to perform maintenance activities requiring work-zones with increased efficiency. There may be a reduction in the number of drivers required for driving the dump truck, if it is replaced by autonomous driving alternative vehicle or fleet operated alternative device. If remote operation capacity is achieved, a single operator may be able to control multiple alternative devices. This would result in reduction in the cost of labor.

Reduced Cost of Vehicular Crashes - Life

In an event of crash, there would be no loss of life if alternative device is operated autonomously. The crash sensing technology will help to reduce the intensity of injury hence, the number of serious injuries, and fatality by providing appropriate warning message to the driver. Decreased fatalities and injuries may result in lower claims and workers compensation expenses for ODOT.

Reduced Cost of Vehicular Crashes – Material and Repair

In an event of crash, the repair cost for the alternative device might be less than the dump truck.

Benefits of Increased Dump Truck Uptime and Availability

When dump trucks are replaced with an alternative device, more dump trucks become available for other operations such as snow and ice removal. Replacing the dump truck with alternative device would ensure availability of more dump trucks and reduce the cost of renting dump truck for other tasks.

14.2. Scenario 1 - Cost Benefit Analysis of New Alternative Device vs. a New Dump Truck

14.2.1. Method and Assumptions

The economic feasibility can be evaluated by calculating the absolute cost and absolute benefits of the purchasing a new alternative device and a new dump truck. Absolute cost of alternative device depends on the range of chosen alternative device, cost of using it and cost of maintaining it. If the difference between the benefits offered by the alternative device over the dump truck is greater than the difference between the cost of alternative device and the cost of dump truck, then buying a new alternative device can be considered to be a good option.

A sample of this scenario is presented below.

Table 33 - Cost Benefit Analysis for New Alternative Device vs. New Dump Truck

	New Alternative Device	New Dump Truck
Absolute Costs	$Cost_{AD}$	$Cost_{DumpTruck}$
Benefits Over Dump Truck	$Benefit_{ADOverDumpTruck}$	

In this scenario:

$$Cost_{AD} = f(ChosenAlternativeDevice, Cost_{ADUse}, Cost_{ADMaintain})$$

$$Benefit_{ADOverDumpTruck} = f(Benefit_{Workers}, Benefit_{ODOT})$$

$$Cost_{DumpTruck} = f(Cost_{DumpTruckPurchase}, Cost_{DumpTruckUse}, Cost_{DumpTruckMaintain})$$

If,

$$Benefit_{ADOverDumpTruck} > diff\left(Cost_{AD}, Cost_{DumpTruck}\right)$$

Then it is feasible to use an Alternative Device over the dump truck for the application.

The following key inputs were used to evaluate economic feasibility for Scenario 1

Key Cost Inputs

- Cost of Alternative Device Vehicle = $50,000.
- Cost of Alternative Device Technology = $150,000.
- Cost of New Dump Truck Purchase = $ 120,000.
- # of Labor required for Alternative Device Operation in a Crew = 3.
- # of Labor required for operation using a new dump-truck = 4.
- Labor Rate = $ 22/hr.
- Labor Rate Premium for use of Alternative Device = 20%.
- Hours spent by device in an active work zone per year = 900 hrs.

Inputs and assumptions govern calculation of parameters like number of hours of Work Zone activity across the State of Ohio, and the cost for integration, customization, and modifications needed to ODOT's equipment, if any.

Key Inputs to calculate Benefits

- Fatalities in Work Zones – National, and State of Ohio, from database.
- Worker Fatalities in Work Zones – National, and State of Ohio, from database.
- Estimates of Serious Injuries in Work Zones per Crash Report Sampling System (CRSS) and General Estimate System (GES)
- Effectiveness of Alternative Device to reduce Serious Injuries for Safety Operator = Low Effectiveness, 50%.
- Effectiveness of Alternative Device to reduce Fatalities for Safety Operator = Low Effectiveness, 50%.
- Effectiveness of Alternative Device to reduce Serious Injuries for Exposed Workers = Low Effectiveness, 20%.
- Effectiveness of Alternative Device to reduce Fatalities for Exposed Workers = Low Effectiveness, 35%.
- Medical cost of Fatalities and Serious Injuries, from database.
- Work Loss Costs (Indemnity) for Fatalities and Serious Injuries, from database.
- Time to repair pickup truck after a crash event = 3 days.

