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ATMA Deployment Toolkit: Cost-Benefit Analysis and Planning Guide for State DOTs

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16. Abstract

The Autonomous Truck-Mounted Attenuator (ATMA) system is gaining traction for its potential to increase worker safety in short-term mobile operations. Despite its safety advantages, ATMA is still a relatively new technology, and decision-makers like the Department of Transportation (DOTs) face operational and financial viability issues. There are few guidelines currently in place; the Manual on Uniform Traffic Control Devices (MUTCD), for instance, offers very little guidance on how to use ATMA operations. This research focuses on developing a decision-making tool that establishes a crucial framework for taking operational and economic deployment feasibility into account in order to close this gap. There are two stages to the tool. To determine a benefit-cost ratio (BCR) and evaluate economic viability, the first step employs a Benefit-Cost Analysis (BCA). Next, the candidate sites (grouped by uninterrupted and interrupted traffic conditions), are ranked using a Multi-Criteria Decision Analysis (MCDA) in the second stage. When assessing the viability of ATMA deployment, this step enables users to take into account important factors like roadway geometry, traffic flow, connectivity, and weather. To evaluate the important criteria with weighted values for each site alternative, the MCDA uses four evaluation techniques including the Preference Ranking Organization Methods for Enrichment Evaluations (PROMETHEE), the Weighted Sum Method (WSM), the Weighted Product Method (WPM), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

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List of Abbreviations and Acronyms

ATMA .... Autonomous Truck-Mounted Attenuator

AMT .... Autonomous Maintenance Technology

ASSHTO .... American Association of State Highway and Transportation Officials

BCA .... Benefit-Cost Analysis

BCR .... Benefit-Cost Ratio

CDOT .... Colorado Department of Transportation

DOT .... Department of Transportation

FDOT .... Florida Department of Transportation

FV .... Follower Vehicle

HCM .... Highway Capacity Manual

LV .... Leader Vehicle

MCDA .... Multi-Criteria Decision Analysis

MoDOT .... Missouri Department of Transportation

MUTCD .... Manual on Uniform Traffic Control Devices

PROMETHEE .. Preference Ranking Organization Methods for Enrichment Evaluations

TMA .... Truck-Mounted Attenuator

TOPSIS .... Technique for Order Preference by Similarity to Ideal Solution

VDOT .... Virginia Department of Transportation

WSM .... Weighted Sum Method

WPM .... Weighted Product Method

Executive Summary

To improve worker safety in short-term mobile operations, the Autonomous Truck-Mounted Attenuator (ATMA) system was established. Despite its safety benefits, ATMA remains a relatively newer technology and faces economic and operational feasibility challenges for decision-makers such as the Department of Transportation (DOTs). Existing guidelines are limited; for example, the Manual on Uniform Traffic Control Devices (MUTCD) provides minimal direction on the use of ATMA operations. To address this gap, this research focuses on the development of a decision-making tool that creates an essential framework for considering economic and operational deployment feasibility. The tool consists of two stages. The first stage uses a Benefit-Cost Analysis (BCA) to calculate a benefit-cost ratio (BCR) and assess economic feasibility. The second stage applies a Multi-Criteria Decision Analysis (MCDA) to rank roadway facility types, such as uninterrupted and interrupted traffic conditions. This stage allows users to consider key variables, including roadway geometry, traffic flow, connectivity, and weather, when evaluating ATMA deployment feasibility. The MCDA incorporates four evaluation methods to assess the key criteria with weighted values for each site alternative. The four methods include the Weighted Sum Method (WSM), the Weighted Product Method (WPM), the Preference Ranking Organization Methods for Enrichment Evaluations (PROMETHEE), and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Together, these two stages enable users to estimate economic feasibility with the BCR and omit site alternative ranking for ATMA deployment feasibility.

