

A multi-criteria decision support framework for autonomous truck-mounted attenuator deployment in mobile work zones accounting for economic and technical feasibility

by

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Abstract

Mobile short-term operations (e.g., patching, mowing) are essential for maintaining roadway functionality but can expose work-zone crews to high-risk conditions and environments, including sideswipe and rear-end crashes. The Autonomous Truck Mounted Attenuator (ATMA) is an innovative technology adopted by several transportation agencies as a safety countermeasure. ATMA operations consist of a leader vehicle (LV) that conducts maintenance work and a follower vehicle (FV) that operates autonomously, providing a safety buffer in mobile work zones. By removing the human operator from the FV, the ATMA system eliminates the possibility of injury to the worker in that vehicle. Despite its effectiveness, ATMA, as a relatively new technology, poses economic and operational feasibility challenges for the DOTs, requiring consideration of multifaceted factors. This research developed a decision-making tool based on a framework to evaluate the economic and operational feasibility of deploying ATMA systems. The decision-making tool includes two primary modules. The first module pertains to a Benefit-Cost Analysis (BCA), which assesses economic feasibility using a benefit-cost ratio (BCR) and sensitivity analyses. The second module is a Multi-Criteria Decision Analysis (MCDA) ranking module for facilities with both interrupted and uninterrupted traffic. This module uses key input variables (e.g., roadway geometry conditions and traffic flow) to evaluate ATMA deployment feasibility. This MCDA applies weighted criteria and evaluates three site alternatives to identify the ideal route segments with appropriate conditions for deployment. Several methods were incorporated into this tool, including the Weighted Sum Method (WSM), the Weight Product Method (WPM), the Preference Ranking Organization Methods for Enrichment Evaluations (PROMETHEE), and the Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS). The integrated framework provides a structured approach to assessing ATMA deployment feasibility, producing outputs such as economic indicators (i.e., BCR) and site alternative rankings. Sensitivity analysis indicated that a higher BCR was obtained when the average annual crashes involving TMAs increased. Also, the BCR increased with a longer ATMA life cycle, and the BCR decreased when the ATMA system integration cost increased.

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List of Abbreviations - BCA Tool

$N_{owned\ TMA_s}$	Number of owned TMAs
$N_{upgraded\ TMA_s}$	Number of TMAs upgraded to ATMA
LC	ATMA life cycle (years)
$N_{ATMA\ worker/unit}$	Number of workers
i	Annuity Rate
CRF	Capital Recovery Factor
$N_{Min\ TMA}$	Minimum number of TMAs needed in one mobile work zone
$N_{Total\ ATMA}$	Total possible ATMA-enabled work zones
$SIK\ Cost_{TMA}$	System integration kit cost unit
$EAV_{ATMA\ System}$	Equivalent annual value of the system integration Cost
$SM_{ATMA\ unit}$	Support and maintenance per unit and year
WHR	DOT worker hourly rate
$Training\ Cost_{ATMA\ unit}$	Training cost/unit
F_{Cost}	Fatal cost
F_{CR}	Fatal crash cost
DI_{Cost}	Disabling injury cost
DI_{CR}	Disabling injury crash rate
MI_{Cost}	Minor injury cost
MI_{CR}	Minor injury crash rate
$Work\ Zone\ Hits_{TMA}$	The average % of TMA hits occurred in a work zone
$FV\ Hits_{TMA}$	Percentage of TMA follower vehicle hits
$Risk\ Rate_{TMA}$	Risk rate probability involving TMA

AAH_{TMA}	Predicted average annual hits involving TMA
$N_{TMA\ Hits}$	Average number of TMA hits
$N_{Injured\ Workers}$	Average number of injured TMA workers
$WIHP_{TMA\ worker\ injury}$	Worker injury hits involving TMA
$N_{Expected\ TMA\ hits}$	Expected number of TMA hits (in a mobile work zone)
CR_{ATMA}	Crash rate involving ATMA
MWI_{ATMA}	Mitigated worker injury using ATMA

List of Abbreviations - MCDA Tool

i	Site Alternative
j	Criteria Variables
S_{ij}	Criteria Total Score
w_j	Criteria Weight
P_{ij}	Performance Criteria Score
V_{ij}	Weighted Sum and Weighted Product Variable
F_{ij}	Feasibility Total Score
r_{ij}	Normalized Criteria
x_{ij}	Criteria Total Score (for each site)
v_{ij}	Weighted Value Normalization
D_i^+	Distance Measurement for Ideal Criteria
D_i^-	Distance Measurement for Non-Ideal Criteria
C_i	Relative Closeness

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1 Introduction

1.1 Background

Highway work zones are considered high-risk environments for maintenance crews. These zones are frequently associated with a significant rate of crashes, injuries, and fatalities that occur each year. It was reported in 2009 through 2023, by the National Highway Traffic Safety Administration (NHTSA) Fatality and Injury Reporting System Tool, that a total of 2,767 motor vehicle crashes occurred within a general work zone (*NHTSA, 2025*). For a maintenance work zone with the same time frame, the total amount of motor vehicle crashes was 805 (*NHTSA, 2025*). These statistics highlight the critical need for comprehensive safety measures to prevent recurring fatalities and injuries in a work zone. The safety concerns associated with work zone traffic crashes vary by location, traffic volume, route geometry, barriers, and other environmental factors. Work zone management includes organizing temporary traffic control in compliance with the Manual on Uniform Traffic Control Devices (MUTCD) and scheduling maintenance activities while prioritizing the safety of Department of Transportation (DOT) employees and road users. Notably, there are several types of work zones in road construction (Table 1), including long-term stationary, intermediate-term, short-term stationary, short-duration, and mobile/moving activities (Datta et al., 2016). Table 2 lists different mobile work zone operations within the context of highway maintenance and construction (Improving the Safety of Mobile Lane Closures, 2009). Within types of work zones, there are two crash cushion types: stationary and mobile (AASHTO, 2011). These crash cushions represent truck or trailer-Truck-Mounted Attenuators (TMAs) (AASHTO, 2011). These TMAs are often used in mobile work zones (involving slow-moving operations, including lane striping, sweeping, bridge flushing, and pothole repair) to ensure safety. The TMA operates with a lead vehicle (LV) doing road repair and a following vehicle (FV) protecting the LV. Furthermore, the FV is operated by a human driver and has a crash cushion that absorbs the shock from potential collisions caused by passing traffic in the work zone (AASHTO, 2011). As a result, serious injuries (or possibly fatal) crashes occur for the worker in the FV of these tractor-trailer or TMA vehicles (AASHTO, 2011).

The Autonomous Truck-Mounted Attenuator (ATMA) is an alternate method that can prevent injury to the FV driver. In contrast to TMA operations, the FV in the ATMA functions independently without any operator. The absence of a human driver in the FV mitigates the risk

of injury and fatality to a DOT worker. The LV is protected against impact and can remain functional. The operation establishes a secure method for vehicles to navigate the work zone safely, thereby averting potential collisions. The Automated Driving System (ADS) enables the FV to sustain a gap distance while protecting the LV. This study concentrates on temporary mobile work zones, particularly analyzing the operational implementation of the ATMA.

Although TMAs are more common than ATMA, they are not the safest option, as ATMA remove the FV driver and operate autonomously. This research will continue to focus specifically on ATMA operations.

Table 1. Work Zone Categories based on Duration

Work Zone Type	Definition
Long-Term Stationary	More than 3 days of work
Intermediate-Term Stationary	Less than or equal to 3 days in daylight, or more than 1 hour at nighttime, for a work zone duration
Short-Term Stationary	More than 1 hour during the daylight hours
Short Duration	Up to 1 hour of work
Mobile	Intermittently or continuously

Table 2. Mobile Operation Types

Mobile Operation Nomenclature	Definition
1. No Shadow Vehicle	Low speed, short duration
2. Single Shadow Vehicle with TMA/AIPV	TMA, Low Speed
3. Two or More Shadow Vehicles with TMA	A second vehicle is added for protection (used on higher speeds, +45 mph, lane stripping/pothole patching)
4. Shadow Vehicle with ATMA	Low speed

1.2 Overview of ATMA Systems

In an ATMA deployment, an LV conducts maintenance work, while an FV, operating autonomously, serves as a safety buffer behind the LV. The FV is equipped with an ADS, which maintains a protective gap distance that shields LV from any foreseen collisions by errant traveling vehicles, see Figure 1 (the LV is on the left and the FV is on the right) (Miller & Pourfalatoun, 2021).



Figure 1. Colorado Department of Transportation (CDOT) - LV and FV of the ATMA Operation

By removing the driver in the FV, the ATMA operation enhances LV safety and significantly reduces the risk of fatalities and injuries (Miller & Pourfalatoun, 2021). ATMA systems have primarily been used for slow-moving maintenance operations, such as pothole patching, street sweeping, and crack sealing, and serve as a key safety solution for roadway operations (Kohls, 2020).

It was recognized that the Virginia Department of Transportation (VDOT) had designed and built an ATMA system that had undergone successful testing and evaluation. The preferred operational testing design components of VDOT's study included an ATMA speed of 15 mph or less, a GPS signal, a commanded following distance of 50-400 feet, commanded lateral offsets of ± 12 feet, clear weather, and night and day operations (White et al., 2021). This research developed an internal human-machine interface (HMI) system for the control operator to take over the lateral and longitudinal offsets of the FV, providing spatial awareness throughout the operation. It was noted that the ATMA system successfully monitors and reacts to objects within the safety zone between the LV and FV using LIDAR-based detection (White et al., 2021).

Additionally, LIDAR-based mapping data was used for navigation in GPS-denied environments (e.g., overpasses and tall obstructions). However, due to limited accuracy, further testing was needed and required to use LIDAR-based mapping in GPS-denied environments (White et al., 2021). Among the various states that have performed these tests, ATMA systems require extensive testing and can pose many challenges for deployment.

1.3 Challenges of ATMA Deployment

1.3.1 Effect of Traffic Environment and Weather

These challenges are relevant to location/facility type, geometry conditions, traffic conditions, connectivity, and weather conditions. The location could be urban, arterial, or have a higher AADT threshold. The geometric conditions include moving through roundabouts, horizontal/vertical curves, signalized intersections, all-way stops, and merging and diverging roadways. It can include route characteristics for interrupted (signalized intersections, merging, and stop/yield routes) and uninterrupted flow (interstate and highways). Past research studies that have tested ATMA under various conditions have identified suggestive guidelines for geometric conditions and determined which environment is best for ATMA operations (see the Literature Review).

The traffic conditions would involve multi-lane, interstate, or interrupted flow. On multi-lane or interstate highways, ATMA operations can cause delays and challenges, since ATMA is typically tested and operated at speeds of 5-15 mph (Agarwal et al., 2021). The slow-moving operation can decrease traffic flow and cause congestion, especially during peak hours. A solution is to deploy ATMA only during off-peak hours. The connectivity happens when vegetation, overpasses, high-rises, and vertical curves may obstruct the connection of the ATMA operation (Agarwal et al., 2021; Kohls, 2020)(Kohls, 2020).

Although this research doesn't provide solutions to the technical components of the ATMA system, it is important to be aware of these connectivity issues. This way, some of these obstructions can be identified and prevented before deployment can occur.

Severe weather conditions that are critical to avoid for ATMA operations include low visibility (e.g., fog/debris), rainfall, snow, and strong winds (Kohls, 2020; White et al., 2021). Severe weather variability can be harmful to connectivity, leading to malfunctions in sensors

and a lack of visibility during ATMA LV and FV operations (Kohls, 2020). Identifying these challenges for ATMA, these conditions can be properly addressed by creating guidelines to ensure the safety of the operations and the public.

1.3.2 Lack of Standards

The MUTCD and the Highway Capacity Manual (HCM) typically provide federal regulations for work zones. The purpose of the MUTCD is to provide regulations that focus on the safety and efficiency of signs, signals, and markings in work zones and non-work zones. The HCM provides guidelines for analyzing traffic flow and capacity, while strategically highlighting safer, efficient, and well-planned options. The American Association of State Highway and Transportation Officials (AASHTO) provides guidance on roadside and work zone safety. It has been identified that the MUTCD lacks clear guidelines and regulations for mobile work zones with ATMA deployments (USDOT, 2023). The regulations in the MUTCD pertain to slow-moving or mobile maintenance operations that are similar to, or are, the TMA operation (USDOT, 2023).

1.3.3 Deployment Guidelines

While ATMAs have emerged as valuable safety technology for protecting highway maintenance workers, there is currently no standardized, data-driven framework to guide state DOTs on when and where to deploy them. Most decisions regarding ATMA use are made on a case-by-case basis without consistent criteria or operational guidance. Additionally, limited research exists on identifying the key parameters and conditions that influence ATMA deployment decisions. This lack of structured guidance creates uncertainty and may hinder the effective and efficient use of ATMAs to reduce injuries and fatalities in work zones. Identifying the aforementioned gaps underscores the need for guidelines and regulations relevant to ATMA operations. It is important to develop a decision-making tool to inform and provide guidelines for the transportation agencies to ensure effective ATMA deployment.

1.4 Research Goals

To provide a decision-making tool to evaluate the economic and operational feasibility of implementing ATMA systems, this research aims to develop an agile framework for stakeholders. There are two primary components of the decision-making process. The first

module, a Benefit-Cost Analysis (BCA), uses a benefit-cost ratio (BCR) and sensitivity assessments to evaluate the economic feasibility of the potential project. The next step is to develop a Multi-Criteria Decision Analysis (MCDA) ranking module for facilities. This module considers both interrupted and uninterrupted traffic and uses significant variable inputs (such as roadway geometry and traffic flow) and procedures to determine whether ATMA deployment is feasible. By using weighted criteria and three site options, this MCDA compares the ideal route segment with acceptable deployment conditions. Several methodologies are incorporated into this tool, including the Weighted Sum Method (WSM), Weight Product Method (WPM), Preference Ranking Organization Methods for Enrichment Evaluations (PROMETHEE), and the Technique for Order Preferences by Similarity to an Ideal Solution (TOPSIS). The established framework, which combines economic and operational feasibility, offers a structured approach to evaluating the viability of ATMA deployment. It does this by producing economic indicators (such as BCR) and site alternative rankings.

2 Literature Review

2.1 Purpose and scope

Mobile work zones that use ATMA systems provide a safer option for the maintenance workers. However, implementing these technologies is challenging due to integration, operations, or system maintenance issues, particularly because ATMA is still a relatively new application in work zones. Therefore, proper evaluation and performance testing are essential before deployment and in developing feasibility guidelines. Past research studies are supported by various states that have tested and deployed ATMA operations. This literature review outlines the key parameters and challenges identified in previous deployments, as well as dimensions relevant to the development of both decision-making tools. The goal is to explore the findings from previous studies and to use those insights to develop the BCA and MCDA tools.

2.2 Safety in Mobile Work Zones

Safety in a work zone is the main priority during maintenance operations. As technology continues to advance, ongoing research builds on past studies to improve safety protocols. These efforts support the implementation of well-tested safety measures that enhance worker protection statewide. For example, one report found that more than 64% of the responding DOTs do not use devices to reduce the exposure of workers on foot in conducting work activities within the mobile work zones, such as automated equipment to perform crack sealing, patching, installing, etc. (Improving the Safety of Mobile Lane Closures, 2009). Among the DOTs that do use the automated equipment, it is mostly used for litter debris removal vehicles, pothole patching trucks, magnet trucks, and channelizing devices (Improving the Safety of Mobile Lane Closures, 2009).

Some operations along the road are either intermittent or continuous and fall under the umbrella of a mobile work zone (Improving the Safety of Mobile Lane Closures, 2009). Intermittent mobile operations often involve frequent short stops, similar to stationary work zones, while continuous operations include workers and equipment moving along the road at low speeds without stopping (Improving the Safety of Mobile Lane Closures, 2009). The TMA and ATMA operations are the main types of mobile work zone operations used. Both consider safety technologies and are often equipped with connectivity and GPS signaling devices. It has been identified that the presence of multiple work vehicles improves driver awareness by providing motorists with signaling a larger work zone operation (Improving the Safety of Mobile Lane Closures, 2009). In general, providing

maintenance vehicles and protective equipment (e.g., ATMA) can benefit the worker from crash risk and create precautions on the roadway for drivers to remain alert while traveling through a work zone. By removing the driver in the FV to decrease potential injuries and fatalities (Miller & Pourfalatoun, 2021).