- Labor rate to repair pickup truck = $140/hr*.
- Time to repair dump truck after a crash event = 5 days.
- Labor rate to repair dump pickup truck = $110/hr*.
- Dump Truck downtime = 10 days per crash event.
- Rental charge for a replacement dump truck to cover operations = $500/day
- For the purposes of calculation, it is assumed that a crash event that necessitates repair and down-time occurs once per year of use for both the Alternative Device and the Dump Truck.
  * Labor rates for repair are commercial estimates, and include overhead.

The differential cost of using an Alternative Device over a dump-truck over the life of the device (assumed 5 years) is calculated using key inputs and assumptions listed above. These costs are compared with the potential benefits accrued by using an alternative device over the dump truck.

14.2.2. Results

Cost-Benefit Analysis for the use of one Alternative Device over one new dump-truck as a shadow vehicle, for 900 hours/year (active Work Zone hours) for a period of 5 years (life), indicates that the device's use is economically marginally-infeasible based on inputs and assumptions used in the evaluation. A summary is captured in Table 34 and additional commentary is presented below.

Table 34 - Summary of Cost-Benefit Analysis for Scenario 1.

Cost-Benefit Analysis	Differential Costs / life	Differential Benefits / life
Scenario 1 – Use of New Alternative Device over a New Dump Truck	$ 84,597	$ 77,563
Is choice feasible?	Marginally-Infeasible	

A breakdown of differential costs indicates that while the Alternative Device is expensive to purchase, the device has the potential to offer benefits during use owing to reduced labor costs (potential to reduce number of workers needed), and reduced vehicle use rate. Also, the maintenance costs for both options are comparable. However, it is not an apples-to-apples comparison as it must be noted that the maintenance

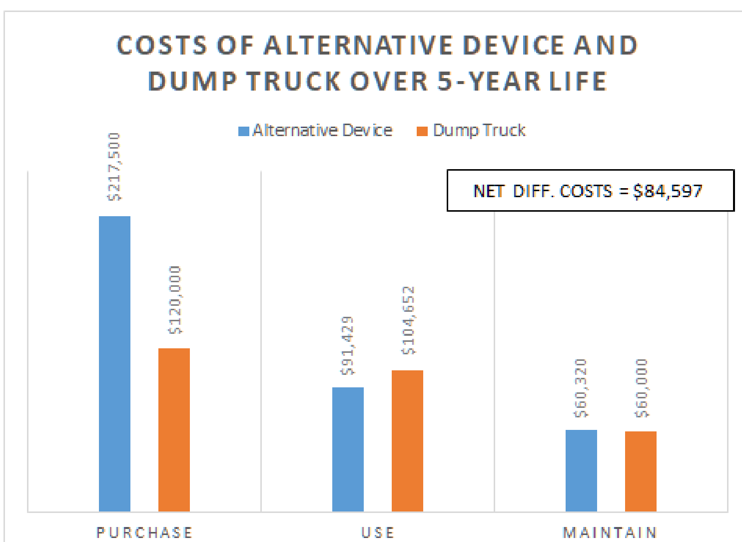


Figure 44 - Comparison of costs for Scenario 1.

cost for the Alternative Device include some budget for software and hardware upgrades, repairs, and labor training for ~40hrs per year/worker for the use of the device. Figure 44 indicates the bar-chart comparison for the differential costs.

The potential benefits to be accrued when using the Alternative Device over the Dump Truck can be categorized as those due to reduced medical costs, reduced Workers Loss Compensation, reduced repair costs, and the reduced costs of downtime and rental of a dump truck to cover for other operations. For Scenario 1, proportion shared between these benefits is outlined in pie-chart Figure 45. Pie-chart indicates that a large share of benefits of using the Alternative Device over the Dump Truck lies in the potential for reduced Workers Compensation Costs as well as reduction in costs borne by ODOT during dump truck downtime and repair.