Chapter 1. Introduction

Roadway work zones are widely recognized as high-risk environments for maintenance personnel, with crash rates increasing each year and resulting in injuries and fatalities. Improving safety in mobile work zones is essential to reducing these risks. Key factors in deploying Autonomous Truck-Mounted Attenuator (ATMA) systems include traffic volumes, route geometry, and environmental conditions. Decision-makers and Department of Transportation (DOTs) must evaluate these factors to identify when ATMA deployment is economically and operationally suitable.

1.1. Mobile Work Zone Safety

There are several types of work zones, including long-term stationary, intermediate-term stationary, short-term stationary, short-duration, and mobile work zones. Mobile operations can also be categorized into several types, including operations with no shadow vehicle, a single shadow vehicle equipped with a Truck-Mounted Attenuator (TMA), two or more shadow vehicles with TMAs, and a shadow vehicle with ATMA. Figure 1 illustrates an ATMA operation involving the lead vehicle (LV) and the follower vehicle (FV) (Miller & Pourfalatoun, 2021).

Figure 1. Colorado Department of Transportation (CDOT) ATMA Operation with Lead and Shadow Vehicle

Maintaining safety within a work zone is the primary priority of these operations. As technology continues to innovate, research studies will also evolve to improve safety protocols and operational practices. In addition, state DOT safety procedures and federal guidelines continue to develop and adapt.

1.2. Motivation

One of the primary challenges associated with deploying ATMA systems is the lack of comprehensive guidelines regarding appropriate deployment locations and route conditions. More specifically, there are limited guidelines within the Manual on Uniform Traffic Control Devices (MUTCD), the Highway Capacity Manual (HCM), and the American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide.

1.2.1 Research Objective

This research focuses on the two primary challenges, which include economic feasibility and operational deployment feasibility. Economic feasibility relates to determining whether upgrading to an ATMA system is financially viable for deployment in a mobile work zone within a given state. Once economic feasibility has been established, guidelines are needed to assess site conditions and route characteristics in order to determine the operational feasibility of ATMA deployment. Furthermore, backed by past research studies, this report identifies variables and factors that were considered for establishing proper guidelines for ATMA deployment.

Chapter 2 Literature Review and Decision-Making Framework

Mobile work zones that use ATMA systems offer improved safety for maintenance workers by reducing direct exposure to traffic, although adoption remains challenging due to integration, operational, and maintenance issues, as ATMA is still a relatively new technology. As a result, thorough evaluation and performance testing are critical for establishing feasibility guidelines. Previous studies, including state-level deployments, highlight key parameters and challenges that inform the development of decision-making tools such as a Benefit-Cost Analysis (BCA) and a Multi-Criteria Decision Analysis (MCDA).

2.1. Past Studies on ATMA Deployment Piloting

Past studies conducted in various states have deployed and tested ATMA operations to integrate the key parameters that influence successful deployment and address challenges faced with deployment, including site conditions and route characteristics.

ATMA deployment in work zones is increasingly being explored by DOTs, alongside ongoing efforts to develop pilot protocols and implementation guidelines. Key considerations include roadway type (e.g., multi-lane highways or two-way roads), traffic volume, speed differentials, and environmental conditions. For example, overgrown vegetation and overhead obstructions can interfere with GPS signals, potentially affecting system performance (Agarwal et al., 2021). These limitations highlight the need to refine operational guidelines based on real-world conditions.

Roadway geometry plays a critical role in ATMA performance. The Florida Department of Transportation (FDOT) reported that the system is best suited for straight roadway segments and may encounter challenges with complex roadway features such as roundabouts, sharp curves, and intersections. Minimum curve radius requirements greater than 65 feet were identified as necessary for safer operational maneuverability (Agarwal et al., 2021). Traffic conditions, including Average Annual Daily Traffic (AADT) and time of operation, also influence deployment feasibility. Because ATMA operations typically travel at slower speeds than surrounding traffic, they can affect flow and roadway capacity. Studies suggest that ATMAs perform effectively on multi-lane highways with moderate traffic volumes, while lower AADT thresholds are more suitable for two-lane roads (Tang et al., 2022). The Virginia Department of Transportation (VDOT) also noted that connectivity and weather conditions significantly affect ATMA reliability. Severe weather conditions, including snow, rain, and high winds, can degrade the performance of the sensors, such as radar and LiDAR, potentially disrupting communication between the leader vehicle (LV) and the follower vehicle (FV) (VDOT, 2021).