2.3 Past Studies on ATMA Deployment Piloting

This section provides insight into the number of states that have invested in and continue to invest in testing ATMA operations. Each state has its slight differences in testing sites, design, and deployment plans (Table 3).

Table 3. ATMA Operations Deployed by State DOT

ATMA Application Considered or Tested	Definition	Site Description	State DOT	Location
Striping	Applying pavement markings (lines) to guide traffic.	Highways, multilane highways	Colorado, Missouri	US 50 near Lee's Summit, Missouri
Pothole Patching	Repairing holes in the pavement surface.	Various types of facilities, low-volume roads.	Missouri, North Dakota, Rhode Island, and Indiana	
Sweeping	Cleaning debris from the road surface.	Various types of facilities, including a mainline highway.	Missouri, North Dakota, Rhode Island	
Trash Pick-up, litter removal	Collecting and removing litter from roadways.	Rural two-lane highways, various types of facilities.	Tennessee, Indiana	Shoulders of roadways.

ATMA Application Considered or Tested	Definition	Site Description	State DOT	Location
Pavement Testing	Assessing the strength and condition of the road pavement, often using a falling weight deflectometer (FWD).	The falling weight deflectometer (FWD) testing is a mobile stop-and-go operation that requires intermittent stops.	Florida	FDOT Maintenance Office in Gainesville, FL
Cone Placement	Setting up traffic cones for lane closures or channelizing traffic.	It could be considered for various road types.	Colorado (considered)	
Litter Removal	Removing trash and debris from the roadside.	Mobile work zone operations.	Indiana	
Crack Sealing	Sealing cracks in the pavement to prevent water infiltration.		Indiana	

2.3.1 Colorado Department of Transportation (CDOT)

CDOT conducted a research study for the deployment of ATMA operations. The operation

performed line striping and traveled more than 200 miles of roadway. It had an AADT of less than 2,500 vehicles per day. It was concluded that the AADT threshold should be 5,000 vehicles per day based on the ATMA line striping operation on rural roads and highways (Brown et al., 2023).

2.3.2 California Department of Transportation (Caltrans)

This research study, initiated by Caltrans, tested the performance of the ATMA on public roadways while complying with DMV (Department of Motor Vehicles) regulations. The purpose of this study was to further understand and enhance the ATMA system and operational standards (Agarwal et al., 2021).

2.3.4 Florida Department of Transportation (FDOT)

This study, conducted by FDOT, was for an ATMA performance test spanning 28 miles of roadway. Along with the test, ATMA was on a closed-loop and an open-loop roadway. The route included various roadway types, such as high-speed, semi-urban, and multi-lane roads. Additionally, the test was integrated into an active work zone and executed a pavement operation (Agarwal et al., 2021).

2.3.5 Minnesota Department of Transportation (MnDOT)

Similar to past DOT studies, MnDOT conducted an ATMA test on a two-week closed and open-to-the-public road. MnDOT had their employees suggest that, during LV performance on lower roads, there was a need for a larger screen and some concerns about the FV's acceleration being too fast. There were two tests: an ATMA operation for shoulder and guardrail repair, and another for lane striping in a rural area (Brown et al., 2023).

2.3.6 Missouri Department of Transportation (MoDOT)

This study conducted a performance test and ATMA deployment for a lane striping maintenance operation, specifically focusing on nighttime and daytime hours. MoDOT examined the ATMA system, including the GPS signal, the gap distance between the LV and FV, and the operational speed. It concluded with potential causes of the dead reckoning (DR) issues, supported by Google Earth and video data (Brown et al., 2023).

2.3.7 Tennessee Department of Transportation (TDOT)

TDOT performed an ATMA operation test within a work zone. The study initiated 24 cases for the operation. The operation was consistent with a roll-ahead distance and noted to consider rangefinders using laser technology capabilities. Based on findings from the gap distance between

the LV and FV and the operation speed, the research concluded that the best environment for the ATMA is within a continuously moving work zone (Kohls, 2020).

2.3.8 Indiana Department of Transportation (INDOT)

INDOT participated in this research study that focused on and analyzed the ATMA system during operation. The system was tested during daytime and nighttime hours on closed and open roadways, including interstates, highways, and local roads. The open-road tests included various types of work zones, including sweeping, trash pickup, crack seal, raised pavement marker (RPM) inspection, and underdrain inspection (Tian et al., 2025).

2.4 Development of ATMA Deployment Guidelines

2.4.1 Limitations of Current Mobile Work Zone Guidelines

The MUTCD provides nationwide guidelines for transportation infrastructure and work zone safety. Some states have their own MUTCD guidelines, and some follow the national MUTCD standards. MUTCD provides general guidelines for mobile work zones; these parameters are limited to traffic control and do not provide direction for using AMT, specifically for ATMAs. For instance, the MUTCD guidelines for mobile operations often involve frequent short stops for activities such as litter cleanup, pothole patching, or utility operations, and are similar to short-duration operations (USDOT, 2023). In other mentions, work zone activities that are continuous, with workers and equipment moving along the roadway at slow speeds, while the warning area moves with the work zone. To minimize disruption and avoid high traffic volumes, mobile operations work should be scheduled during off-peak hours (USDOT, 2023). Establishing clear guidelines for mobile work zones used in ATMA operations will help DOTs and other agencies navigate the decision-making process for deployment.

2.4.2 Integrating New Guidelines and Considerations

Encouraging ATMA deployment for work zones is increasingly becoming common for DOTs to consider implementing, testing, and applying guidelines. Some of the major conditions and guidelines look at roadway segments, whether that be multi-lanes/interstates or two-way lane roads, the impact of traffic volumes with speed reduction of the ATMA, weather, and environmental conditions. For instance, environmental conditions, such as overgrown foliage and overhead obstructions, can negatively impact GPS signal reception (Agarwal et al., 2021). These limitations and capabilities of the ATMA are among the various factors needed to revise the

guidelines for this operation. The following subsections present the operational characteristics identified in past research by many state DOTs.

2.4.3 Roadway Geometry Conditions

Specific roadway geometry conditions can negatively impact ATMA operations, including roundabouts with a particular threshold radius, horizontal curves, intersections, grade percentage, terrain, lane width, and shoulder width. It was noted that the ATMA system is designed for tangent operation, and, as such, roundabout, untraditional, or innovative intersection designs must be avoided (Agarwal et al., 2021). For roundabouts, the ATMA can handle a minimum of 130 feet or (65-foot radius). For non-severe curves, a radius of greater than 65 feet is required (Agarwal et al., 2021).

2.4.4 Traffic Conditions - AADT and Time of Operation

Mobile work zones typically operate at lower speeds than typical traffic flow. A traffic flow model was developed in a study (Tang et al., 2022) that examined capacity along the route. This was particularly needed to examine vehicle delay and density using next-generation simulation (NGSIM) data. This model produced an effective discharge rate discount, achieving errors of 6.3% to 13.6%. This results in a more desirable design, specifically looking at a multi-lane highway. The modeling K factor was 0.09, the D factor was 0.6, and the peak hour factor was 0.9 (Tang et al., 2022). This study showed that the level of service (LOS) was categorized as C level, with an average annual daily traffic (AADT) threshold of 40,000 vehicles per hour. Therefore, the AADT resulted in a free-flow state with zero delays. Lastly, it was concluded that the slow-moving ATMA operation allows vehicles to safely maneuver without delay (Tang et al., 2022).

Another research study focused on enhancing multi-state merging for a two-lane highway with an ATMA operation. One challenge was accounting for the reduced maneuverability caused by the speed discrepancy between the ATMAs and regular vehicles, which can lead to congestion. An analytical model was developed that yielded better outcomes and greater accuracy than HCM. This concluded that the ATMA operation should have an AADT that is below 11,000 vehicles per day (Tang & Hu, 2022).

The ATMA systems can have limitations regarding the time of operation. Operations that occur at night, when traffic flows are lower, have a lower impact on traffic. Although there are some additional risks to operating at night, such as reduced visibility, the potential for higher travel

speeds resulting from lighter traffic volumes, and differences in both drivers' and workers' behavior (Improving the Safety of Mobile Lane Closures, 2009). It is important to note that typical mobile lane closures do occur at night, and proper operational cautions for both peak and non-peak hours are needed regardless. The following are some of the common mobile lane closure operations that occur at night (Table 4) (Improving the Safety of Mobile Lane Closures, 2009).

Table 4. Common Maintenance Performance Types for Mobile Lane Closure Operations at Night Only

Type	Performance & Explanation
Pavement marking	Installation & removal
Raised pavement markers	Installation & replacement
Shoulder rumble strips	Installation
Pavement sweeping	Cleaning maintenance
Pavement sampling	Coring, pavement soundings, skid tests, etc.
Pavement repairs	Limited in scope, such as pothole patching and other small repairs.
Debris cleanup	Routine cleanup and removal of debris, and emergency removal of storm debris and spilled material.
Vegetation control	Application of herbicides adjacent to the shoulders.
Post-mounted delineators	Repair, replacement, installation
Small roadside signs	Repair, replacement, installation
Cleaning drainage facilities	Catch basins, drop inlets, etc.
Emergency repairs	Miscellaneous operations necessary to restore safe highway operations that can be completed within a few minutes. Operations requiring longer exposure of work crews should use stationary traffic control setups.
Incident management	Unplanned incidents may require the setup of detours, road closures, diversions, etc., to control traffic through or around the incident area.

2.4.5 Connectivity, Obstructions, and Weather Conditions

Florida tested and evaluated ATMA in an active work zone. The tests included maintenance on pavement operations. It reported that weather conditions such as heavy rain, wind, fog, and snow degrade the connectivity of the sensors (radar and lidar), thereby jeopardizing the GPS signal connection, and potential loss of communication with the LV and FV. VDOT also concluded that heavy rain, snow, wind, and fog are not conducive to ATMA and can impair its functionality (VDOT, 2021). Additionally, other research studies found that foliage and tree canopies in the way of the ATMA operation resulted in connectivity issues, including GPS signal reception errors. The overgrown foliage or tree height could be an important consideration to seek before deployment (Agarwal et al., 2021). Not only tree canopies, but also overpasses, obstructions such as structures, or poor infrastructure conditions within a highway can result in GPS signal errors (Kohls, 2020).

2.5 Decision-Making Tool Applications

The purpose of applying a decision-making tool for ATMA deployment was to properly evaluate factors and conditions that can positively or negatively impact the operation. This provides users with a simpler way of approaching the decision-making process. Using these two tools can help formulate responses to whether the ATMA is economically feasible, when and where to deploy, and which route criteria would need to be considered for deployment.

Furthermore, the decision-making tool utilizes a framework for users to gather the process of how this tool and application can be used (Figure 2). The framework begins with identifying if there is a pre-existing TMA or equivalent for implementing an ATMA update within the inventory fleet. This depends on DOTs or other agencies to check inventory needs. Once the operational system is available, the data collection is needed to input costs, crash data, and then route characteristics into the tools. The decision-making tool is broken up into two parts that start with the BCA and are followed by the MCDA tool. The BCA must be evaluated first to identify if the ATMA system is economically feasible to move forward with the next tool. As long as the BCR output exceeds 1.0, meaning the ATMA is feasible. The MCDA dives into the route characteristics that include geometry, traffic flow, and weather-related factors for the ATMA to operate successfully. The MCDA provides weighted criteria and site alternatives with each method (e.g., WSM) to further determine the ATM deployment feasibility score. If the feasibility score yields a lower value, then the ATMA is no longer a feasible option, and the BCA is not needed anymore.

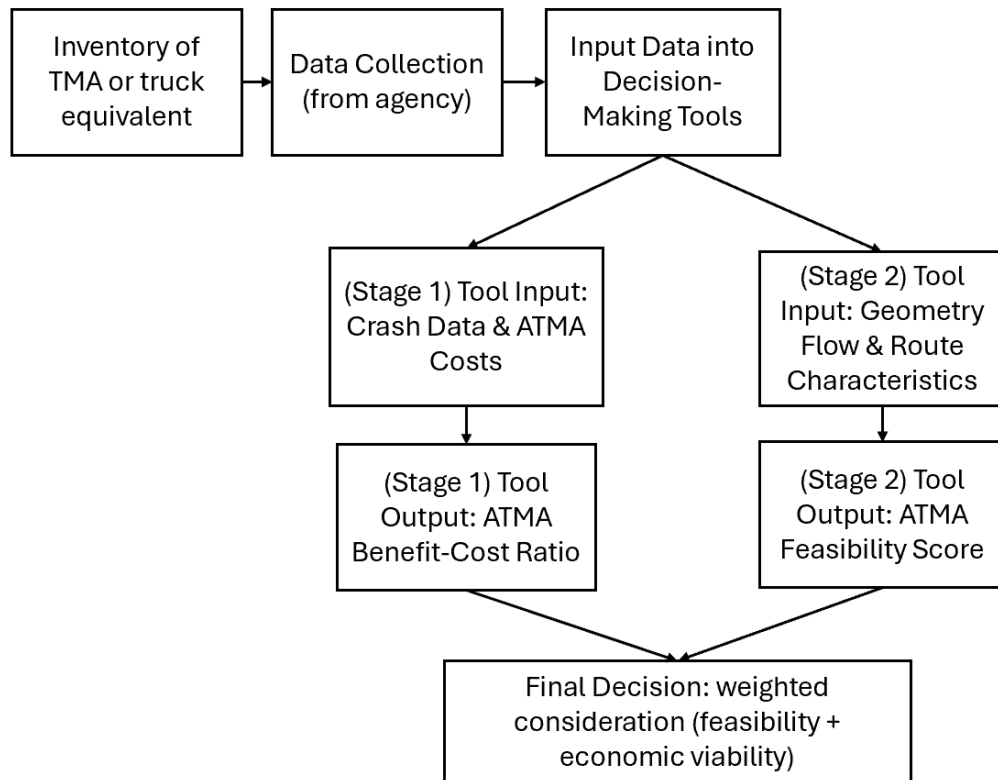


Figure 2. Decision-Making Framework for ATMA Deployment

2.5.1 BCA Tool

In MoDOT’s research efforts, an economic analysis tool was developed to quantify the benefits and costs of the Leader-Follower TMA (or ATMA) deployment (Brown et al., 2023). The tool provided costs that include system integration, maintenance, worker hourly rate, and training for users to input. Additionally, including crash-severity costs, which resulted in cost reductions when utilizing the ATMA. This ATMA system provides FV worker crash avoidance and reduction in worker hourly rates, and other associated economic costs. The results of the tool had a BCR of 0.83, which indicated that the ATMA would not have been seen as feasible or successful (Brown et al., 2023). The BCR would have needed to be greater than 1 for this ATMA deployment to be considered beneficial. In conclusion, the BCA tool benefits and costs would have needed to be adjusted for the BCR to result as a feasible option for ATMA.

2.5.2 MCDA Tool

The MCDA tool is used in the second phase to determine ATMA feasibility. As long as the BCR is considered to be of benefit. This MCDA tool incorporates route characteristics and criteria (e.g., roadway geometry, traffic conditions) based on ATMA operational components. Various methods were used to create and compute each multi-criteria and site alternative for comparing which ATMA scenario is best and most feasible for deployment. The following methods that were integrated into the tool are the WSM (with a value tree representation), WPM, PROMETHEE, and TOPSIS methods. Evaluating past reports provided guidance on the computation of the WSM and WPM (Equations 1 and 2) (Bozorg-Haddad et al., 2020).

$$V_{ij} = \sum_{j=1}^n w_j \times r_{(ij)} \quad \forall i \quad (\text{Equation 1})$$

$$V_{ij} = \sum_{j=1}^n [r_{(ij)}]^{w_j} \quad \forall i \quad (\text{Equation 2})$$

The value tree included was based on past research studies that developed an understanding of normalization and weights. The value tree provides multi-level relative weights that determine the normalizing cumulative weights of tree members (e.g., leaf, branch, root) (Bruhn & Leleur, 2014). This value tree can be added to any of the other methods to provide a visual representation and a weighted hierarchy for multi-level criteria.