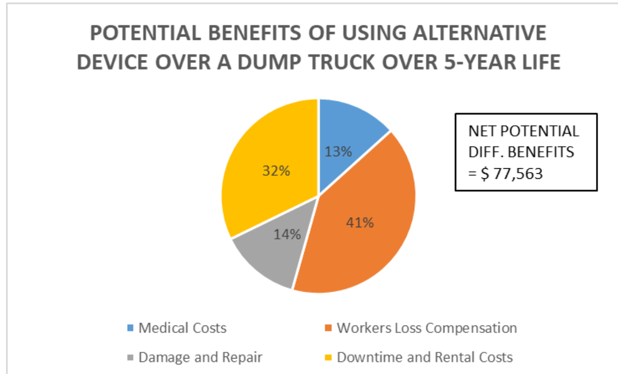


Figure 45 - Share of potential benefits accrued by the use of Alternative Device over the dump-truck in a Work Zone.

In summary, the differential costs of using the Alternative Device over the dump-trucks are dominated by purchase costs. However, an estimate of potential benefits indicates that costs are closely matched with the benefits to be accrued by the use of the Alternative Device in Scenario 1. It is recognized that a large share of potential benefits lies in the reduced costs for Workers Compensation and lower downtime and rental costs to cover for a dump truck damaged in a Work Zone.

The current economic analysis indicates that the alternative device is marginally-infeasible. While this assessment is true, it is also recognized that a narrow set of tangible benefits were included in the calculation. A choice of the use of Alternative Device may also lead to intangible benefits such as a chance to offer programs that impart training and increase technology skills for ODOT's Highway Technicians, increasing ODOT/DriveOhio recognition for advancing Work Zone safety. The use of an Alternative Device offers ODOT an opportunity to advance Work Zone safety and accrue these benefits. Additionally, cost factors may be actually lower than estimated due to continued advances in constituent technology elements in the near-future. An assessment of such favorable tailwind factors, scalability of the solution, and potential benefits that may be unlocked by using the device across the state's network should be performed and included in the decision making process.

It must be noted that the estimates of Costs and Benefits, such as those derived for Scenario 1, are sensitive to the inputs and assumptions used in the calculation model. As recognized earlier, the real outcome of the Economic Analysis is the development of a Cost Benefit Analysis Calculation Tool that can be used to evaluate sample scenarios. Care must be taken to appropriately identify correct inputs and assumptions that can be fed into the model.

14.2.3. Supplementary Documentation for Economic Analysis

(yellow)	Inputs
(green)	Calculated Outputs

ESTIMATE OF PURCHASE PRICE COSTS INVOLVED IN THE BUYING OF AN ALTERNATIVE DEVICE AND THE DUMP TRUCKS

Vehicle Options	Existing ODOT Truck	New Truck	New Dump Truck with all features and options				
Vehicle Options Pricing	0	$ 50,000	$ 120,000				*Pricing based on RFI feedback and preliminary market research.*
Technology Options	Only to be selected in pairs stated below						
Leader/Follower Perception	GPS Tracking + V2V Communication	GPS Tracking + V2V Communication	Camera/Vision based follower	Camera/Vision based follower	Limited In-Workzone Automated Driving System	None	
Leader/Follower Actuation	BTR + Steer Robot	BTR + Steer Robot + Parking & Trailer Brake Robot	BTR + Steer Robot	BTR + Steer Robot + Parking & Trailer Brake Robot	Drive-by-Wire Kit	None	
SOLUTION NAME	TYPE-A1	TYPE-A2	TYPE-B1	TYPE-B2	TYPE-C	None	
Technology Options Pricing	$ 200,000	$ 300,000	$ 150,000	$ 200,000	$ 150,000	$ -	*Pricing based on feedback received in RFI. May need to be updated.*
Technology Solution Integration	Low	High	None				
Technology Solution Integration Pricing	5%	20%	0%	*Configurable parameters*			
Technology Solution Customization	Low	High	None				
Technology Solution Customization Pricing	5%	20%	0%	*Configurable parameters*			
Modifications needed to ODOT's existing equipment	Low	High	None				
Pricing of Modifications	5%	20%	0%	*Configurable parameters*			