2.2. Decision-Making Tool Application Overview

This decision-making tool for ATMA deployment is designed to evaluate key factors that influence operational suitability, supporting users to determine economic feasibility and operational route suitability. Additionally, the decision-making tool establishes a framework for users to identify how the tool and application are used (Figure 2) (Roes, 2026). The framework for this tool begins with identifying whether the existing TMA or truck equivalent is available for upgrade within an agency's fleet. Once the system is confirmed, users collect data on operational costs, crash history, and roadway characteristics (Figure 2). The tool consists of two stages: the BCA followed by the MCDA.

2.2.1 Stage 1 – BCA

The Missouri Department of Transportation (MoDOT) and FDOT conducted a study establishing an economic analysis tool to quantify the costs and benefits of Leader-Follower TMA (ATMA) deployment (Brown et al., 2023). This tool included factors such as system integration, maintenance, worker hourly rates, and training, along with crash-severity costs that would be reduced through the use of ATMA (Brown et al., 2023). The benefits were improving worker safety, particularly by eliminating exposure for the FV operator, and reducing work hourly rates. Incorporating this study into this research has provided a framework for the development of the BCA tool. Furthermore, the purpose of this BCA tool allows users to input key information that could be specific to their local jurisdiction, thus promoting ATMA deployment as the safer option for consideration. This tool outputs a Benefit-Cost Ratio (BCR), which helps users determine whether this ATMA system is economically viable.

2.2.2 Stage 2 – MCDA tool

The MCDA tool serves as the second stage of evaluation, which is applied and used only when the BCR is economically feasible. This MCDA tool looks at two types of facilities, uninterrupted and interrupted flow. The uninterrupted flow segments look at the uniform roadway without intersections, and are broken up into two segments: the two-way homogeneous segment and the multi-lane/interstate homogeneous segment. These segments provide criteria that look at geometry conditions, traffic flow, connectivity, and weather. The interrupted flow segment is considered to be a uniform roadway with a network of intersections that provides criteria for route characteristics, connectivity, and weather conditions. Within each facility type, four methods were used to assess and compare site alternatives for identifying the most feasible deployment scenarios. These four methods include the Weighted Sum Method (WSM), the Weighted 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). A value tree was integrated based on past research studies pertaining to normalization and weighted criteria. This tree created a visual representation of multi-level relative weights (e.g., leaf, branch, root) (Bruhn & Leleur, 2014).