The TOPSIS and PROMETHEE methods were described in past reports, including their computations and processes. The TOPSIS method was used to identify the best alternative, the one closest to the positive ideal solution (optimal solution) and farthest from the negative ideal solution (inferior solution) (Tzeng & Huang, 2011). The PROMETHEE method has an outranking system built into each criterion that uses pairwise comparisons of alternatives to determine different relation-degrees between them (Tzeng & Huang, 2011). This method has four versions that differ in the type of order used by each set of alternatives. For instance, the PROMETHEE (II) uses the complete preorder, which is an easier approach to decision-making and yields a single complete solution (Tzeng & Huang, 2011). The complete preorder is the only option suitable for the desirable outcome in the PROMETHEE method.

3 BCA Methodology

3.1 Overview

This chapter describes the methodology of the developed BCA tool, which generates a benefit-cost ratio (BCR) to evaluate the economic feasibility of deploying ATMA systems within a given jurisdiction (e.g., statewide deployment). This evaluation in this analysis pertains to mitigating worker injuries and crash avoidance. This serves as an economic feasibility decision-support tool before applying the MCDA framework, focusing on the site-specific technical and operational feasibility of the ATMA systems. When the calculated BCR is less than 1, the MCDA tool would no longer be needed, making it economically infeasible.

The developed BCA tool leverages previous efforts by the FDOT and the MoDOT. These studies and efforts evaluated key assumptions for the BCR computation. One of these assumptions encouraged the utilization of pre-existing trucks or TMAs that are readily owned and operated by DOTs, which can be retrofitted to support ATMA systems. This approach avoids the need to purchase new trucks and TMAs, thus reducing capital and inventory costs. In addition, most ATMA vendors have a system integration kit specifically designed for retrofitting existing trucks and TMA systems.

3.2 Purpose of BCA

The purpose of developing the BCA tool was to provide transportation agencies with a clear understanding of the return on investment associated with ATMA deployment. While improving worker safety is the main objective, the ATMA operations can offer economic benefits. These benefits include reductions in labor costs associated with the FV. Because the ATMA FV operates autonomously, removing the driver reduces exposure to potential crash risks, thereby decreasing worker injury and fatality rates.

Furthermore, this BCA tool allows DOTs to incorporate their own jurisdiction-specific operational costs and key variables as necessary to obtain the BCR. These variable inputs include the distribution of crash severity, estimated crash costs, TMA risk, and past TMA hits (Figures 3 and 4). Agencies are expected to evaluate and provide these inputs, along with any additional information, before applying them to the BCA tool. The crash data and variables are extracted to quantify the need for the ATMA system, particularly seeking to mitigate worker injuries.

3.3 The Cost and Benefit Elements

The BCA framework establishes a diverse array of cost and benefit variables that serve as a realistic economic support tool for ATMA deployment. Cost elements include ATMA operational and maintenance costs, crash costs, and agency worker training costs. The benefit elements reflect reductions in crash costs, worker hourly savings, and the economic cost savings from avoided worker injuries through the use of the ATMA operation. Crash costs were used from KDOT, but users are encouraged to input their local state crash costs (FY 2026 Crash Costs, 2025). The crash severity information is used to estimate the benefits associated with the avoidance of worker-injury outcomes from ATMA operations.

The BCA primarily pertains to components and variables considered on a per-unit basis for the ATMA or TMA, meaning the benefit does not change if the number of upgraded TMAs exceeds one. Crash cost data and related parameters are treated as input variables, enabling agencies to provide accurate, jurisdiction-specific information. By using proportional crash-severity data and cost inputs, the BCA tool produces a realistic BCR. It is important to recognize that these variables are subject to change over time, and agencies may incorporate additional information related to the ATMA present-value costs and benefits as they see fit.

3.4 Workflow of the Tool

The workflow consists of four steps that address cost components, benefit components, and calculations required to obtain the BCR (Figure 3). This workflow uses a comprehensive example that shows pre-determined values and computational procedures based on FDOT and MoDOT reports, providing a clear representation of the tool applications.

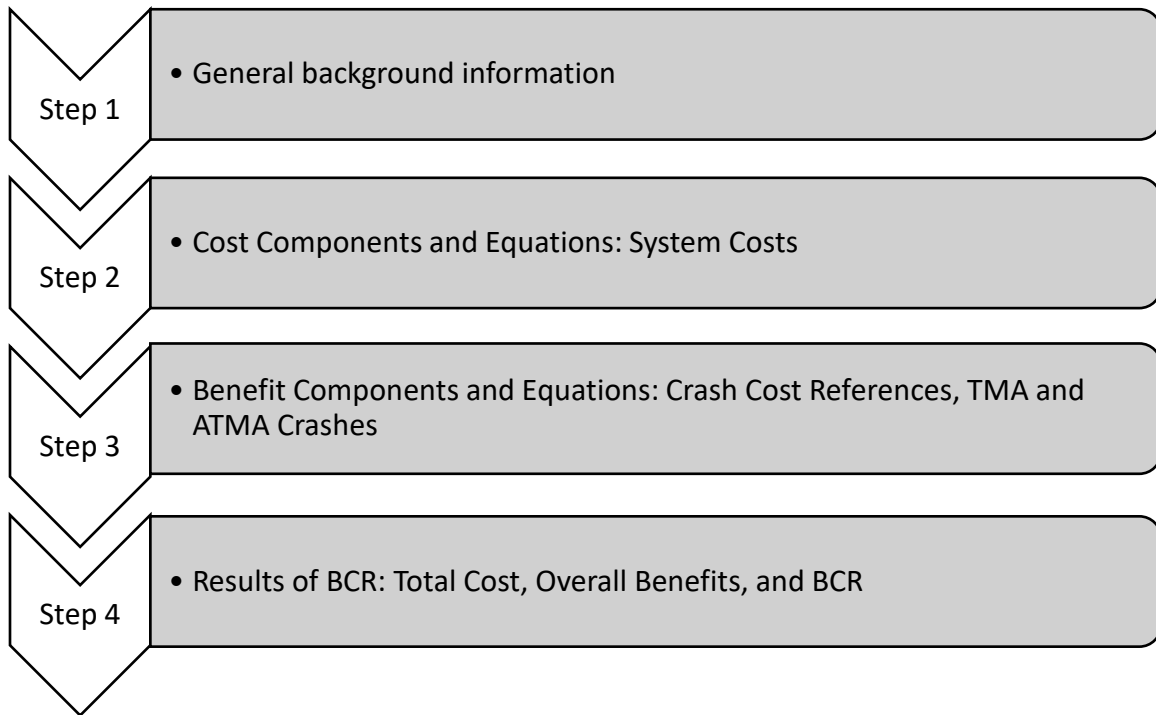


Figure 3. Workflow of the Developed BCA Tool

3.4.1 Step 1 - General background information

This BCA tool begins with incorporating background information and establishing any key assumptions. The purpose of including this background information is to support predecessor computations and to utilize pre-existing resources and data to customize the tool for each DOT. These resources and components specifically address using pre-existing trucks or TMAs to encourage DOTs to upgrade them to the ATMA system. Looking at the operational or salvageable conditions required for the ATMA upgrade to be considered. This upgrade suggests a more cost-effective solution than buying a new ATMA system if the ATMA upgrade is available to DOTs with pre-existing TMAs. It is recognized that TMAs must have at least 2 trucks (LV and FV) in a mobile work zone operation. The upgrade to ATMA would account for only one truck, specifically the FV. Therefore, the number of ATMAs would be half of the TMA fleet.

In addition, with the use of the ATMA system, the life cycle would also need to be addressed, depending on the vendor's criteria. This provides DOTs with an accurate timeline for these ATMA service lives, reflecting a good investment. The number of workers in each operational unit in a TMA operation should be considered to assess the benefits of improving worker safety through

ATMA deployment. Establishing other components, such as the annuity rate and the capital recovery factor (CRF), provides a baseline for calculating the present value of the BCR. The CRF is used to convert a present value to equal annual payments over time. The CRF pertains to the initial investment recovered from a specific period with a given interest rate or annuity rate. The annuity rate provides the costs and benefits to be accounted for as present value with the designated interest rate, equal periodic payments, and the number of pay periods. This CRF is then used to derive the equivalent annual value (Equation 3) (Brown et al., 2023).

$$CRF = \frac{i(1+i)^{LC}}{(1+i)^{LC}-1} \quad (\text{Equation 3})$$

3.4.2 Step 2 - Cost Components and Equations

The primary cost components were limited to using existing TMA system equipment (for pre-existing trucks and TMA), maintenance support costs, training costs, and fuel (Brown et al., 2023). The cost of the existing TMA system includes technical integration. More specifically, this kit provides equipment that is retrofitted for these pre-existing trucks or TMAs. This cost may vary depending on the vendor and DOTs that own trucks or TMAs. The system integration cost and the CRF for the ATMA system were used to establish the equivalent annual value (Equation 4). The upgraded ATMA system will need to account for any maintenance support costs if damage or operational malfunction were to occur. Additionally, this necessitates operational maintenance for the ATMA if the system experiences issues or incurs additional operational fees. Before deployment, the need for maintenance support cannot be foreseen; it is essential to include it in the BCA to provide DOTs with an accurate BCR for establishing whether this ATMA is a good investment.

$$EAV_{ATMA\ System} = SIK\ Cost_{TMA} \times CRF \quad (\text{Equation 4})$$

Along with maintenance costs, worker hourly rates, and training costs, the tool included these costs. The worker costs pertain to the hourly rate per operation route for each worker who would operate the LV in the ATMA unit. The training is for the ATMA workers to test and perform the operation before deployment. Typically, the vendor offers a week-long training program, which can be delivered by MoDOT engineers (Brown et al., 2023). The training cost per ATMA unit

includes the worker's hourly rate and the training hours (Equation 5). Lastly, the fuel cost for the ATMA operation was provided to obtain realistic costs for the tool BCA.

$$Training\ Cost_{ATMA\ unit} = N_{ATMA\ worker/unit} \times Hours\ per\ week \times WHR$$

(Equation 5)

The crash severity costs and crash rates were incorporated into a tool that estimated costs. The types of crash severities pertain to: fatal, disabling injury, minor injury, and property damage only (Table 5) (Brown et al., 2023; FY 2026 Crash Costs, 2025). Property-damage-only crashes were excluded from all computations because this tool is primarily concerned with the avoidance of worker injury severity. The crash severity costs were based on the state of Kansas cost-of-living adjustment factors and the consumer price index ratios for each severity (Brown et al., 2023). The proportional crash rate for TMA hits is an estimate across all roadway facility types and potential severities that can occur during operation. It is assumed that all facility types produce the same crash-severity distribution within TMA and ATMA (Brown et al., 2023).

Table 5. Crash Cost Reference - Estimated TMA Crash Proportions

Crash Severity	Comprehensive Crash Injury Cost	Proportional Crash Rate for TMA hits (all roadway types)
Fatal: F_{Cost}, F_{CR}	\$14,068,681.00	0.009
Disabling Injury: DI_{Cost}, DI_{CR}	\$780,971.00	0.041
Minor Injury: MI_{Cost}, MI_{CR}	\$252,626.00	0.228
Property Damage Only (PO)	-	0.722

3.4.3 Step 3 - Benefits Components and Equations

The primary benefits of using an ATMA include removing the FV worker from harm's way, reducing worker hourly rates/costs, and reducing potential crash costs. Many specific variables were essential to include in this tool to acquire this primary benefit. These variables pertain to the TMA risk rate, the average annual TMA hits, and the possibility of a worker injury TMA hit rate may require historical data and further analysis to obtain. Furthermore, to quantify the benefits,

the analysis incorporates the average percentage of a TMA hit that occurs within a mobile work zone, and the percentage of the TMA FV or the last vehicle to be hit. Incorporating both percentages presents the risk rate that involves the TMA. The risk rate looks at the probability of the TMA hits and the occurrence of the last TMA being hit (Equation 6). The probability of the TMA risk rate is within 0-1; if the value is closer to 1, then that would be a greater risk of harm. The purpose of calculating the risk rate pertains to the reduction of TMA hits and worker injury when using the ATMA.

$$Risk\ Rate_{TMA} = Work\ Zone\ Hits_{TMA} * FV\ Hits_{TMA} \quad (Equation\ 6)$$

The predicted average annual hits involving TMA not within a mobile work zone and the worker injury hit rate were calculated using historical data about previous years' crash reports. The predicted average annual hits is estimated from historical data from 3 to 5 years to obtain the total amount of TMA hits, also pertaining to non-mobile work zones. The worker injury hit rate, in particular, was based on predictive probability due to the lack of accurate data pertaining to TMA. The average number of TMA hits and the average number of injured workers were key inputs for the estimated proportion of a TMA crash in which the worker was injured (Equation 7). This proportion is supportive evidence that ATMA could avoid this worker injury outcome. It is important to take away that not all TMA hits lead to worker injury, which is the evidence as to why the expected injury proportion is necessary. Including this TMA hits data and other variables constitutes the risks of TMA, thus further promoting the use of ATMA and obtaining potential low-risk benefits. This is due to notable TMA hits and estimations that can also be treated to further encourage the use of ATMA operations.

$$WIHP_{TMA\ worker\ injury} = \frac{N_{Injured\ workers}}{N_{TMA\ Hits}} \quad (Equation\ 7)$$

The crash rate and mitigated worker injury outcomes were assessed, with the result of a reduction in crashes and injury when ATMA is involved. The expected number of TMA hits was based on historical data from the calculated risk rate and the average annual hits involving TMA (Equation 8).

$$N_{Expected\ TMA\ hits} = Risk\ Rate_{TMA} * AAH_{TMA} \quad (\text{Equation 8})$$

This value represents an estimation of TMA hits that could occur. The probability that ATMA would avoid injury was derived from the number of upgraded TMAs and the total ATMA FV in a work zone (Equation 9). The total number of pre-existing owned TMAs considers the LV and FV; the ATMA would just account for the FV to be upgraded, thus the total TMA fleet would be cut in half.

$$P_{ATMA\ avoid\ injury} = \frac{N_{upgraded\ TMAs}}{N_{Total\ ATMA}} \quad (\text{Equation 9})$$

Based on the probability that an ATMA would avoid injury and the expected number of TMA hits, the crash rate would need to be considered. This crash rate only looks at the estimated crashes that involved the ATMA, which includes just the 1 truck or FV (Equation 10).

$$CR_{ATMA} = N_{Expected\ TMA\ hits} \times P_{ATMA\ avoid\ injury} \quad (\text{Equation 10})$$

The mitigated worker injury using ATMAs was calculated using the estimated proportion of workers injured in a TMA hit rate and the estimated crash rate that involved ATMAs (Equation 11). This variable helps identify the ATMA benefit from reducing worker injury. The proportional rates of the crash rate and mitigated worker injury from ATMA (Brown et al., 2023). For every benefit component, proportion, and average given as input can be found through the respective state's DOT and its historical crash database.

$$MWI_{ATMA} = WIHP_{TMA\ worker\ injury} \times CR_{ATMA} \quad (\text{Equation 11})$$

3.4.4 Step 4 - Results of BCR

The cumulative benefit of upgrading an ATMA is reducing or eliminating worker injury severity, worker hours, and their designated costs. Compiling each step of this BCA is crucial to obtaining the end goal of the BCR. In step 2, each cost was included to get the total cost of using an ATMA

system (Equation 12). These cost items were determined by input data from the general information regarding the number of upgraded TMAs, the system integration kit cost with the annuity rate, and the additional system cost items. The system integration kit cost with the annuity rate and life cycle of 10 years was considered to be an equivalent annual value of the ATMA system.

$$Total\ Cost = N_{upgraded\ TMAs} \times (EAV_{ATMA\ System} + SM_{ATMA\ unit} + Training\ Cost_{ATMA\ unit} + Fuel\ Cost)$$

(Equation 12)

In this final step, the overall present value benefits were strategically calculated using crash costs such as the weighted average comprehensive crash injury cost, with the proportional probability of each crash severity, all pertaining to one injured worker (Equation 13). Additionally, the life cycle (e.g., 10 years), annuity (e.g., 2 %), and the mitigated worker injury using ATMA were also provided as default values and can be input by the user in the overall benefit computation.

$$Overall\ Benefit = \frac{(F_{Cost} \times F_{CR} + DI_{Cost} \times DI_{CR} + MI_{Cost} \times MI_{CR})}{(F_{CR} \times DI_{CR} \times MI_{CR})} \times MWI_{ATMA} \times LC \times CRF$$

(Equation 13)

The total cost and overall benefits were used to find the BCR (Equation 14). If the BCR were greater than 1, this would result in a significant economic benefit of using an ATMA. The cost adjustments and other varying factors, such as lower crash costs and lower system costs, can outweigh and increase the benefit of using an ATMA.

$$BCR = \frac{Overall\ Benefit}{Total\ Cost}, BCR > 1$$

(Equation 14)

3.5 Computational Demonstration

This computational example provides a complete walkthrough and output of the BCA tool. The users would follow each step and input the designated values as needed. These inputs are denoted in the orange cells, and the derived calculations are in the orange font (Figures 4 and 5).