ESTIMATES FOR LABOR TIME, EQUIPMENT, AND WORK ZONE ACTIVITIES

Type of Work Zone Activity	LOW USE (A.D)	HIGH USE (A.D)	LOW USE (TRUCK)	HIGH USE (TRUCK)	
# of Labor using monitoring the device for an activity	3	3	4	4	*Assumed that use of Alternative Device reduces the number of labor required by 1 per mission.*
# of Hours per Labor Resources for the activity / year	2700	4050	3600	5400	
# of Hours of Equipment use/year	900	900	900	900	
Rate for Labor [$/hr]	22				$22/hr HT average
Labor Wage Premium Type	High	None			
Labor Premium Value [%]	20%	0%			
Type of Vehicle Used	223 - PICKUP, 1 TON	253 - DUMP TRUCK, GVWR <= 26000 LB			
Rate for Vehicle Use [$/hr]	$ 17.91	$ 28.28			
Rate Premium for Technology	Alternative Device	Regular Device			
Rate Premium Value [%]	25%	0%			

ESTIMATES FOR LABOR TIME - WORK ZONES IN OHIO

# of People per Crew	4	people/crew	*An average crew size of 4 people per crew*
# of Crews per Garage	1.5	crew/garage	*Some garages may have multiple crews. However most garages have just one full-time crew*
# of Garage per County	1	garage/county	*Average number of garages in the county. Some urban counties have more garages and a mixture of outposts*
# of Counties in Ohio	88	counties	
# of active hours in a Work Zone, per worker, per day	6	hours/worker/day	*An estimate of active time in a Work Zone activity spent by the worker per day. Other time is spent in traveling to the worksite or weather related downtime.*
# of months of Active Work on Roadways	5	months/year (15May-15Oct)	*# of months of active work zone operation*
# of days per month	30	days/month	*# of days per month*

# of work hours per worker in a year	900	work-hours/worker/year	
# of total work hours in State of Ohio	475200	work-hours/year	
# of crews using Alternative Device	1	# of crews	*# of crews using the alternative device*
# of Alternative Devices	1	# of A.D.	
Time spent by X crews using an Alternative Device	2700	work-hours/year	
Time spent during use of X Alternative Device	900	work-hours/year	
% coverage offered per crew using Alternative Device	0.57%	% coverage	
Use Factors for Alternative Device	LOW	HIGH	*Alternative Device use multiplier*
Values	1.0	1.5	
# of Hours in Ohio's Work Zones with use of TMAs	50%		*It is assumed that 50% of work hours spent in Ohio need the use of an Alternative Device*

It is assumed that the crew performs all of their Work using the Alternative Device or a Dump Truck as a shadow vehicle on roads with speeds greater than 45mph.
Additionally such a crew always uses a TMA during their Work Zone Activity