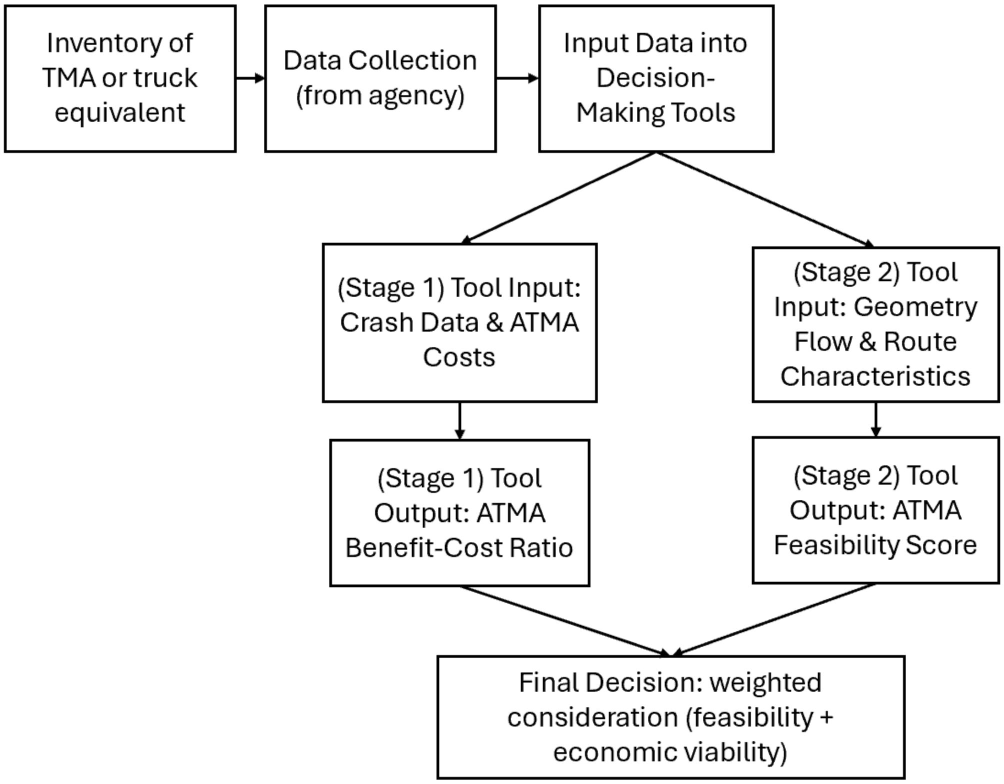

Figure 2. Decision-Making Framework *(Roes, 2026)*

Chapter 3 Stage 1 – Methodology

This BCA tool assesses the costs and benefits of developing the BCR in order to obtain the economic feasibility of ATMA deployment. Specific input values and data are required for users to implement into the tool. This is to make the BCA adjustable for each state DOT and for any additional information that can be included in the tool. Additionally, some key information regarding costs may require historical data based on the local state jurisdiction.

Based on past studies from FDOT and MoDOT, key assumptions were made for evaluating the BCA. One key approach is the use of existing trucks or TMAs already owned by agencies, which can be retrofitted with ATMA systems. This reduces the capital costs by avoiding the need for new vehicle purchases.

The purpose of the BCA tool is to evaluate the benefits of using this system in a work zone. In addition to improving worker safety, using ATMA can significantly reduce worker costs and lower crash-risk severity.

3.1. Example of BCA Tool

The BCR establishes a workflow framework that goes through each step for the costs, benefits, and the BCR calculations. This workflow uses a similar framework to FDOT and MoDOT (Figure 3) (Roes, 2026). This framework includes step-by-step examples that illustrate how the BCA tool is used and provides as a supportive tool for DOTs.