The results of this example, concluded in a BCR of 1.10, are considered to be of benefit to deploy an ATMA.

General Info		
Number of Owned TMAs, $N_{owned\ TMAs}$	500	
Number of TMAs Upgraded to ATMA, $N_{upgraded\ TMAs}$	1	
Min. Number of TMAs needed in one mobile work zone, $N_{Min\ TMA}$	2	
Total Possible ATMA-enabled work zones, $N_{Total\ ATMA}$	250	
ATMA Life Cycle (Years), LC	10	
Number of Workers, $N_{TMA\ worker/unit}$	4	
Annuity Rate, i	0.02	
Capital Recovery Factor, CRF	0.111	
Cost Items & Calculations		
System Integration Kit Cost per ATMA unit, $SIK\ Cost_{ATMA}$	\$ 298,245.00	
Equivalent Annual Value of the System Integration Cost, $EAV_{ATMA\ System}$	\$ 33,202.58	
Support and Maintenance/unit/year, $SM_{ATMA\ unit}$	\$ 1,000.00	
DOT Worker Hourly Rate, WHR	\$ 14.00	
Training cost/unit, $Training\ Cost_{ATMA\ unit}$	\$ 2,240.00	
Fuel Cost/unit	\$ 1,000.00	
Other costs (optional)		
Crash Cost Reference		
Crash Severity	Comprehensive Crash Injury Cost	Estimated Proportions
Fatal: F_{Cost}, F_{CR}	\$14,068,681.00	0.009
Disabling Injury: DI_{Cost}, DI_{CR}	\$780,971.00	0.041
Minor Injury: MI_{Cost}, MI_{CR}	\$252,626.00	0.228
Property Damage Only (PO)	-	0.722

Figure 4. BCA Example - General Information, Cost Calculations, and Crash Cost Reference

TMA Crashes	
Average % of TMA Hits occurred in a work zone, Work Zone Hits $_{TMA}$	84.2%
% of Time TMA Follower Vehicle Hits, FV Hits $_{TMA}$	70.0%
Risk Rate Probability Involving TMA (Follower TMA Risk Rate), Risk Rate $_{TMA}$	58.9%
Average Annual Hits Involving TMA (number of TMA hits), AAH $_{TMA}$	45
(Total) Average Number of TMA Hits, N $_{TMA}$ hits (work zone)	159
Average Number of Injured Workers, N $_{Injured\ workers}$	71
Worker Injury Hit Rate Involving TMA (Possibility of a worker being injured in a TMA hit), WIHP $_{TMA\ worker\ injury}$	0.447
ATMA Crashes	
Expected Number of TMA Hits, N $_{Expected\ TMA\ hits}$	26.52
Probability that ATMA would avoid injury, P $_{ATMA\ avoid\ injury}$	0.004
Crash Rate Involving ATMA (Number of crashes with ATMA), CR $_{ATMA}$	0.106
Mitigated Worker Injury using ATMA (Number of workers injured mitigated by ATMA), MWI $_{ATMA}$	0.047
Benefit-Cost Ratio	
Total Cost	\$37,442.58
Overall Benefit	\$41,022.97
BCR	1.10

Figure 5. BCA Example – TMA Crashes, ATMA Crashes, and BCR

3.6 BCA Sensitivity Analysis

The BCA sensitivity analysis provides an understanding of how this tool can perform and identify the best options for the BCR outputs. There are three analyses that obtain changes with the ATMA life cycle, the ATMA system integration cost, and the annual average TMA hits, all with respect to the BCR changing. The first analysis shows that as the ATMA life cycle increases in time, the BCR will also increase (Figure 6). The second analysis shows that as the ATMA system integration cost increases, the BCR decreases due to the cost outweighing the benefit (Figure 7). The third analysis displays that as the annual average TMA hits increase, the BCR also increases (Figure 8). This means that the benefit increases with using ATMA as a replacement for TMA when it increases in hits.

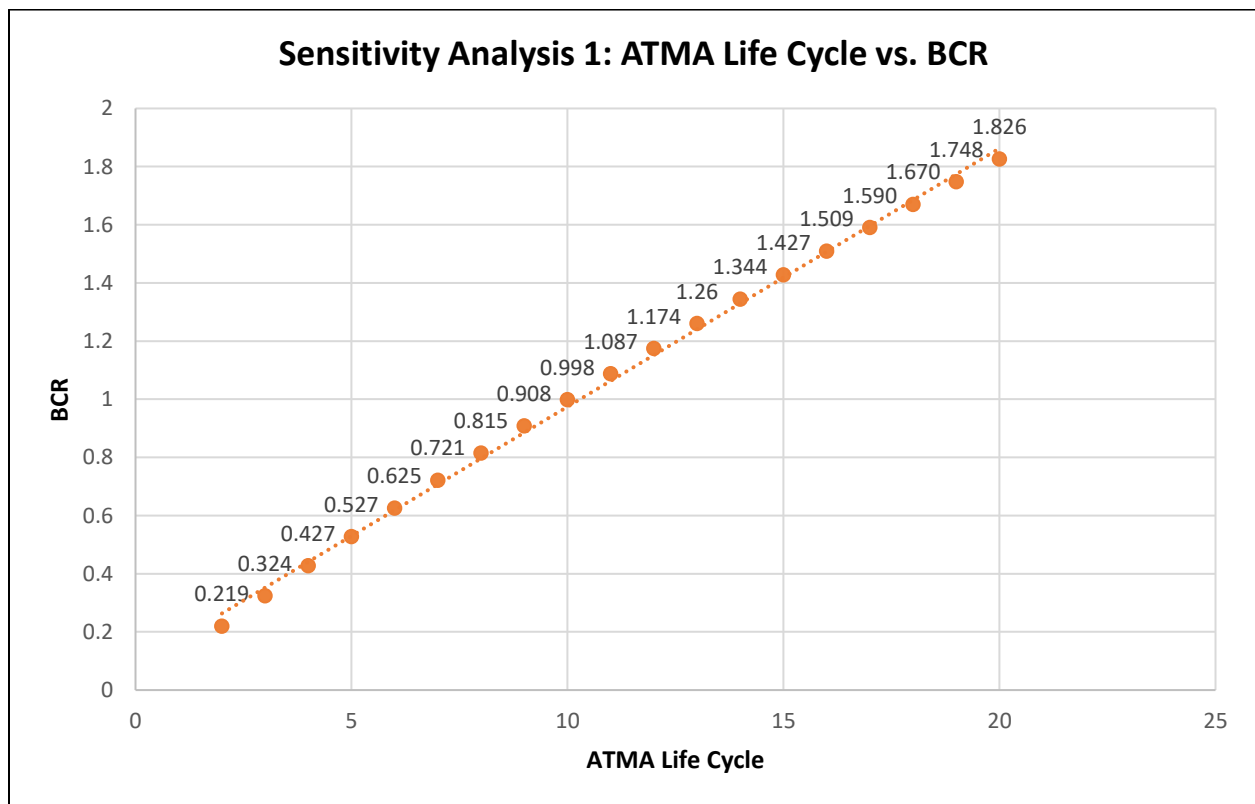


Figure 6. Sensitivity Analysis 1 – ATMA Life Cycle vs. BCR

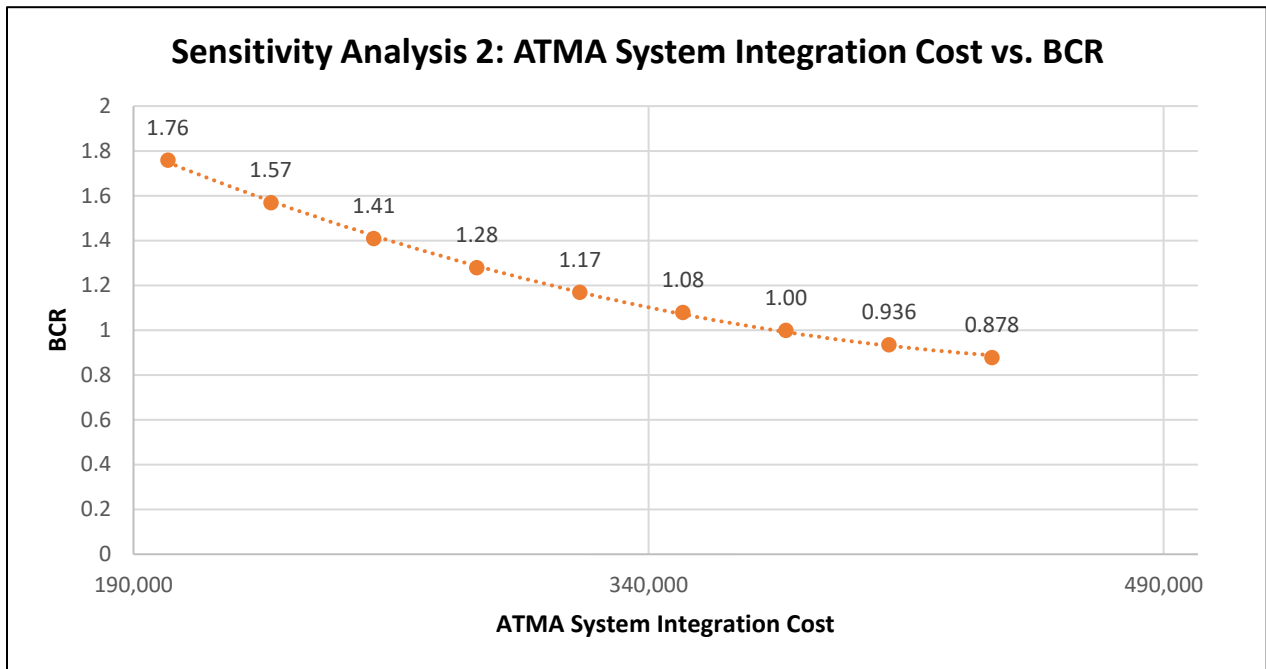


Figure 7. Sensitivity Analysis 2 - ATMA System Integration Cost vs. BCR

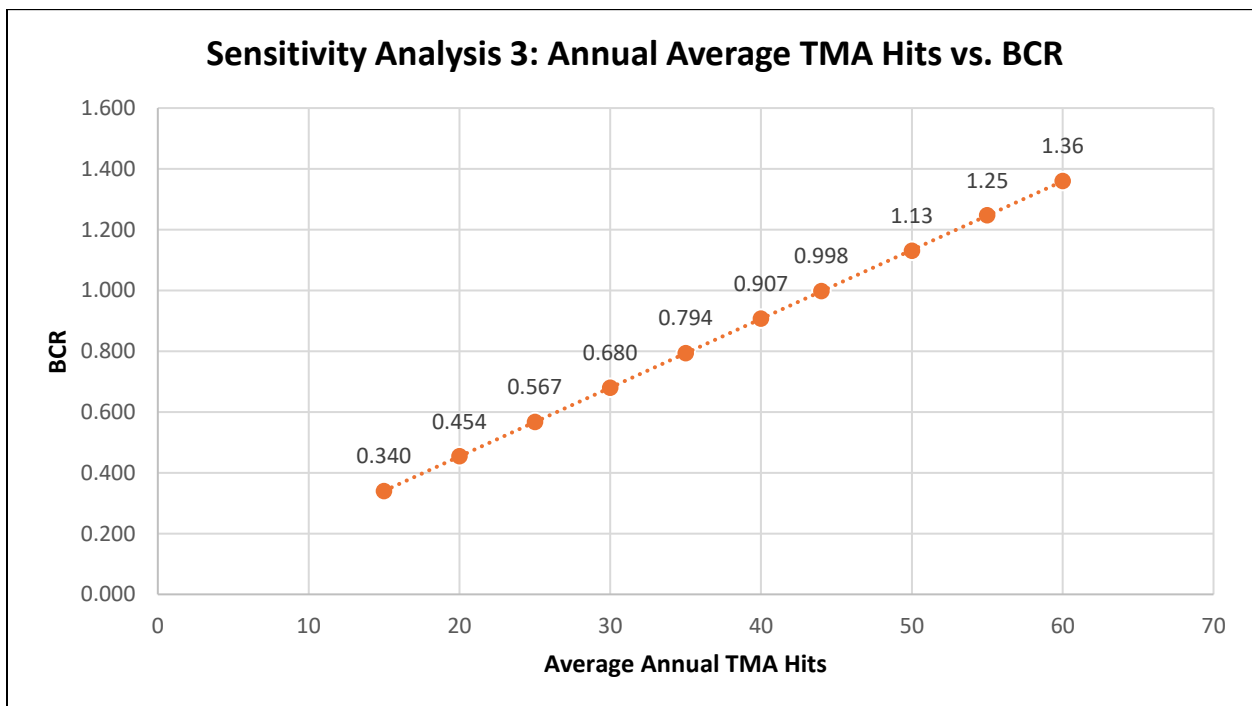


Figure 8. Sensitivity Analysis 3 – Annual Average TMA Hits vs. BCR

4 MCDA Methodology

4.1 Overview

This chapter provides the research methodology focusing on the development processes of the decision-making tool involving ATMA operations. Based on the upcoming need for mobile work zones utilizing ATMA, the tool supports the evaluation and development process. The main objective of ATMA operations is to enhance proper safety precautions by using appropriate protective measures and route conditions within the work zone. This tool is intended for DOTs and other branches of authorities to utilize and identify the best-suited projects and environments to deploy ATMA.

4.2 Purpose of MCDA

The MCDA was integrated into this research to provide a structured framework for the decision-making tool process. This framework incorporates multiple methods that utilize weighted alternatives using a normalized ranking system. Each method considers both interrupted and uninterrupted traffic flow conditions, which define specific segment criteria and site alternatives. Interrupted flow refers to roadway segments with network intersections (e.g., signalized intersections), along with factors such as connectivity and weather. In contrast, uninterrupted flow applies to homogeneous roadway segments, including two-way, multi-lane, and interstate facilities, and evaluates criteria such as geometry conditions, traffic flow, connectivity, and weather.

For both interrupted and uninterrupted flow conditions, each method evaluates site alternatives based on defined route characteristics. While the criteria differ between these traffic conditions, they are consistently structured across all methods. Each method also includes a default set of weights that can be adjusted by the user. The MCDA tool, developed in Microsoft Excel, incorporates several methods, including the Weighted Sum Method (WSM) with a values tree, Weighted Product Method (WPM), PROMETHEE Method, and TOPSIS Method.

To provide consistency, the tool applies scoring rules for each roadway configuration (e.g., interrupted and uninterrupted traffic flow), with values ranging from 0 to 100, where 0 represents the least desirable alternative, and 100 represents the most desirable alternative. These scores are

based on predefined, arbitrary values that standardize comparisons across methods to provide normalization. Similarly, each method includes default weighted values, ranging from less than 0.2 (low importance) to 0.5 or greater (high importance), which can be modified as needed.

This analysis tool accounts for site alternatives using their designated weights to generate an overall feasibility output. The purpose of assembling this framework was to provide an approach for representing preferences on multiple criteria (Bruhn & Leleur, 2014). The three site alternatives (e.g., A, B, C) serve as comparative options for ATMA deployment, each corresponding to specific route characteristics and deployment conditions. Having more than three sites is doable, but may require reconfiguration of the tool.

Transportation agencies, such as DOTs, can use this tool by inputting criteria values for every alternative. For example, lane width can be selected (by DOTs) from a predetermined list within the tool that includes the specific widths to select from. Decision-makers are responsible for selecting appropriate route characteristics for each work zone or site alternative, after which the tool computes the output for the ATMA feasibility score.