		ALTERNATIVE DEVICE	TRUCKS	UNITS OF MEASURE	NOTES
Description of Work Zone Scenario					
Information of Work Zone Scenario					
	Type of Work Zone Activity	LOW USE (A.D)	LOW USE (TRUCK)	Type of Activity	*From a drop-down menu.*
	Hours for Each Activity	2700	3600	hours/year	
	Life of Vehicle	5	5	years	
Costs of Purchase (One Time Purchase)				UNITS	
Vehicle Used		New Truck	New Dump Truck with all features and options		*From a drop-down menu.*
	Cost	$ 50,000	$ 120,000	$ / unit	
Proposed Technology Solution		TYPE-C	None		*From a drop-down menu.*
	Cost	$ 150,000	$ -	$ / unit	
Technology Solution Integration		Low	None		*From a drop-down menu.*
		5%	0%	% of Purchase Price	
	Cost	$ 7,500	$ -	$	
Technology Solution Customization		Low	None		*From a drop-down menu.*
		5%	0%	% of Purchase Price	
	Cost	$ 7,500	$ -	$	
Modifications needed to ODOT's existing equipment		Low	None		*From a drop-down menu.*
		5%	0%	% of Purchase Price	
	Cost	$ 2,500	$ -	$	
TOTAL PURCHASE COST		$ 217,500	$ 120,000	$	
Costs of Use (Recurring Costs per Use, Calculated for Entire Life)					
Labor Cost of Using the Equipment					
	Time Needed to Conduct WZ Activity	2700	3600	Hrs	
	Rate for Labor	$ 22.00	$ 22.00	$ / hr	
	Labor Premium	High	None		
	Labor Premium Value	20%	0%	% of Labor Rate	
	Cost for Labor over Life of Vehicle	$ 71,280	$ 79,200	$	
Cost of Using the Vehicle for WZ Activity					
	Time Needed to Conduct WZ Activity	900	900	Hrs	
	Type of Vehicle Used	223 - PICKUP, 1 TON	253 - DUMP TRUCK, GVWR <= 26000 LB		
	Rate for Vehicle Use	$ 17.91	$ 28.28	$ / hr	*Use rate assumed to include - Material Costs, Insurance Costs, Equipment Use Costs*
	Rate Premium for Technology	Alternative Device	Regular Device		
	Rate Premium for Technology Value	25%	0%	% of Equipment Use Rate	
	Cost of Equipment Use over Life of Vehicle	$ 20,149	$ 25,452	$	
TOTAL COST OF USE		$ 91,429	$ 104,652		
Costs of Maintenance (Periodic Costs over the Lifetime of Equipment)					
Cost of Upgrades to Proposed Technology Solution					
	Software	$ 15,000	$ -	$ / life	*10% premium applied to enable software upgrades over the life of alternative device*
	Hardware	$ 15,000	$ -	$ / life	*10% premium applied to enable hardware upgrades over the life of alternative device*
Cost of Maintenance					
	Vehicle Maintenance	5%	10%	% of Purchase Cost/Year	*Lumped percentage of Vehicle Maintenance, Repair Costs*
	Vehicle Maintenance Cost	$ 12,500	$ 60,000	$ / life	
Cost of Labor Training					
	Periodic Labor Training	$ 17,820	$ -	$ / life	*Operating crew for the Alternative Device gets training for 5% of time device is used every year.*
TOTAL COST OF MAINTENANCE		$ 60,320	$ 60,000		
TOTAL COST FOR PURCHASE, USE, MAINTENANCE OVER A LIFETIME PER UNIT OF VEHICLE		$ 369,249	$ 284,652		
DIFFERENTIAL COST OF USING AN ALTERNATIVE DEVICE AS A REPLACEMENT OVER TRUCK					
DIFFERENTIAL PURCHASE COST		$ 97,500		$/unit	
DIFFERENTIAL USE COST		$ (13,223)		$/unit	
DIFFERENTIAL MAINTENANCE COST		$ 320		$/unit	
TOTAL DIFFERENTIAL COST PER UNIT		$ 84,597		$/UNIT	