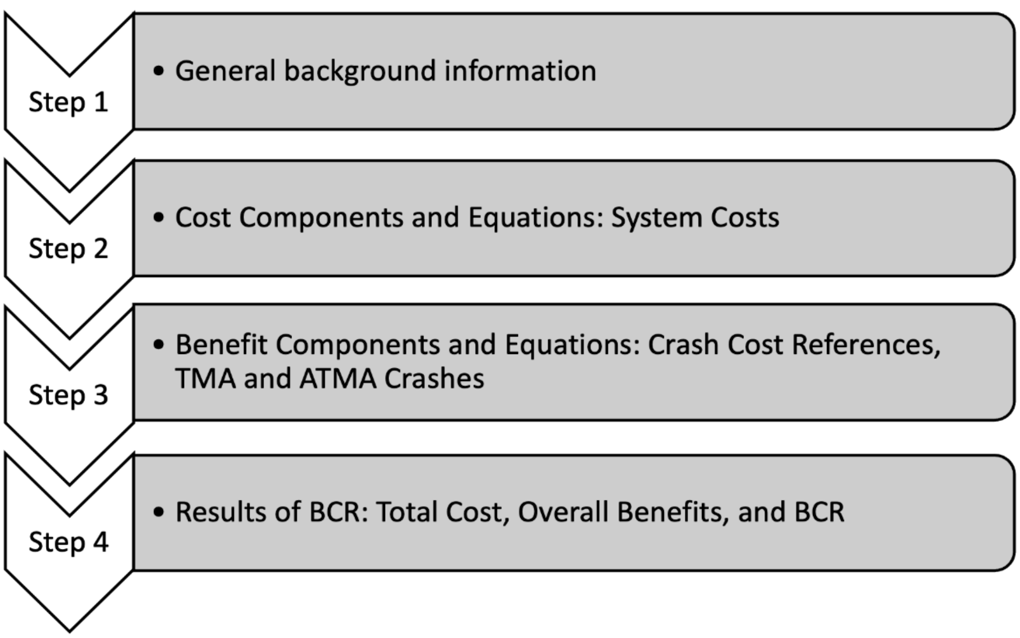

Figure 3. BCA Tool Workflow*(Roes, 2026)*

3.1.2 Step 1 – Background Information

This first step is crucial in order to acquire correct and accurate BCR output. It starts with inputting background information such as TMA or truck inventory, ATMA life cycle, and annuity rate. The ATMA system's life cycle is based on the vendor specifications to ensure a realistic investment timeline. Financial components such as the annuity rate and capital recovery factor (CRF) were used to convert costs and benefits into present and annualized values. The CRF was based on the interest rate and time period to estimate the equivalent annual cost and benefits for the BCR computation. As seen in Figure 4, the highlighted orange cells represent values that users would input (Roes, 2026). This information allows users to customize it for their local state.

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

Figure 4. Step 1 – BCA Example

3.1.3 Step 2 – Cost Components

This step is where specific cost items pertaining to the ATMA system and worker costs can be input into the tool. The derived costs, such as the equivalent annual value of the system and the training costs, were computed automatically. The primary cost components in the BCA tool include retrofitting existing TMA equipment, maintenance, training, worker labor, and fuel (Brown et al., 2023). The maintenance costs are also included to account for potential system damages, malfunctions, and any ongoing operational support that could occur. Although these costs are uncertain prior to deployment, they are necessary for accurately estimating the BCR. The worker's hourly rate and training costs were incorporated as well to reflect the worker operating the leader vehicle, and the training is required for personnel to operate these systems.

Crash-related costs are key components of this analysis, which focuses on injury severity levels such as fatal, disabling, and minor injuries (Figure 5) (Brown et al., 2023; FY 2026 Crash Costs, 2025). Property-damage-only (PO) crashes were excluded from this tool because they were not intended to focus on reducing work injuries. Since the tool focuses only on the scenario in which TMAs are replaced by ATMAs, the initial assumption is that the PO crash-related elements will be the same in both cases. Also, the tool is based on predicted TMA-hits and the damage related to PO can be significantly uncertain considering the crash mechanism. The analyst can include optional fixed cost item to account for PO crash damages if needed within the tool. For the other types of crashes, economic costs are adjusted using state-specific factors, such as cost-of-living and consumer price index (Brown et al., 2023). Additionally, crash rates are estimated based on TMA-related crashes across all types of roadways, with the assumption that crash severity distributions are similar for TMA and ATMA operations (Brown et al., 2023).

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 5. Step 2 - BCA Example

3.1.4 Step 3 – Benefit Components

This step helps identify the benefits of ATMA deployment by removing the FV operator from harm's way, furthermore, reducing worker cost, and lowering crash costs. These benefits were derived from incorporating key variables such as TMA risk rate, the average annual TMA hits, and worker injury rates, all of which require historical data (Figure 6). The TMA risk rate reflects the probability that a crash will occur in a mobile work zone that involves the FV worker. The higher the value, the greater the risk. For estimating the average annual TMA hits and injury probabilities, specific data would be required for users to input. By inputting these variables, the tool gathers and calculates the derived outputs to obtain the benefit for ATMA. Use of these systems has the potential to reduce the likelihood of worker injuries and mitigate them, further demonstrating the safety benefit of this operation.