4.3 Method Selection for the MCDA Tool

The four methods that were incorporated in this MCDA tool provide users with the choice of using the most suitable method for their given parameters. Each method is unique and best suited for specific reasons for deployment. For instance, if the user wants to identify the right site alternative in which to pilot, the TOPSIS method would be best. The TOPSIS method is best for comparing the best and worst-case solutions. The PROMETHEE is best for complex decision-making that uses a pairwise ranking and a positive and negative net flow ranking. The WSM and WPM are best for simple absolute and relative comparisons, respectively.

4.4 Value Tree

The MCDA framework cultivated and developed a multi-level value tree that represents hierarchy and pre-determined weights. This structure facilitates the application of relative and cumulative weighting within the decision-making process (Bruhn & Leleur, 2014). Relative weights are arbitrary and assigned to branch and leaf criteria, all of which are connected through a common root.

This value tree is displayed and organized from right to left, beginning with the leaf level, followed by the branch and root levels, and culminating in the overall result. The leaf nodes are assigned the same scoring range of 0 to 100, and the branch and root take on the score of the leaf with its designated weight score for each criterion. At the far-left end of the value tree, the structure converges into a single overall score, which represents the outcome of the analysis and provides the ATMA feasibility score.

4.4.1 Workflow of Value Tree

The value tree provides a framework for the development of the MCDA tool and serves as a visual representation to enhance user comprehension. The tree outlines the criteria and their associated weights for each site alternative. These weights can be adjusted by the user based on the relative importance of each criterion at the leaf, branch, and root levels.

Each level of the value tree (leaf, branch, and root) represents specific characteristics of the route under evaluation. The value tree was directly incorporated into the weighted sum method (WSM) to properly distinguish the comprehensive tree or hierarchy structure and weighting of criteria. While the value tree can also be applied to other methods used in this MCDA tool (e.g., WPM, TOPSIS, PROMETHEE), it is not necessarily required for each method, and it does not affect the overall feasible outcome. The other methods, including WPM, TOPSIS, and PROMETHEE, do not have the separate weighted values for each leaf, branch, and root. Instead, it has one level of weighted values for each criterion, which encompasses all levels of weighted values from the value tree.

4.4.2 Value Tree Example – Uninterrupted and Interrupted Segments

This example of the value tree displays the structure of the uninterrupted and interrupted criteria for one site alternative. Both uninterrupted and interrupted examples include the values using the (WSM calculations) for each leaf, branch, and root, along with the arbitrary weighted values (Figures 9, 10, and 11). For this example, only the WSM for uninterrupted (two-way and multi-lane/interstate) homogeneous segment and interrupted (network of intersections) displays the value tree, but can still be incorporated into other methods. A homogeneous segment represents a uniform roadway with consistent traffic conditions throughout.

Overall, users will be able to include criteria and weights in the WSM or any method, and the value tree will automatically update and compute each value to get the ATMA feasibility score.

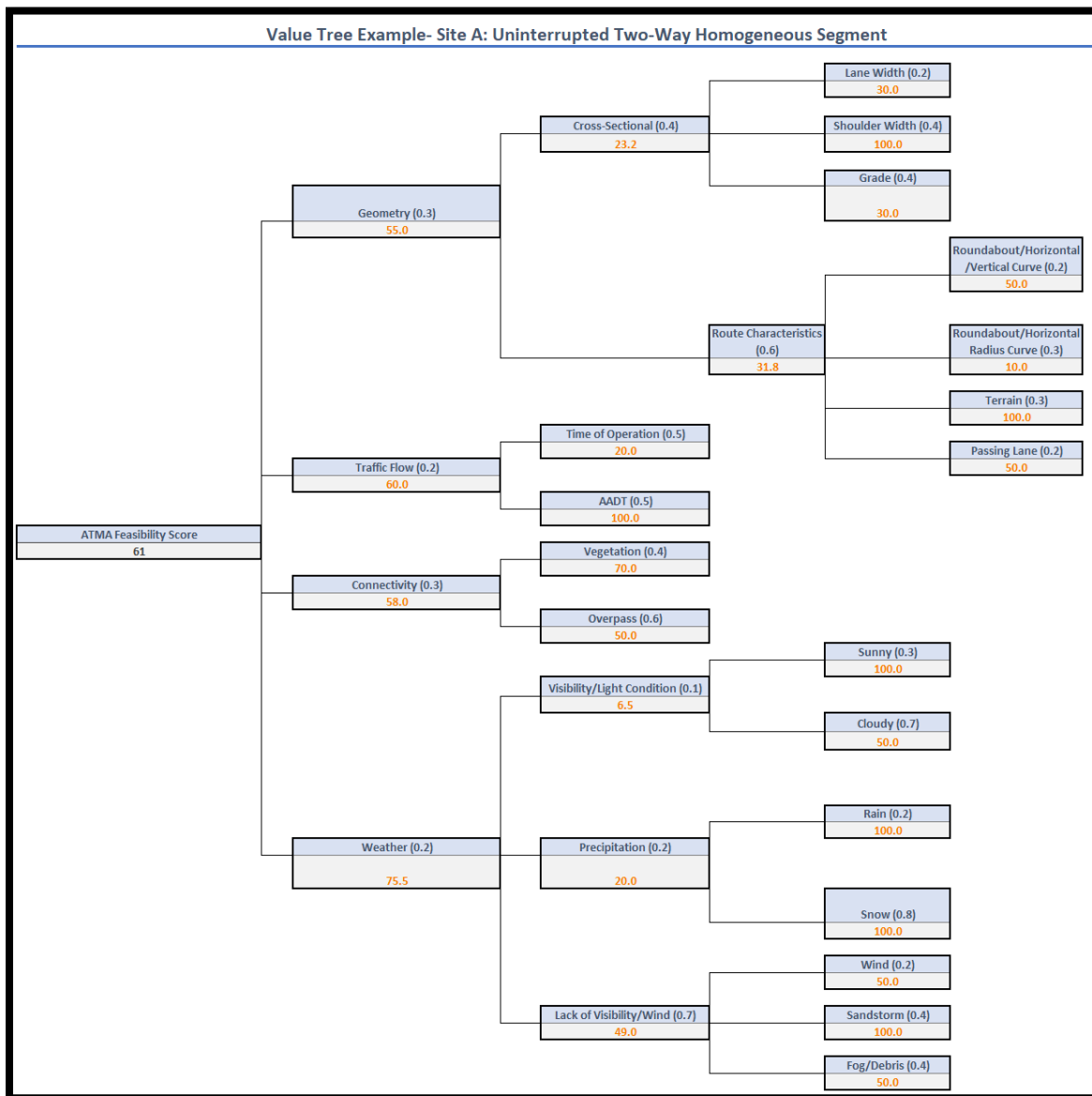


Figure 9. Value Tree Example – Uninterrupted Two-Way Homogeneous Segment (Site A)

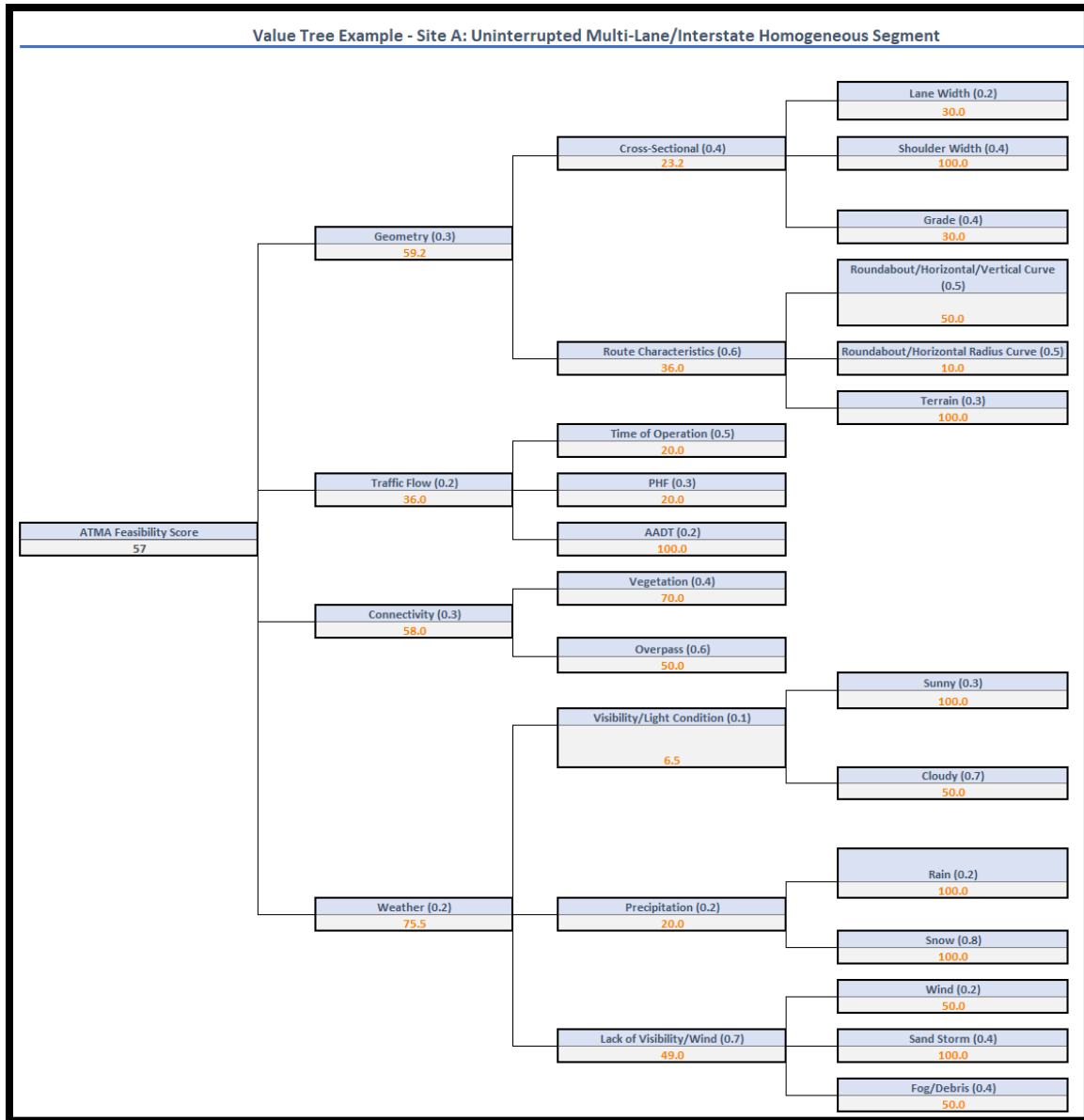


Figure 10. Value Tree Example – Uninterrupted Multi-Lane/Interstate Homogeneous Segment (Site A)

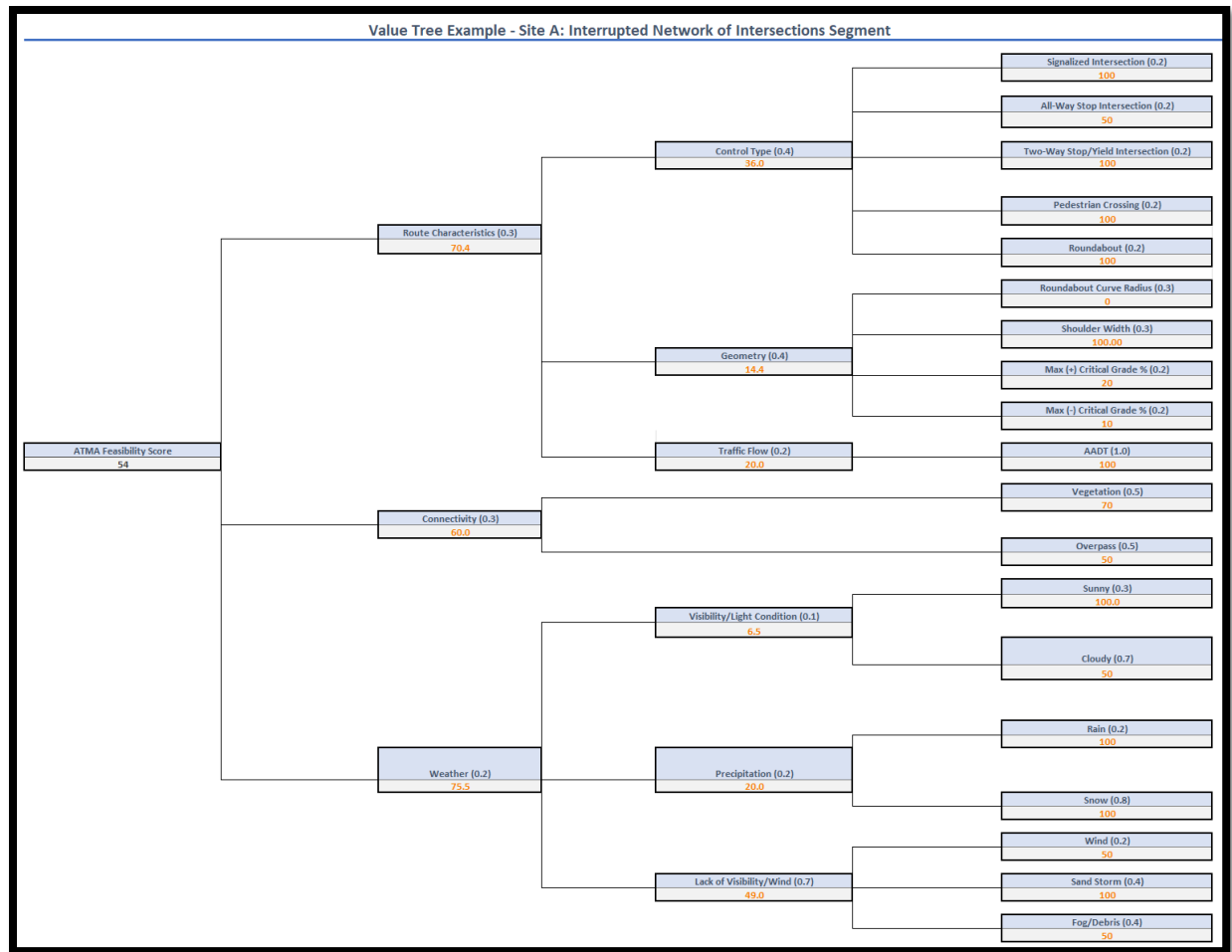


Figure 11. Value Tree Example – Interrupted Network of Intersections Segment (Site A)

4.5 Weighted Sum Method

The WSM was incorporated into this MCDA tool to provide a straightforward approach for developing absolute weights using predetermined scoring rules. This approach reflects the real-life criteria for a work zone route, all within the ATMA operating route. Across all MCDA methods, a consistent structure is maintained, utilizing the same conditions and criteria (for interrupted and uninterrupted), scoring rules (ranging from 0 to 100), and predetermined weights. As a result, this method provides a simplistic baseline for evaluating ATMA feasibility. It is also more user-friendly compared to the other methods and integrates the hierarchical structure of the value tree.

4.5.1 Workflow of WSM

The WSM, when combined with the value tree, calculates the results by multiplying the weight at each level (leaf, branch, and root) and summing the weighted values to produce an overall score. Furthermore, WSM can also be computed and applied independently of the value tree structure. As mentioned previously, it can be integrated into any other MCDA method.

4.5.2 Step 1 - Background Information

The WSM with combinations of the value tree has the general inputs for each criterion level for the leaf, branch, and root. Users input each criterion and weight with each site alternative (e.g., A, B, C).

4.5.3 Step 2 - Weighted Sum Computation

Once the background information is input from the user, the tool will automatically compute the weighted sum for each site alternative. The computation expression is as follows (Equation 15) (Bozorg-Haddad et al., 2020).

$$V_{ij} = \sum_{j=1}^n w_j \times r_{(ij)} \quad (\text{Equation 15})$$

4.5.4 Step 3 - Total Feasibility Score

After the weighted sum is computed, the total feasibility score for each site-alternative is used to determine the suitability of ATMA deployment. This final WSM score ranges from 0 to 100, where 0 represents the least desirable solution and 100 represents the most desirable solution.

4.5.5 WSM Example - Uninterrupted and Interrupted Segments

The WSM example showcases each uninterrupted and interrupted segment for one alternative. This tool operates based on user input highlighted in orange cells. The results of the uninterrupted two-way segment concluded with an ATMA feasibility score of 69, which is considered able for deployment; however, the closer to 100, the better (Figure 12 and Table 6). Table 6 lists the overall uninterrupted (two-way) results with a ranking system that compares each site's alternatives (A, B, and C). The site A for the uninterrupted multi-lane/interstate segment came out to have a feasibility score of 57, and site A, the interrupted segment, had a feasibility score of 54 (Figures 13 and 14).