Inputs / Calculated Outputs	VALUES	UNIT OF MEASURE	NOTES
ESTIMATION OF FATALITIES IN WORK ZONES			
How many Fatalities in National Work Zones	6966	#	*Cumulative sum of national fatal crashes for 2010-2019.*
How many Work Zone Worker Fatalities in National Work Zones	1249	#	Above info from - https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#national
% Worker Fatalities (National)	18%	%	
Average # of Fatalities in National Work Zones per year (2010-2019)	696.6	# / year	
Average # of Work Zone Worker Fatalities in National work Zones per year (2010-2019)	124.9	# / year	
How many crashes in Ohio's Work Zones			
How many Worker Fatalities in Ohio's Work Zones	197	#	*Cumulative sum of Fatal Crashes in Ohio for 2010-2019.*
How many Work Zone Worker Fatalities in Ohio's Work Zones	42	#	*Cumulative sum of Fatal Worker Crashes in Ohio for 2010-2019.*
% Worker Fatalities (Ohio)	21%	%	Above info from - https://www.workzonesafety.org/crash-information/work-zone-fatal-crashes-fatalities/#ohio
Average # of Fatalities in Ohio's Work Zones per year (2010-2019)	19.7	# / year	
Average # of Work Zone Worker Fatalities in Ohio's Work Zones per year (2010-2019)	4.2	# / year	
% of Work Zone Worker Fatal Crashes in Ohio's Work Zones over National #	0.60%		
Estimate of Serious Injuries in National Work Zones	39,000	# / year	*Estimates of injuries occurring in work zones come from the Crash Report Sampling System (CRSS) and the General Estimates System (GES).*
Estimate of Serious Injuries in Ohio's Work Zones	235	# / year	*It is assumed that the ratio of serious injury occurance in Workers in Ohio vs the Nation is similar to that observed in (Worker Fatalities in Ohio)/(Fatalities Nationwide)*
Total Number of Work Hours in Ohio's Work Zones for all kinds of WZs	475,200	hrs	*Data now calculated using an assumption. Total # of Work Hours spent by all crews in Ohio per year.*
Total Number of Work Hours in Ohio's Work Zones using TMAs	237,600	hrs	*Data now calculated using an assumption. Assumed that 50% of all Work Zone Activity requires the use of a TMA.*
Total Number of Hours using the Alternative Device per year for 1 unit	900	hrs	*Data now calculated using an assumption. Coverage offered by 1 crew using 1 alternative device.*
Expected Crash Statistics in Ohio's Work Zones using Alternative Device			*It is assumed that rate of fatalities and serious injuries is linearly proportional to the number of work-hours spent in an activity, regardless of type of activity.*
Fatalities of Work Zone Workers	2.10	# / year	
Serious Injuries of Work Zone Workers	117.57	# / year	
Expected fatalities of Work Zone Workers covered when using Alternative Device	0.004		
Expected serious injuries of Work Zone Workers covered when using Alternative Device	0.22		
% Fatalities of Exposed Workers	60%	%	Data obtained from link 1 referenced below
% Fatalities of Equipment Safety Operators	40%	%	Data obtained from link 1 referenced below
For Exposed Workers using Alternative Device			
Fatalities of Exposed Work Zone Workers	0.0024	# / year	
Serious Injuries of Exposed Work Zone Workers	0.134	# / year	
For Safety Operators using Alternative Device			
Fatalities to Safety Operator Workers	0.0016	# / year	
Serious Injuries to Safety Operator Workers	0.089	# / year	
Estimated Medical and Work Loss Costs for Motor Vehicle Injuries			
Medical costs assigned to an injury that leads to a fatality in motor vehicle crashes	$ 11,114	$ / instance	*Based on data pulled from nationwide estimates. https://www.cdc.gov/injury/wisqars/cost/*
Medical costs assigned to serious injury motor vehicle crashes leading to Hospitalization	$ 54,197	$ / instance	
Medical costs assigned to serious injury motor vehicle crashes leading to ED Treatement and Discharge	$ 3,222	$ / instance	
Work Loss costs assigned to a motor vehicle crash leading to Fatality	$ 1,206,210	$ / instance	
Work Loss costs assigned to a motor vehicle crash leading to Hospitalization	$ 119,618	$ / instance	
Work Loss costs assigned to a motor vehicle crash leading to ED Treatement and Discharge	$ 3,935	$ / instance	

BENEFITS OF USING AN ALTERNATIVE DEVICE OVER A DUMP TRUCK

	Low Effectiveness	High Effectiveness	No Change	Notes
Reduced Chance of Serious Injuries to Exposed Workers	Low Effectiveness	High Effectiveness	No Change	*The use of Alternative Device solutions enables the application of Automatic Emergency Brakes or Object Detection, Collision Avoidance and Braking when workers are detected ahead post-crash. The presence of these features reduces risks for serious injuries and fatalities*
Value of Reduced Chance	20%	40%	0%	*These numbers on effectiveness of a solution are estimates.*
Reduced Chance of Fatalities to Exposed Workers	Low Effectiveness	High Effectiveness	No Change	*The use of Alternative Device solutions enables the application of Automatic Emergency Brakes or Object Detection, Collision Avoidance and Braking when workers are detected ahead post-crash. The presence of these features reduces risks for serious injuries and fatalities*
Value of Reduced Chance	35%	50%	0%	*These numbers on effectiveness of a solution are estimates.*