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

Figure 6. Step 3 - BCA Example

3.1.5 Step 4

After the input costs and benefits are evaluated, the BCR can be obtained to get a better understanding of whether this ATMA system is economically feasible. As long as the BCR exceeds 1.0, the ATMA system is considered to be feasible. If it does not exceed 1.0, then the ATMA is not feasible, and the MCDA tool is no longer applicable. In this example, the BCR came out to be 1.10, which results in the ATMA being economically feasible (Figure 7) (Roes, 2026). Therefore, the second stage can be initiated.

Benefit-Cost Ratio

Total Cost	$37,442.58
Overall Benefit	$41,022.97
BCR	**1.10**

Figure 7. Step 4 – BCA Example

Chapter 4 Stage 2 – Methodology

This stage pertains to the MCDA tool that focuses on the established and developed criteria that make up this decision-making process. Furthermore, to evaluate the operational guidelines for this ATMA system, for DOTs to use to their benefit, for the consideration of deployment. The MCDA approach integrates a framework for assessing route-specific site alternatives that considers the uninterrupted and interrupted traffic flow conditions. The uninterrupted flow homogeneous segment has criteria pertaining to a uniform roadway with an option of using two-way, multi-lane, and interstate facilities. The criteria that are used for this segment include geometry, traffic flow, connectivity, and weather conditions. The interrupted flow includes a network of intersections with the following criteria: route characteristics, connectivity, and weather conditions. Additional criteria can be included by the user if desired. Across all methods (e.g., WSM (with a value tree), WPM, PROMETHEE, TOPSIS), users are able to choose which method to use, and the outputs remain constant throughout as long as the criteria stay the same. For example, this report illustrates the same given criteria for each method that uses the uninterrupted two-way homogeneous segment for site A. The example will also show the interrupted segment for site A. Both segments consist of guarantees of similar site ranking outputs. The uninterrupted multi-lane and interstate segment was not included in this example because it is very similar in criteria to the uninterrupted two-way segment.

4.1. Value Tree

The MCDA tool included this value tree to identify multi-level weighted values that create a structure for visually connecting with each criterion. Each of the relative weights was estimated; the user can adjust, if needed, to the desired level of importance a criterion may have. This tree has leaf, branch, and root levels, followed by the cumulative result. The leaf level has criteria that have a scoring range of 0 to 100, and the branch and root take on the score of the leaf, with the weighted values for each level (Roes, 2026). Figure 8 illustrates the multi-level value tree for uninterrupted flow using two-way homogeneous segment criteria with relative weights and criteria scoring to get the ATMA feasibility score (Roes, 2026). The interrupted flow, with its designated criteria and estimates, weighted values to obtain the ATMA feasibility score (Figure 9) (Roes, 2026). The computation of both value trees uses the WSM, but it can be applied to the other methods (e.g., WPM, PROMETHEE, TOPSIS). It is important to note that each of these examples only shows site alternative A; there would be two other sites (e.g., B and C) to further compare which site is the most suitable for the ATMA. Additionally, users are welcome to include more than three site alternatives if desired.