Site A Alternative									
Weight Look-Up: <= 0.2= Not critical (low importance), 0.3 = Moderate, 0.4 to 0.5 or >= Critical (high importance)									
Root Weight	Criteria			Assigned (Estimated) Weight	Score from Defined Rules (0-100)	Leaf Weighted Score	Branch Weighted Score	Root Weighted Score	
0.3	Geometry Conditions	Lane Width	10 ft	0.2	30	6.0	23.2	55.0	
		Shoulder Width	>4 ft	0.4	100	40.0			
		Grade	(-4% to -2%)	0.4	30	12.0			
		Roundabout/Horizontal/Vertical Curve	Present	0.2	50	10	31.8		
		Roundabout/Horizontal/Radius Curve	<65 ft	0.3	10	3.0			
		Terrain	Level	0.3	100	30.0			
		Passing Lane	Not Present	0.2	50	10.0			
		Cross-Sectional			0.4	N/A	N/A		N/A
		Route Characteristics			0.6				
0.2	Traffic Flow	Time of Operation	4 PM-6 PM	0.5	20	10.0	N/A	60.0	
		AADT	500 to 1000	0.5	100	50.0			
0.3	Connectivity	Vegetation	<50%	0.4	70	28.0	N/A	58.0	
		Overpass	Present	0.6	50	30.0			
0.2	Weather	Sunny	Yes	0.3	100	30.0	6.5	75.5	
		Cloudy	No	0.7	50	35.0			
		Rain	No	0.2	100	20.0			
		Snow	No	0.8	100	80.0	20.0		
		Wind	Yes	0.2	50	10.0			
		Sand Storm	No	0.4	100	40.0			49.0
		Fog/Debris	Yes	0.4	50	20.0			
		Visibility/Light Condition			0.1	N/A	N/A		
		Precipitation			0.2				
		Lack of Visibility/Wind			0.7				
ATMA Feasibility Score		61							

Figure 12. WSM – Uninterrupted Two-Way Homogeneous Segment (Site A)

Table 6. WSM Uninterrupted Two-Way Example Results with Site Alternative Ranking

Site	Results	Ranking	Key Limiting Factors
A	61	Rank 2	- Moderate geometry feasibility - Moderate traffic flow - Moderate connectivity issues - Low severe weather
B	69	Rank 1	- Moderate to low geometry feasibility - Optimal traffic flow - Low connectivity issues - Low severe weather
C	59	Rank 3	- Low geometry feasibility - Poor traffic flow - Low connectivity issues - Low severe weather

Site A Alternative									
Weight Look-Up: <= 0.2= Not critical (low importance), 0.3 = Moderate, 0.4 to 0.5 or >= Critical (high importance)									
Root Weight	Criteria			Assigned (Estimated) Weight	Score from Defined Rules (0-100)	Leaf Weighted Score	Branch Weighted Score	Root Weighted Score	
0.3	Geometry Conditions	Lane Width	10 ft	0.2	30	6	23.2	59.2	
		Shoulder Width	>4 ft	0.4	100	40			
		Grade	(-4% to -2%)	0.4	30	12			
		Roundabout/Horizontal/Vertical Curve	Present	0.5	50	25	36.0		
		Roundabout/Horizontal/ Curve Radius	<65 ft	0.5	10	5			
		Terrain	Level	0.3	100	30			
		Cross-Sectional		0.4	N/A	N/A	N/A		
		Route Characteristics		0.6					
0.2	Traffic Flow	Time of Operation	4 PM-6 PM	0.5	20	10	N/A	36.0	
		PHF	0.75-0.85	0.3	20	6			
		AADT	500 to 1000	0.2	100	20			
0.3	Connectivity	Vegetation	<50%	0.4	70	28	N/A	58.0	
		Overpass	Present	0.6	50	30			
0.2	Weather	Sunny	Yes	0.3	100	30	6.5	75.5	
		Cloudy	No	0.7	50	35			
		Rain	No	0.2	100	20			
		Snow	No	0.8	100	80	20.0		
		Wind	Yes	0.2	50	10			
		Sand Storm	No	0.4	100	40			
		Fog/Debris	Yes	0.4	50	20	49.0		
		Visibility/Light Condition		0.1	N/A	N/A			N/A
		Precipitation		0.2					
		Lack of Visibility/Wind		0.7					
ATMA Feasibility Score		57							

Figure 13. WSM – Uninterrupted Multi-Lane/Interstate Homogeneous Segment (Site A)

Site A Alternative									
Weight Look-Up: <= 0.2= Not critical (low importance), 0.3 = Moderate, 0.4 to 0.5 or >= Critical (high importance)									
Root Weight	Criteria			Assigned (Estimated) Weight	Score from Defined Rules (0-100)	Leaf Weighted Score	Branch Weighted Score	Root Weighted Score	
0.3	Route Characteristics	Signalized Intersection	No	0.2	100	20	36.0	70.4	
		All-Way Stop Intersection	Yes	0.2	50	10			
		Two-Way Stop/Yield Intersection	No	0.2	100	20			
		Pedestrian Crossing	No	0.2	100	20			
		Roundabout	No	0.2	100	20			
		Roundabout Curve Radius	N/A	0.2	0	0	14.4		
		Shoulder Width	>4 ft	0.3	100	30			
		Max (+) Critical Grade %	4%	0.2	20	4			
		Max (-) Critical Grade %	< -6%	0.2	10	2			
		AADT	500 to 1000	1	100	100			20.0
		Control Type			0.4	N/A	N/A		N/A
		Geometry			0.4				
		Traffic Flow Conditions			0.2				
0.3	Connectivity	Vegetation	<50%	0.5	70	35	N/A	60.0	
		Overpass/Tall Building/Obstruction	Present	0.5	50	25			
0.2	Weather	Sunny	Yes	0.3	100	30	6.5	75.5	
		Cloudy	No	0.7	50	35			
		Rain	No	0.2	100	20			
		Snow	No	0.8	100	80	20.0		
		Wind	Yes	0.2	50	10			
		Sand Storm	No	0.4	100	40			49.0
		Fog/Debris	Yes	0.4	50	20			
		Visibility/Light Condition			0.1	N/A	N/A		
		Precipitation			0.2				
		Lack of Visibility/Wind			0.7				
ATMA Feasibility Score		54							

Figure 14. WSM – Interrupted Network of Intersections Segment (Site A)

4.6 Weighted Product Method

This method evaluates each site alternative based on the multiplicative aggregation approach, in which multi-criteria values are combined through a product function (Wang & Rangaiah, 2025). The WPM operates similarly to the WSM; however, it differs in that values are multiplied rather than summed, and weights are applied as exponents. The resulting product is then normalized based on the corresponding criteria weights (Wang & Rangaiah, 2025).

The purpose of the WPM is to identify the site alternative with the highest overall score, representing the most feasible option for ATMA deployment. This final output provides a ranking system of the top three site alternatives, supporting agencies in selecting the best option for deployment location, and identifying the necessary route characteristics.

Users can access this method through the MCDA tool, where site-specific or route-specific input criteria are entered into the spreadsheet. The tool then computes the necessary variables and generates outputs for each site alternative. These methods assist DOTs and other agencies in evaluating roadway characteristics along a work zone segment to determine the best feasible option for ATMA.

4.6.1 Workflow of WPM

The evaluation of WPM involves key steps within the framework. These steps outline the computational process and provide a structured analysis. By breaking down each calculation, the method improves clarity, organization, and overall user comprehension.

4.6.2 Step 1 - Background Information and Total Score Summary

Throughout the initial step of each method within the MCDA tool, a detailed breakdown of the input criteria is provided (e.g., geometry conditions, traffic conditions, connectivity, and weather conditions). These inputs vary depending on whether the segment is interrupted or uninterrupted. The corresponding scoring rules are then included for every criterion to be used in the WPM.

4.6.3 Step 2 - Site Alternative with Criteria Total Score

This step calculates the total score for each criterion for each site alternative, establishing a baseline for comparison. Higher total scores represent greater relative importance. For instance, if the geometry condition total score came to be 500 out of 600, it would be considered more influential than a lower score. However, the final importance of each criterion is also affected by its assigned

weight.

4.6.4 Step 3 - Performance Criteria Score

In this step, weights are incorporated as exponents into the criteria for each site alternative (Equation 16) (Bozorg-Haddad et al., 2020). Depending on the weighted value, it significantly influences the positive or negative final result. For example, a traffic condition total score criterion of 150 out of 200 with a weight of 0.2 would have less impact than if the weight were 0.3. Since the criterion score is relatively high, the lower weight reduces its overall contribution to the final outcome. In general, higher weights increase the influence and importance of the corresponding criterion. It is important to recognize that these weights are arbitrary and user-defined, which can be adjusted as needed.

$$V_{ij} = [r_{(ij)}]^{w_j} \quad \forall i \quad \text{(Equation 16)}$$

4.6.5 Step 4 - Feasibility Total Score and Site Alternative Ranking

The final step of the WPM examines the total score site ranking for each alternative by multiplying each criterion together (from the results of step 2) (Equation 17). The ranking system is evaluated in the same order, where higher values equate to a higher importance as the final rank outcome. The ranking system is compared by each site alternative and has a range from 1 to 3, where 1 represents the highest feasibility and 3 the lowest feasibility of ATMA deployment.

$$F_{ij} = \prod V_{ij} \quad \text{(Equation 17)}$$

4.6.6 WPM Example - Uninterrupted and Interrupted Segments

This example shows the uninterrupted (two-way and multi-lane/interstate) segments and the interrupted segment. Figures 15, 17, and 19 provide the route criteria inputs that correspond to each segment. The uninterrupted two-way and multi-lane/interstate results concluded that sites B and A were the ideal feasibility for ATMA deployment (Figures 16 and 18). Table 7 displays the results of all uninterrupted two-way site alternatives with a comparison ranking system and the key limiting factors. The interrupted segment result came to site C, which is the most feasible for deployment (Figures 19 and 20).

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Geometry Conditions	Lane Width	10 ft	30	370
	Shoulder Width	>4 ft	100	
	Grade	(-4% to -2%)	30	
	Roundabout/Horizontal/Vertical Curve	Present	50	
	Roundabout/Horizontal/ Curve Radius	<65 ft	10	
	Terrain	Level	100	
	Passing Lane	Not Present	50	
Traffic Flow	Time of Operation	4 PM-6 PM	20	120
	AADT	500 to 1000	100	
Connectivity	Vegetation	<50%	70	120
	Overpass	Present	50	
Weather	Sunny	Yes	100	550
	Cloudy	No	50	
	Rain	No	100	
	Snow	No	100	
	Wind	Yes	50	
	Sand Storm	No	100	
	Fog/Debris	Yes	50	

Figure 15. WPM Example – Uninterrupted Two-Way Homogeneous Segment (Site A)

Weighted Values	0.3	0.2	0.3	0.2
Total Score Summary				
Site Alternatives	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	370	120	120	550
B	400	150	150	600
C	310	50	170	550
Total Score with Weighted Value				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	5.89	2.61	4.20	3.53
B	6.03	2.72	4.50	3.59
C	5.59	2.19	4.67	3.53
Product Final Results		Site Ranking	Description	
A	228	Rank 2	This final step calculates the overall WPM score for each site by multiplying the values of all criteria. Higher scores indicate better ATMA feasibility with a higher ranking.	
B	266	Rank 1		
C	202	Rank 3		

Figure 16. WPM Example – Uninterrupted Two-Way Homogeneous Segment with Site Alternative Comparison

Table 7. WPM Uninterrupted Two-Way Example Results with Site Alternative Ranking

Site	Results	Ranking	Key Limiting Factors
A	228	Rank 2	• Moderate geometry feasibility • Moderate traffic flow • Low connectivity issues • Low severe weather
B	266	Rank 1	• Moderate geometry feasibility • Moderate traffic flow • Low connectivity issues • Low severe weather
C	202	Rank 3	• Moderate geometry feasibility • Poor traffic flow • Low connectivity issues • Low severe weather

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Geometry Conditions	Lane Width	11 ft	50	350
	Shoulder Width	>4 ft	100	
	Grade	(-4% to -2%)	30	
	Roundabout/Horizontal /Vertical Curve	Present	50	
	Roundabout/Horizontal / Curve Radius	>65 ft	100	
	Terrain	Mountainous	20	
Traffic Flow	Time of Operation	8 PM-10 PM	100	170
	PHF	0.75-0.85	20	
	AADT	1000 to 2000	50	
Connectivity	Vegetation	<10%	100	200
	Overpass	Not Present	100	
Weather	Sunny	Yes	100	600
	Cloudy	Yes	100	
	Rain	No	100	
	Snow	No	100	
	Wind	No	100	
	Sand Storm	Yes	50	
	Fog/Debris	Yes	50	

Figure 17. WPM Example – Uninterrupted Multi-Lane/Interstate Homogeneous Segment (Site A)

Weighted Values	0.3	0.2	0.3	0.2
Total Score Summary				
Site Alternatives	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	320	170	200	600
B	300	170	150	600
C	220	70	170	550
Total Score with Weighted Value				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	5.64	2.79	4.90	3.59
B	5.54	2.79	4.50	3.59
C	5.04	2.34	4.67	3.53
Product Final Results		Site Ranking	Description	
A	278	Rank 1	This final step calculates the overall WPM score for each site by multiplying the values of all criteria. Higher scores indicate better ATMA feasibility with a higher ranking.	
B	250	Rank 2		
C	195	Rank 3		

Figure 18. WPM Example – Uninterrupted Multi-Lane/Interstate Homogeneous Segment with Site Alternative Comparison

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Route Characteristics	Signalized Intersection	No	100	680
	All-Way Stop Intersection	Yes	50	
	Two-Way Stop/Yield Intersection	No	100	
	Pedestrian Crossing	No	100	
	Roundabout	No	100	
	Roundabout Curve Radius	N/A	0	
	Shoulder Width	>4 ft	100	
	Max (+) Critical Grade %	4%	20	
	Max (-) Critical Grade %	< -6%	10	
	AADT	500 to 1000	100	
Connectivity	Vegetation	<50%	70	120
	Overpass/Tall Building/Obstruction	Present	50	
Weather	Sunny	Yes	100	550
	Cloudy	No	50	
	Rain	No	100	
	Snow	No	100	
	Wind	Yes	50	
	Sand Storm	No	100	
	Fog/Debris	Yes	50	

Figure 19. WPM Example – Interrupted Network of Intersections Segment (Site A)

Weighted Values	0.4	0.4	0.2
Total Score Summary			
Site Alternatives	Route Characteristics	Connectivity	Weather
A	680	120	550
B	640	170	650
C	620	170	700
Total Score with Weighted Value			
	Geometry Conditions	Connectivity	Weather
A	13.58	6.79	3.53
B	13.26	7.80	3.65
C	13.09	7.80	3.71
Product Final Results		Site Ranking	Description
A	326	Rank 3	This final step calculates the overall WPM score for each site by multiplying the values of all criteria. Higher scores indicate better ATMA feasibility with a higher ranking.
B	378	Rank 2	
C	379	Rank 1	

Figure 20. WPM Example – Interrupted Network of Intersections Segment with Site Alternative Comparison

4.7 PROMETHEE Method

The PROMETHEE method, performance ranking organization method for enrichment evaluations, is an MCDA technique based on outranking relationships, in which alternatives are compared pairwise using preference measures (Tzeng & Huang, 2011). This outranking system evaluates the degree to which one is preferred over another across multiple criteria. Similarly, to the other MCDA methods used, PROMETHEE incorporates multiple alternatives and criteria to ensure comparison and consistency.

There are several variations of the PROMETHEE method; however, PROMETHEE II was selected for this tool because it produces a complete order of ranking alternatives. This variation is suitable for deterministic comparisons; it provides a single, fully ordered set of results. The other variations may produce partial rankings or multiple feasible solutions. Given the need to evaluate multiple site alternatives and criteria, a complete ranking order is essential for comparison and determining ATMA deployment feasibility.