Reduced Chance of Serious Injuries to Safety Operator	Low Effectiveness	High Effectiveness	No Change	*In many cases use of the Alternative Device implies that safety operator is not present in the cabin. Hence the value of effectiveness of the solution to reduce injury is fairly high > 50%*
Value of Reduced Chance	50%	90%	0%	*These numbers on effectiveness of a solution are estimates.*
Reduced Chance of Fatalities to Safety Operator	Low Effectiveness	High Effectiveness	No Change	*In many cases use of the Alternative Device implies that safety operator is not present in the cabin. Hence the value of effectiveness of the solution to reduce injury is fairly high > 50%*
Value of Reduced Chance	50%	90%	0%	*These numbers on effectiveness of a solution are estimates.*

BENEFITS OF USING A PICKUP TRUCK OVER A DUMP TRUCK FROM MAINTENANCE, REPAIR, AND AVAILABILITY PERSPECTIVE	**VALUES**	**UNIT OF MEASURE**	**NOTES**
REPAIR COST ESTIMATES - When a truck gets damaged in a motor vehicle crash this number seeks to capture the estimate of labor and material costs			
Truck / Pickup Truck Repair Estimates			
Time to repair pickup truck	3	days	
Labor rate to repair pickup truck	140	$/hour	Used CEL Labor Rate Estimates for 2021. https://www.carmd.com/wp/vehicle-health-index-introduction/2020-carmd-state-index/
% value of repair parts and material	100%	%	Expressed as percentage of labor. For estimation assumed to match labor
Cost of parts and material	$ 3,360	$	
Total Estimate for Repair	$ 6,720	$	
Dump Truck Repair Estimates			
Time to repair dump truck	5	days	*Assumption - Diesel Dump Trucks need longer to work on.*
Labor rate to repair dump truck	110	$/hour	*Labor rate estimates*
% value of repair parts and material	100%	%	
Cost of parts and material	$ 4,400	$	
Total Estimate for Repair	$ 8,800	$	
Differential Benefits accrued in Repair of Regular Truck over Dump Truck	$ 2,080	$ / crash instance	
DOWNTIME AND RENTAL COSTS			
Truck / Pickup Truck Downtime Estimates			
Repair Turnaround Time [Repair Time + Scheduling Delays]	6	days	*Assumed scheduling delays are equal to repair time*
Rental Cost of a substitute to support mission critical winter operations	0	$ / day	*It is assumed that the pickup trucks scheduled to become a part of the alternative device are not used for snow&ice winter operations*
Pickup Truck Downtime Costs	0	$	
Dump Truck Downtime Estimates			
Repair Turnaround Time [Repair Time + Scheduling Delays]	10	days	*Assumed scheduling delays are equal to repair time*
Rental Cost of a substitute to support mission critical winter operations	500	$ / day	*This quote needs correction and review from ODOT. Data obtained from web search indicates $500/day Link (2)*
Dump Truck Downtime Costs	$ 5,000.00	$	
Differential Benefits accrued in Downtime Costs of Regular Truck over Dump Truck	$ 5,000.00	$ / crash instance	

Links and References

1 https://www.workzonesafety.org/crash-information/worker-fatalities-and-injuries-at-road-construction-sites-trends-and-statistics/transportation-incidents-causing-highway-worker-fatalities-at-road-construction-sites/