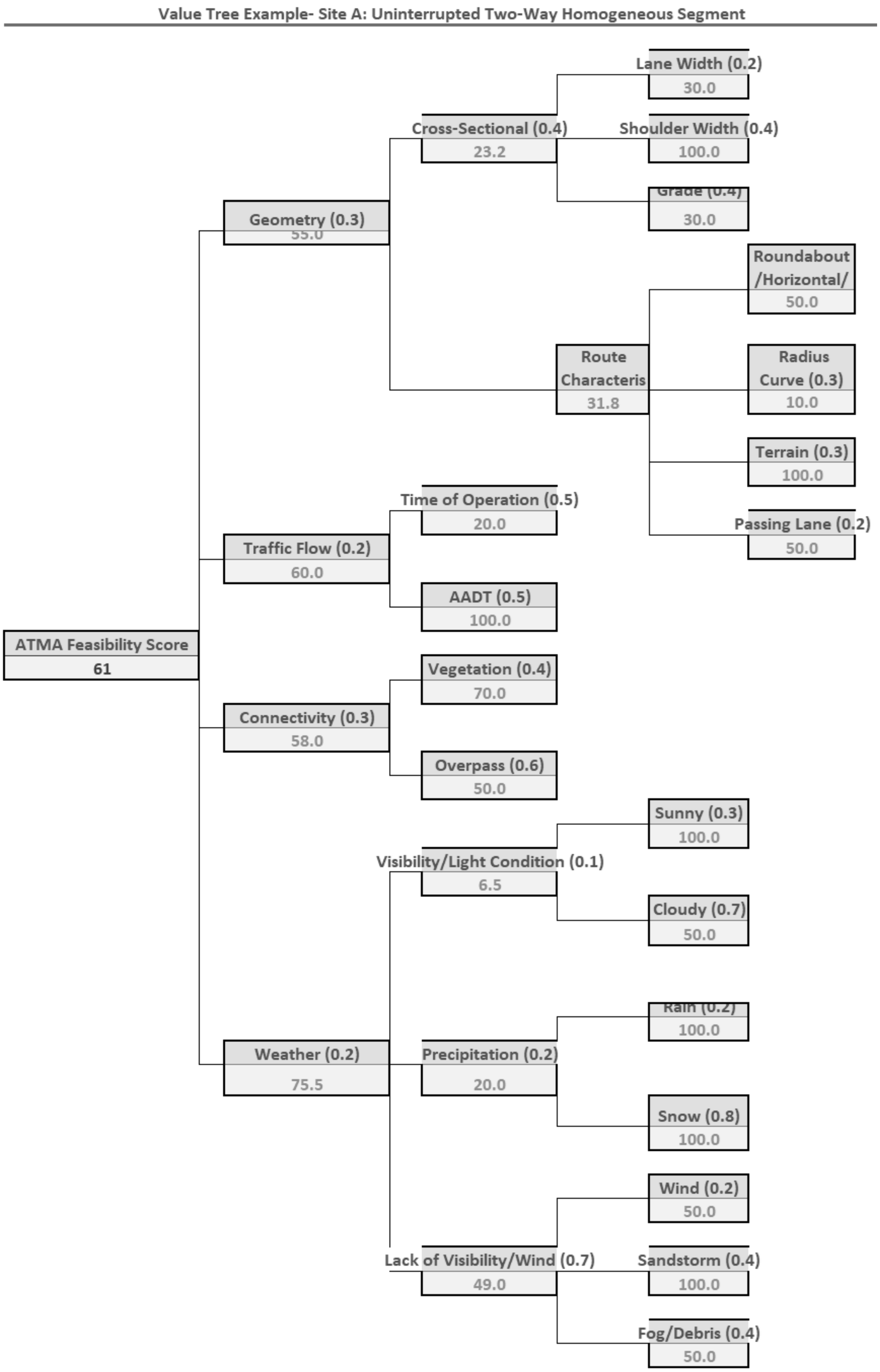

Figure 8. Value Tree Uninterrupted Flow Example for Site A

Figure 9. Value Tree Interrupted Flow Example for Site A

4.2. Weighted Sum Method

This method within the MCDA tool has the absolute weights with assigned score values, also represented as criteria. The WSM example uses the value tree structure; however, it can be used without it, and the value tree can be implemented in any of the methods. Additionally, this method enables users to input real-world criteria that reflect site alternatives for the work zone route. The structure for each method has standard conditions throughout the tool to provide consistency. The scoring rules for each method have a range from 0 to 100, indicating that closer to 100 is more desirable for feasibility (Roes, 2026).