This method allows users to compare differences between site alternatives using positive and negative rankings to generate a net flow for each alternative. The final score ranking provides a clear understanding of which site alternatives, from most to least suitable, are optimal for ATMA deployment.

4.7.1 Workflow of PROMETHEE Method

The PROMETHEE II method consists of five steps that structure the evaluation process. These steps incorporate route characteristics and environmental factors into the analysis and produce a complete ranking based on net flow values. This method provides full comparability with the alternatives and results in a clear numerical ranking from best to worst (Tzeng & Huang, 2011).

4.7.2 Step 1 - Background Information and Total Score Summary

Background information is essential to the tool's accuracy in estimating the ATMA feasibility final score. This step provides a baseline for evaluating each site's alternative values across all MCDA methods. Similar to the other methods, each site alternative has characteristics and criteria (e.g., geometry conditions, traffic flow) that are all weighted and can play a factor in the feasibility score. The only input variables that require the assistance of a user input would be including the criteria

characteristics values (e.g., lane width), the designated score associated with the value (e.g., 10 feet equals 30), and lastly, the weight score for each criterion. The rest of the PROMETHEE method supplies the derived outputs built into the Excel sheet. The method provides an output that includes a feasibility net flow score and how it is ranked from best to worst.

4.7.3 Step 2 - Performance Difference and Preference Function

This step calculates the performance difference for each site alternative to enable comparison of how each option performs relative to others. Specifically, alternatives are compared pairwise to determine whether one performs better or worse than another with respect to a given criterion. This comparison helps identify whether the difference in performance is significant or negligible. This performance difference looks at the gap between sites' alternatives (e.g., A, B, and C for each criterion) (Equation 18) and forms the basis for pairwise comparison (Tzeng & Huang, 2011).

$$D_{A-B} = S_A - S_B \quad (\text{Equation 18})$$

Based on the differences, a preference function is applied to quantify the degree of preference. A binary preference function is used; if the performance difference is greater than 0, the preference is assigned a value of 1; if the difference is less than or equal to 0, the preference is assigned a value of 0.

A preference value of 1 indicates that one alternative is preferred over another for the given criterion, while a value of 0 indicates no preference. In general, larger positive differences are more likely to result in a preference value of 1, whereas smaller or negative differences result in a value of 0 (Expression 1) (Tzeng & Huang, 2011).

$$D(A, B) = \begin{cases} 0, & |D| \leq q \\ 1, & \text{otherwise} \end{cases} \quad (\text{Expression 1})$$

4.7.4 Step 3 - Aggregated Preference

This step performs the weighted average of criteria based on the preference function. The aggregate preference looks at how much the alternatives are preferred to each other, considering the cumulative criterion and their designated weights, with the preference ranging from 0 to 1 (Tzeng & Huang, 2011). When the aggregated preference is closer to 1, it indicates the most ideal comparison, and closer to 0 indicates the less ideal comparison (Equation 19) (Tzeng & Huang, 2011).

$$\pi(A, B) = \sum w_j * D_j(A, B) \quad (\text{Equation 19})$$

4.7.5 Step 4 - Positive and Negative Flow

This step incorporates the positive and negative flow calculation. The positive flow represents the extent to which a given alternative outranks the other alternatives, indicating its relative strength. The negative flow reflects the extent to which an alternative is outranked by others, indicating its relative weakness (Tzeng & Huang, 2011).

For each site alternative, the positive and negative flows are computed by averaging the aggregated preference values obtained from the pairwise comparisons (Tables 8 and 9). These flows provide complementary measures of performance, with the positive flow that captures the dominance over the other alternatives, while the negative flow captures the degrees to which an alternative is dominated. Collectively, the positive and negative flows are used to evaluate and compare the three sites' alternatives, forming the determination of the overall ranking.

Table 8. Positive Flow Variables

Site Alternative	Positive Flow, Φ^+
Site A	$\Phi^+ = \frac{\pi(A, B) + \pi(A, C)}{2}$
Site B	$\Phi^+ = \frac{\pi(B, A) + \pi(B, C)}{2}$
Site C	$\Phi^+ = \frac{\pi(C, A) + \pi(C, B)}{2}$

Similarly, to the aggregated preference values, the positive flow incorporates a scaling system in which values closer to 1 represent a more favorable idea alternative, while values closer to 0 represent a less favorable alternative.

Table 9. Negative Flow Variables

Site Alternative	Negative Flow, Φ^-
Site A	$\Phi^- = \frac{\pi(B, A) + \pi(C, A)}{2}$
Site B	$\Phi^- = \frac{\pi(A, B) + \pi(C, B)}{2}$

Site C	$\Phi^- = \frac{\pi(A, C) + \pi(B, C)}{2}$
--------	--

The negative flow represents a flow that is opposite to the positive flow, with the scaling system that has values closer to 1 indicating a less favorable option, while values closer to 0 indicate a more favorable option.

4.7.6 Step 5 - Net Flow with Site Ranking

The net flow evaluates the balance between the positive flow (degree of strength) and the negative flow (degree of weakness) (Tzeng & Huang, 2011). It is calculated as the difference between the positive and negative flow values, providing an overall measure of preference. Based on the net flow values, the three site alternatives are ranked from most ideal to least ideal (e.g., Rank 1 to Rank 2, and Rank 3). For simplicity, the same equation is applied to the remaining site alternatives (B and C) (Equation 20) (Tzeng & Huang, 2011). This final step produces the result of the ATMA feasibility score.

$$\Phi(A) = \Phi^+(A) - \Phi^-(A) \quad (\text{Equation 20})$$

This net flow score typically ranges from -1 to 1, where values closer to 1 indicate a more favorable alternative, and values closer to -1 indicate a less favorable alternative. The ranking system is designed to correlate with the net flow values, with Rank 1 indicating the most suitable option, while Rank 3 indicates the least suitable option for ATMA deployment feasibility.

4.7.7 PROMETHEE Example - Uninterrupted and Interrupted Segments

This example provides the uninterrupted (two-way and multi-lane/interstate) and interrupted segments. The uninterrupted two-way segment resulted in site B being the most feasible ATMA deployment outcome (Figures 21, 22, and 23). The uninterrupted multi-lane/interstate results were site A, having the highest feasibility score (Figures 24, 25, and 26). The interrupted segment concluded with site B being the best feasible solution (Figures 27, 28, and 29). It is important to note that all input criteria from Figures 21, 24, and 27 were slightly different values for each of the uninterrupted (two-way and multi-lane/interstate) and interrupted segments; however, for each method, the criteria inputs remain the same for each segment.

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Geometry Conditions	Lane Width	10 ft	30	370
	Shoulder Width	>4 ft	100	
	Grade	(-4% to -2%)	30	
	Roundabout/Horizontal/Vertical Curve	Present	50	
	Roundabout/Horizontal/Curve Radius	<65 ft	10	
	Terrain	Level	100	
	Passing Lane	Not Present	50	
Traffic Flow	Time of Operation	4 PM-6 PM	20	120
	AADT	500 to 1000	100	
Connectivity	Vegetation	<50%	70	120
	Overpass	Present	50	
Weather	Sunny	Yes	100	550
	Cloudy	No	50	
	Rain	No	100	
	Snow	No	100	
	Wind	Yes	50	
	Sand Storm	No	100	
	Fog/Debris	Yes	50	

Figure 21. PROMETHEE Example – Uninterrupted Two-Lane Homogeneous Segment (Site A)

Weighted Values	0.3	0.2	0.3	0.2
Total Score Summary				
Site Alternatives	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	370	120	120	550
B	400	150	150	600
C	310	50	170	550
Performance Differences				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
D _{A-B}	-30.0	-30.0	-30.0	-50.0
D _{A-C}	60.0	70.0	-50.0	0.0
D _{B-A}	30.0	30.0	30.0	50.0
D _{B-C}	90.0	100.0	-20.0	50.0
D _{C-A}	-60.0	-70.0	50.0	0.0
D _{C-B}	-90.0	-100.0	20.0	-50.0
Preference Function: Ideal = 1, Not Ideal = 0				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
D(A,B)	0.0	0.0	0.0	0.0
D(A,C)	1.0	1.0	0.0	0.0
D(B,A)	1.0	1.0	1.0	1.0
D(B,C)	1.0	1.0	0.0	1.0
D(C,A)	0.0	0.0	1.0	0.0
D(C,B)	0.0	0.0	1.0	0.0
Aggregated Preference			Description	
π(A,B)	0.0		Considering all criteria and their associated weights, this step evaluates the degree to which the alternatives are preferred relative to one another. The result ranges from 0 to 1, where values closer to 1 indicate stronger preference and values closer to 0 indicate weaker preference.	
π(A,C)	0.5			
π(B,A)	1.0			
π(B,C)	0.7			
π(C,A)	0.3			
π(C,B)	0.3			

Figure 22. PROMETHEE Example – Uninterrupted Two-Lane Homogeneous Segment

Positive Flow, Φ^+		Description	Negative Flow, Φ^-	
$\Phi^+(A)$	0.25	Positive flow measures how strongly one alternative outranks others. Values closer to 1 indicate a stronger or more ideal option, while values closer to 0 indicate a weaker or less ideal option.	$\Phi^-(A)$	0.65
$\Phi^+(B)$	0.85		$\Phi^-(B)$	0.15
$\Phi^+(C)$	0.3		$\Phi^-(C)$	0.6
Site Alternatives	Net Flow	Site Ranking	Description	
A	-40	Rank 3	This final step evaluates the strength indicated by the positive flow and the weakness indicated by the negative flow. It compares these measures to determine the most feasible and ideal option for the deployment of ATMA.	
B	70	Rank 1		
C	-30	Rank 2		

Figure 23. PROMETHEE Example – Uninterrupted Two-Lane Homogeneous Segment with Site Alternative Comparison

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Geometry Conditions	Lane Width	12 ft	100	320
	Shoulder Width	<1 ft	20	
	Grade	(-4% to -2%)	30	
	Roundabout/Horizontal/Vertical Curve	Present	50	
	Roundabout/Horizontal/ Curve Radius	>65 ft	100	
	Terrain	Mountainous	20	
Traffic Flow	Time of Operation	8 PM-10 PM	100	170
	PHF	0.75-0.85	20	
	AADT	1000 to 2000	50	
Connectivity	Vegetation	<10%	100	200
	Overpass	Not Present	100	
Weather	Sunny	Yes	100	600
	Cloudy	Yes	100	
	Rain	No	100	
	Snow	No	100	
	Wind	No	100	
	Sand Storm	Yes	50	
	Fog/Debris	Yes	50	

Figure 24. PROMETHEE Example – Uninterrupted Multi-Lane/Interstate Homogeneous Segment with Site Alternative Comparison

Weighted Values	0.3	0.2	0.3	0.2
Total Score Summary				
Site Alternatives	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	320	170	200	600
B	300	170	150	600
C	220	70	170	550
Performance Differences				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
D _{A-B}	20.0	0.0	50.0	0.0
D _{A-C}	100.0	100.0	30.0	50.0
D _{B-A}	-20.0	0.0	-50.0	0.0
D _{B-C}	80.0	100.0	-20.0	50.0
D _{C-A}	-100.0	-100.0	-30.0	-50.0
D _{C-B}	-80.0	-100.0	20.0	-50.0
Preference Function: Ideal = 1, Not Ideal = 0				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
D(A,B)	1.0	0.0	1.0	0.0
D(A,C)	1.0	1.0	1.0	1.0
D(B,A)	0.0	0.0	0.0	0.0
D(B,C)	1.0	1.0	0.0	1.0
D(C,A)	0.0	0.0	0.0	0.0
D(C,B)	0.0	0.0	1.0	0.0
Aggregated Preference			Description	
$\pi(A,B)$	0.6		Considering all criteria and their associated weights, this step evaluates the degree to which the alternatives are preferred relative to one another. The result ranges from 0 to 1, where values closer to 1 indicate stronger preference and values closer to 0 indicate weaker preference.	
$\pi(A,C)$	1.0			
$\pi(B,A)$	0.0			
$\pi(B,C)$	0.7			
$\pi(C,A)$	0.0			
$\pi(C,B)$	0.3			
Positive Flow, Φ^+		Description	Negative Flow, Φ^-	
$\Phi^+(A)$	0.8	Positive flow measures how strongly one alternative outranks others. Values closer to 1 indicate a stronger or more ideal option, while values closer to 0 indicate a weaker or less ideal option.	$\Phi^-(A)$	0
$\Phi^+(B)$	0.35		$\Phi^-(B)$	0.45
$\Phi^+(C)$	0.15		$\Phi^-(C)$	0.85

Figure 25. PROMETHEE Example – Uninterrupted Multi-Lane Homogeneous Segment

Site Alternatives	Net Flow	Site Ranking
A	80	Rank 1
B	-10	Rank 2
C	-70	Rank 3

Figure 26. PROMETHEE Example – Uninterrupted Multi-Lane Homogeneous Segment with Site Alternative Comparison

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Route Characteristics	Signalized Intersection	No	100	680
	All-Way Stop Intersection	Yes	50	
	Two-Way Stop/Yield Intersection	No	100	
	Pedestrian Crossing	No	100	
	Roundabout	No	100	
	Roundabout Curve Radius	N/A	0	
	Shoulder Width	>4 ft	100	
	Max (+) Critical Grade %	4%	20	
	Max (-) Critical Grade %	< -6%	10	
	AADT	500 to 1000	100	
Connectivity	Vegetation	<50%	70	120
	Overpass/Tall Building/Obstruction	Present	50	
Weather	Sunny	Yes	100	550
	Cloudy	No	50	
	Rain	No	100	
	Snow	No	100	
	Wind	Yes	50	
	Sand Storm	No	100	
	Fog/Debris	Yes	50	

Figure 27. PROMETHEE Example – Interrupted Network of Intersections Segment (Site A)

Weighted Values	0.4	0.4	0.2
Total Score Summary			
Site Alternatives	Route Characteristics	Connectivity	Weather
A	680	120	550
B	640	170	650
C	620	170	650
Performance Differences			
	Route Characteristics	Connectivity	Weather
D _{A-B}	40.0	-50.0	-100.0
D _{A-C}	60.0	-50.0	-100.0
D _{B-A}	-40.0	50.0	100.0
D _{B-C}	20.0	0.0	0.0
D _{C-A}	-60.0	50.0	100.0
D _{C-B}	-20.0	0.0	0.0
Preference Function: Ideal = 1, Not Ideal = 0			
	Route Characteristics	Connectivity	Weather
D(A,B)	1.0	0.0	0.0
D(A,C)	1.0	0.0	0.0
D(B,A)	0.0	1.0	1.0
D(B,C)	1.0	0.0	0.0
D(C,A)	0.0	1.0	1.0
D(C,B)	0.0	0.0	0.0
Aggregated Preference			
π(A,B)	0.4		
π(A,C)	0.4		
π(B,A)	0.6		
π(B,C)	0.4		
π(C,A)	0.6		
π(C,B)	0.0		

Figure 28. PROMETHEE Example – Interrupted Network of Intersections Segment

Positive Flow, Φ^+		Description	Negative Flow, Φ^-	
$\Phi^+(A)$	0.4	Positive flow measures how strongly one alternative outranks others. Values closer to 1 indicate a stronger or more ideal option, while values closer to 0 indicate a weaker or less ideal option.	$\Phi^-(A)$	0.6
$\Phi^+(B)$	0.5		$\Phi^-(B)$	0.2
$\Phi^+(C)$	0.3		$\Phi^-(C)$	0.4
Site Alternatives	Net Flow	Site Ranking	Description	
A	-20	Rank 3	This final step evaluates the strength indicated by the positive flow and the weakness indicated by the negative flow. It compares these measures to determine the most feasible and ideal option for the deployment of ATMA.	
B	30	Rank 1		
C	-10	Rank 2		

Figure 29. PROMETHEE Example – Interrupted Network of Intersections Segment with Site Alternative Comparison

4.8 TOPSIS Method

TOPSIS allocates a normalized and weighted set of criteria that examines the balance of feasibility. Considering the positive and negative alternatives in a more nuanced approach. This method allows for the most suitable outcome with a comparison of the best and worst options. In other words, this method in particular picks out the best alternative that is nearest to the positive optimal solution and farthest from the negative optimal solution (Tzeng & Huang, 2011). The positive and negative solutions are derived from the maximum and minimum values, which is best for sorting out the most ideal alternative. Each output alternative is ranked as seen fit for the specific criteria input of the decision-making tool.