2 https://www.costowl.com/automotive/auto-dump-truck-rent-cost.html

BENEFITS OF USING THE ALTERNATIVE DEVICE OVER A TRUCK FOR ONE YEAR	BENEFITS VALUE	UNITS OF MEASURE	NOTES
Benefits are discussed in terms of differential benefits of using ONE alternative device over a dump truck.			
Benefits to Workers (Medical Costs)			
Reduced Serious Injuries to Safety Operator			
# of Serious Injuries in Ohio Workzones when using A.D	0.089	# / year	
Reduced Chance of Serious Injuries	Low Effectiveness	Effectiveness Category	
Reduced Chance of Serious Injuries - Value	50%	%	
Medical Cost of Serious Injuries	$ 28,710	$ / instance	*Assumed that of 50% of all serious injuries need Hospitalization and*
Potential benefits	$ 1,279	$ / year	*50% need Emergency Department Visit*
Reduced Fatalities of Safety Operator			
# of Serious Fatalities in Ohio Workzones when using A.D	0.0016	# / year	
Reduced Chance of Fatalities	Low Effectiveness	Effectiveness Category	
Reduced Chance of Fatalities - Value	50%	%	
Medical Cost of Fatalities	$ 11,114	$ / instance	
Potential benefits	$ 9	$ / year	
Reduced Serious Injuries to Exposed Workers			
# of Serious Injuries in Ohio Workzones when using A.D	0.134	# / year	
Reduced Chance of Serious Injuries	Low Effectiveness	Effectiveness Category	
Reduced Chance of Serious Injuries - Value	20%	%	
Medical Cost of Serious Injuries	$ 28,710	$ / instance	*Assumed that of 50% of all serious injuries need Hospitalization and*
Potential benefits	$ 767	$ / year	*50% need Emergency Department Visit*
Reduced Fatalities of Exposed Workers			
# of Serious Injuries in Ohio Workzones when using A.D	0.0024	# / year	
Reduced Chance of Fatalities	Low Effectiveness	Effectiveness Category	
Reduced Chance of Fatalities - Value	35%	%	
Medical Cost of Fatalities	$ 11,114	$ / instance	
Potential benefits	$ 9	$ / year	
Summation of Potential Medical Benefits	$ 2,064	$ / year	
Benefits to ODOT (Work Loss, Reduced Damage, Increased Dump Truck Uptime)			
Reduced cost of Indemnity for Motor Vehicular Crashes;			
For: Exposed Workers			
Work Loss Costs of Fatalities	$ 1,206,210	$ / instance	
Work Loss Costs of Serious Injuries	$ 61,777	$ / instance	*Assumed that of 50% of all serious injuries need Hospitalization and*
Potential Benefits	$ 2,658		*50% need Emergency Department Visit*
For: Safety Operator			
Work Loss Costs of Fatalities	$ 1,206,210	$ / instance	
Work Loss Costs of Serious Injuries	$ 61,777	$ / instance	
Potential Benefits	$ 3,711		
Reduced cost of Vehicular Crashes - Damage and Repair			
Differential Benefits of Repair Costs	$ 2,080	$ / instance	
# of Crash Instances needing repair	1	instance	*Assumed 1 crash instance (conservative) per 40hours of*

Reduced Cost of Repair	$ 2,080	$ / year	*Alternative Device Use*
Differential Benefits of reduced Downtime and Rental Costs			
Differential Benefits of Downtime and Repair Costs	$ 5,000.00		
# of Crash Instances needing repair	1	instance	
Reduced Cost of Downtime and Repair	$ 5,000.00	$ / year	
Summation of Potential Benefits to ODOT (Reduced Indemnity, Repair, Downtime & Rental)	$ 13,449	$ / year	This figure indicates the potential benefits to ODOT per 900 hours of A.D. deployment per year
TOTAL DIFFERENTIAL BENEFITS	$ 15,513		

SUMMARY OF SCENARIO EVALUATED

# of Alternative Devices	1	
Used for Job	LOW USE (A.D)	
Choice of Alternative Device	New Truck	
Choice of Technology	TYPE-C	
Weighted against	New Dump Truck with all features and options	
For a Work Zone Activity of	900	hrs/year

Economic Analysis suggests that,

DIFFERENTIAL COST OF USING CHOSEN ALTERNATIVE DEVICE OVER EXISTING CHOICE	$ 84,597	$/life
DIFFERENTIAL BENEFITS OF USING THE CHOSEN ALTERNATIVE DEVICE OVER EXISTING CHOICE	$ 15,513	$/year
Assumed life-time of device	5	years/life
DIFFERENTIAL BENEFITS OF USING THE CHOSEN ALTERNATIVE DEVICE OVER EXISTING CHOICE	$ 77,563	$/life

Is Alternative Device Economically Feasible	**Marginally-Infeasible**