4.8.1 Workflow of TOPSIS Method

The framework of this method provides five steps that assess and identify the ATMA feasibility score. This method encompasses the ability to normalize the criteria and the weighted value. The users would input the variables and any background parameters for the ATMA operational route.

4.8.2 Step 1 - Background Information and Total Score Summary

This background information pertains to the same criteria inputs used in the previous methods, including the selection of the interrupted or uninterrupted traffic flow for each segment configuration. These inputs account for intersection characteristics of the type of interrupted intersection (e.g., signalized, all-way stop intersection) and the uninterrupted route characteristics (e.g., geometry conditions). The total score summary represents the combined derived calculation of all criteria for a specific site alternative.

4.8.3 Step 2 - Criteria Normalization

The TOPSIS method produces normalized criteria to generate a consistent base level for comparing each site alternative. The normalized criteria were computed using the following equations from Form 1 of the TOPSIS method (Equation 21) (Tzeng & Huang, 2011).

$$r_{kj}(x) = \frac{x_{kj}}{\sqrt{\sum_{k=1}^n x_{kj}^2}}, k = 1, \dots, n; j = 1, \dots, m. \quad (\text{Equation 21})$$

4.7.4 Step 3 - Weighted Value Normalization

This step provides the base level for the weighted normalized value. This weighted value normalization value was applied to the normalized criterion for further comparison (Equation 22) (Tzeng & Huang, 2011).

$$v_{kj}(x) = w_r r_{kj}(x), k = 1, \dots, n; j = 1, \dots, m. \quad (\text{Equation 22})$$

4.8.5 Step 4 - Positive Ideal and Negative Ideal Criteria

This step supports and establishes the positive and negative ideal criteria for each site alternative. It includes the minimum and maximum values for each normalized weighted value (Equations 23 and 24) (Tzeng & Huang, 2011). This procedure emphasizes determining the ideal threshold for each positive and negative value. Furthermore, it identifies the best and worst values for each criterion across all alternatives, which allows for comparison between the most and least desirable options.

$$\begin{aligned} \text{Positive ideal point} = A^+ &= \{v_1^+(x), v_2^+(x), \dots, v_j^+(x), \dots, v_m^+(x)\} \\ &= \{(max_i v_{ij}(x) | j \in J_1), (min_i v_{ij}(x) | j \in J_2) | i = A, \dots, n\}, \end{aligned} \quad (\text{Equation 23})$$

$$\text{Negative ideal point} = A^- = \{v_1^-(x), v_2^-(x), \dots, v_j^-(x), \dots, v_m^-(x)\}$$

$$= \{(min_i v_{ij}(x) | j \in J_1), (max_i v_{ij}(x) | j \in J_2) | i = A, \dots, n\}, \quad (\text{Equation 24})$$

4.8.6 Step 5 - Distance Measurements for Ideal and Non-Ideal Criteria

This step compares each site alternative to its positive and negative ideal solutions. It measures how far each alternative is from the ideal and non-ideal solutions. The closer an alternative is to the ideal and the farther it is from the worst, the better the option for ATMA deployment (Equations 25 and 26) (Tzeng & Huang, 2011).

$$D_i^+ = \sqrt{\sum_{j=1}^m [v_{ij}(x) - v_j^+(x)]^2}, i = A, \dots, n \quad (\text{Equation 25})$$

$$D_i^- = \sqrt{\sum_{j=1}^m [v_{ij}(x) - v_j^-(x)]^2}, i = A, \dots, n \quad (\text{Equation 26})$$

4.8.7 Step 6 - Relative Closeness Ideal and Final Solution with Ranking

This final step represents the overall performance of each site alternative. The distance measurements are combined to produce a single score for each alternative, ranging from 0 to 100. Scores closer to 100 indicate a more ideal solution, while scores nearer 0 indicate a non-ideal solution (Equation 27) (Tzeng & Huang, 2011). The site rankings reflect these scores, with alternatives ranked from best to worst (e.g., Rank 1) for ATMA deployment feasibility.

$$C_i = \frac{D_i^-}{(D_i^+ + D_i^-)}, i = A, \dots, n \quad (\text{Equation 27})$$

4.8.8 TOPSIS Example - Uninterrupted and Interrupted Segments

This example provides the computational process for the uninterrupted (two-way and multi-lane/interstate) and interrupted segments. The uninterrupted two-way segment results were site B, representing the best feasible outcome for ATMA deployment (Figures 30 and 31). The uninterrupted multi-lane/interstate example resulted in site B being the more suitable solution (Figures 32 and 33). The interrupted segment resulted in site B as more feasible (Figures 34 and 35). All input criteria were slightly different, and other site criteria (e.g., B and C) that were not displayed were slightly different in values across uninterrupted and interrupted segments.

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Geometry Conditions	Lane Width	10 ft	30	370
	Shoulder Width	>4 ft	100	
	Grade	(-4% to -2%)	30	
	Roundabout/Horizontal/Vertical Curve	Present	50	
	Roundabout/Horizontal/Curve Radius	<65 ft	10	
	Terrain	Level	100	
	Passing Lane	Not Present	50	
Traffic Flow	Time of Operation	4 PM-6 PM	20	120
	AADT	500 to 1000	100	
Connectivity	Vegetation	<50%	70	120
	Overpass	Present	50	
Weather	Sunny	Yes	100	550
	Cloudy	No	50	
	Rain	No	100	
	Snow	No	100	
	Wind	Yes	50	
	Sand Storm	No	100	
	Fog/Debris	Yes	50	

Figure 30. TOPSIS Example – Uninterrupted Two-Lane Homogeneous Segment (Site A)

Weighted Values	0.3	0.2	0.3	0.2
Total Score Summary				
Site Alternatives	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	370	120	120	550
B	400	150	150	600
C	310	50	170	550
Criteria Normalization				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	0.590	0.605	0.468	0.560
B	0.638	0.756	0.585	0.611
C	0.494	0.252	0.663	0.560
Weighted Value Normalization				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	0.177	0.121	0.140	0.112
B	0.191	0.151	0.175	0.122
C	0.148	0.050	0.199	0.112
Positive Ideal and Negative Ideal Criteria				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
Positive Ideal (Max. Value)	0.191	0.151	0.199	0.122
Negative Ideal (Min. Value)	0.148	0.050	0.140	0.112
Distance Measurements for Ideal and Non-Ideal Criteria			Description	
Site A (+)	0.068		This step compares each site alternative to its positive and negative ideal solutions. It measures how far each alternative is from the ideal and non-ideal solutions. The closer an alternative is to the ideal and the farther it is from the worst, the better the option.	
Site A (-)	0.076			
Site B (+)	0.023			
Site B (-)	0.116			
Site C (+)	0.110			
Site C (-)	0.058			
Relative Closeness Ideal - Final Solution		Site Ranking	Description	
A	53	Rank 2	This represents the overall performance of each site alternative. The distance measurements are combined to produce a single score for each alternative, ranging from 0 to 100. Scores closer to 100 indicate a more ideal solution, while scores nearer 0 indicate a non-ideal solution. The site rankings reflect these scores, with alternatives ranked from best to worst (e.g., rank 1–3).	
B	83	Rank 1		
C	35	Rank 3		

Figure 31. TOPSIS Example – Uninterrupted Two-Lane Homogeneous Segment with Site Alternative Comparison

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Geometry Conditions	Lane Width	12 ft	100	220
	Shoulder Width	<1 ft	20	
	Grade	(-4% to -2%)	30	
	Roundabout/Horizontal /Vertical Curve	Present	50	
	Roundabout/Horizontal / Curve Radius	N/A	0	
	Terrain	Mountainous	20	
	Time of Operation	8 PM-10 PM	100	
Traffic Flow	PHF	0.75-0.85	20	170
	AADT	1000 to 2000	50	
Connectivity	Vegetation	<10%	100	200
	Overpass	Not Present	100	
Weather	Sunny	Yes	100	600
	Cloudy	Yes	100	
	Rain	No	100	
	Snow	No	100	
	Wind	No	100	
	Sand Storm	Yes	50	
	Fog/Debris	Yes	50	

Figure 32. TOPSIS Example – Uninterrupted Multi-Lane/Interstate Homogeneous Segment (Site A)

Weighted Values	0.3	0.2	0.3	0.2
Total Score Summary				
Site Alternatives	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	220	170	200	600
B	300	170	200	600
C	220	70	170	550
Criteria Normalization				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	0.509	0.679	0.606	0.593
B	0.694	0.679	0.606	0.593
C	0.509	0.280	0.515	0.544
Weighted Value Normalization				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
A	0.153	0.136	0.182	0.119
B	0.208	0.136	0.182	0.119
C	0.153	0.056	0.155	0.109
Positive Ideal and Negative Ideal Criteria				
	Geometry Conditions	Traffic Flow	Connectivity	Weather
Positive Ideal (Max. Value)	0.208	0.136	0.182	0.119
Negative Ideal (Min. Value)	0.153	0.056	0.155	0.109
Distance Measurements for Ideal and Non-Ideal Criteria			Description	
Site A (+)	0.056		This step compares each site alternative to its positive and negative ideal solutions. It measures how far each alternative is from the ideal and non-ideal solutions. The closer an alternative is to the ideal and the farther it is from the worst, the better the option.	
Site A (-)	0.085			
Site B (+)	0.000			
Site B (-)	0.102			
Site C (+)	0.102			
Site C (-)	0.000			
Relative Closeness Ideal - Final Solution		Site Ranking	Description	
A	60	Rank 2	This represents the overall performance of each site alternative. The distance measurements are combined to produce a single score for each alternative, ranging from 0 to 100. Scores closer to 100 indicate a more ideal solution, while scores nearer 0 indicate a non-ideal solution. The site rankings reflect these scores, with alternatives ranked from best to worst (e.g., rank 1–3).	
B	100	Rank 1		
C	0	Rank 3		

Figure 33. TOPSIS Example – Uninterrupted Multi-Lane/Interstate Homogeneous Segment with Site Alternative Comparison

Site A Alternative				
Criteria			Score from Defined Rules (0-100)	Total Score
Route Characteristics	Signalized Intersection	No	100	680
	All-Way Stop Intersection	Yes	50	
	Two-Way Stop/Yield Intersection	No	100	
	Pedestrian Crossing	No	100	
	Roundabout	No	100	
	Roundabout Curve Radius	N/A	0	
	Shoulder Width	>4 ft	100	
	Max (+) Critical Grade %	4%	20	
	Max (-) Critical Grade %	< -6%	10	
	AADT	500 to 1000	100	
Connectivity	Vegetation	<50%	70	120
	Overpass/Tall Building/Obstruction	Present	50	
Weather	Sunny	Yes	100	550
	Cloudy	No	50	
	Rain	No	100	
	Snow	No	100	
	Wind	Yes	50	
	Sand Storm	No	100	
	Fog/Debris	Yes	50	

Figure 34. TOPSIS Example – Interrupted Network of Intersections Segment (Site A)

Weighted Values	0.4	0.4	0.2
Total Score Summary			
Site Alternatives	Route Characteristics	Connectivity	Weather
A	680	120	550
B	640	170	650
C	620	170	650
Criteria Normalization			
	Route Characteristics	Connectivity	Weather
A	0.607	0.447	0.513
B	0.571	0.633	0.607
C	0.553	0.633	0.607
Weighted Value Normalization			
	Route Characteristics	Connectivity	Weather
A	0.243	0.179	0.103
B	0.228	0.253	0.121
C	0.221	0.253	0.121
Positive Ideal and Negative Ideal Criteria			
	Route Characteristics	Connectivity	Weather
Positive Ideal (Max. Value)	0.243	0.253	0.121
Negative Ideal (Min. Value)	0.221	0.179	0.103
Distance Measurements for Ideal and Non-Ideal Criteria			
Site A (+)	0.077		
Site A (-)	0.021		
Site B (+)	0.014		
Site B (-)	0.077		
Site C (+)	0.021		
Site C (-)	0.077		
Relative Closeness Ideal - Final Solution			
A	22	Rank 3	
B	84	Rank 1	
C	78	Rank 2	

Figure 35. TOPSIS Example – Interrupted Network of Intersections Segment with Site Alternative Comparison

4.9 Method Comparison Results

Based on the example that was previously used, looking at the uninterrupted two-way homogeneous segment, the results were combined for each method. As seen in Table 10, the

results show that site alternative B was ranked best across all methods. This indicates that when all input criteria are consistent across each site, the result remains the same within each method. It is important to note that since each method has its own way of computing, the values are not going to be identical. Overall, the selection of which method to use remains dependent on the user's preference and the objective of utilization.

Table 10. Site Alternative Results for each Method – Uninterrupted Two-Way Homogeneous Segment

Site	WSM	WPM	TOPSIS Method	PROMETHEE Method	Ranking
A	61	228	53	-40	Rank 2
B	69	266	83	70	Rank 1
C	59	202	35	-30	Rank 3

5 Conclusion

5.1 Summary

The research concludes that proper guidelines for ATMA deployment are essential and provide users (e.g., DOTs) with a better understanding of the economic and route conditions for deployment. Since ATMA operations are essential for ensuring safety in a mobile work zone, these guidelines were established and supported by prior studies, prompting this research to develop two decision-making tools (the BCA and MCDA). The BCA tool provided the benefits and costs needed to obtain the BCR for users. As long as the BCR exceeds 1.0, the next phase (MCDA tool) can commence. The MCDA tool provides key route characteristics and work zone conditions for proper consideration before deployment. With each method (e.g., WSM, WPM, PROMETHEE, and TOPSIS), the user can select whichever criteria or route characteristics are needed to achieve the desired accuracy of the ATMA feasibility score. Every method is computed differently; however, depending on the consistency of the input criteria, the final feasibility score should remain constant.

5.2 Major Implications for Work Zone Safety

ATMA operations are known to enhance safety within a mobile work zone by eliminating the FV driver from harm's way through autonomous operation. This approach can significantly reduce the risk of injuries or fatalities. For example, an inattentive driver approaching a slow-moving operation may be forced to react suddenly, increasing the likelihood of losing control. In such situations, the ATMA FV provides a protective buffer for LV, helping mitigate potential impacts.

However, it is important to note that this operational system is still a relatively new technology, and sensor issues or system malfunctions may occur. For instance, ATMA operations performing maintenance at a signalized intersection may encounter difficulties with stopping, potentially disrupting the intended gap distance between the LV and FV. Additionally, various intersection configurations and operational limitations must be carefully considered when deploying these systems.

5.3 Limitations of the Tool

The BCA tool relies on expected and estimated values, which could limit its overall accuracy. For example, ATMA crash estimates are derived using probabilistic assumptions and existing TMA system crash data. The TMA crash data, particularly the number of impacts, must be provided by the user, along with other key inputs. However, obtaining reliable data may be challenging, given that these mobile operations are relatively recent.

The MCDA tool incorporates several methods (e.g., WSM, WPM, PROMETHEE, and TOPSIS), which may feel overwhelming for users when selecting the most appropriate approach. In many cases, the choice may depend on the user's familiarity with or preference for a particular mathematical method. Additionally, if users choose to incorporate more detailed inputs, such as route-specific characteristics or a value tree manual, the entry can become complex, though it remains possible.

5.4 Future Recommendations

Based on past research involving ATMA deployment trials and lessons learned, additional economic variables, route characteristics, and environmental components could be evaluated and incorporated into the BCA and MCDA tools to further enhance their effectiveness. Upcoming research that introduces new economic variables and route characteristics would also improve the accuracy of these tools. For the BCA tool specifically, collecting ATMA-related

crash data would be valuable for establishing accurate benefit estimates when compared to traditional TMA crash data.

For both BCA and MCDA tools, developing a survey questionnaire for state DOTs that have participated in ATMA deployment could help identify new criteria and limiting factors affecting deployment. This would provide a significant advantage in refining both tools. For example, identifying limiting factors could support a mobile work zone flow analysis to evaluate how ATMA operations affect traffic flow. Additionally, a queuing delay analysis could be conducted to examine mobile work zones, particularly those involving ATMA operations, that pass through signalized intersections.

AI Tool Use Acknowledgment

AI tools, including Grammarly and ChatGPT, were used in this document to check grammar and identify typos. Google LM Notebook was used to find information for a specific literature review. No generative texts are used in this document.

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