4.2.1 Step 1 – Background Information

This initial step allows users to input specific site criteria for their desired location or route. A drop-down will appear when selecting a criterion (highlighted in the orange cell), and the user will be able to adjust the weighted values (Figures 9 and 10) (Roes, 2026). Once the criteria are selected, the tool will automatically calculate the result.

4.2.2 Step 2 – Weighted Sum Computation

The WSM that uses the value tree structure computes the weighted criteria and the scoring rule (0-100) by multiplication for each level (e.g., leaf, branch, root), then sums all the roots with the weighted values to obtain the feasibility score (Figures 10 and 11) (Roes, 2026).

4.2.3 Step 3 – Total Feasibility Score

The final step for each example gathers the results of each site alternative (e.g., site A). Sites B and C, which were not displayed, used slightly different criteria throughout each method to get a better understanding of how this tool compares. Table 1 provides an example (uninterrupted two-way segment) of how the site alternatives are ranked, with site B being the most suitable for deployment (Roes, 2026). Overall, this output looks at the suitability for ATMA deployment score, which typically ranges from 0-100, with 100 indicating the most desirable outcome.

Site A Alternative

Root Weight	Criteria			Assigned (Estimated) Weight	Score from Defined Rules (0-100)	Leaf Weighted Score	Branch Weighted Score	Root Weighted Score
Weight Look-Up: <= 0.2= Not critical (low importance), 0.3 = Moderate, 0.4 to 0.5 or >= Critical (high importance)								
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	20.0	
		Snow	No	0.8	100	80.0		
		Wind	Yes	0.2	50	10.0	49.0	
		Sand Storm	No	0.4	100	40.0		
		Fog/Debris	Yes	0.4	50	20.0		
		Visibility/Light Condition		0.1	N/A	N/A	N/A	
		Precipitation		0.2				
		Lack of Visibility/Wind		0.7				

ATMA Feasibility Score	61

Figure 10. WSM Uninterrupted Two-Way Homogeneous Segment for Site A

Table 1. WSM Uninterrupted Two-Way 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	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	20.0	
		Snow	No	0.8	100	80		
		Wind	Yes	0.2	50	10	49.0	
		Sand Storm	No	0.4	100	40		
		Fog/Debris	Yes	0.4	50	20		
		Visibility/Light Condition		0.1	N/A	N/A	N/A	
		Precipitation		0.2				
		Lack of Visibility/Wind		0.7				

ATMA Feasibility Score	54

Figure 11. WSM Interrupted Network of Intersections Segment for Site A

4.3. Weighted Product Method

This method is similar to the WSM, except it performs a multiplicative aggregation for the multi-criteria values when combined with the product function (Wang & Rangaiah, 2025). The purpose of this method is to look at the site alternatives ranking system, which can be helpful for decision-makers. The WPM involves a framework that follows specific steps for users to select their criteria and determine the best route conditions for this ATMA system. This method uses a simpler value tree structure with a root and leaf level, which is a more straightforward way of evaluation. Both the PROMETHEE and TOPSIS methods use this approach, in which the root is decomposed into criteria (leaves).

4.3.1 Step 1 – Background Information and Total Score

Step 1 allows users to incorporate these route characteristics and criteria into the tool. Within these uninterrupted two-way and interrupted examples, users may include criteria pertaining to geometry conditions, traffic flow, connectivity, route characteristics, and weather (Figures 12 and 13) (Roes, 2026). Once the criteria are input, the tool will calculate using the designated method. Once the background information is input into the tool, it will automatically calculate the total score for each criterion by summation.

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 12. WPM Uninterrupted Two-Way Homogeneous Segment for Site A

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 13. WPM Interrupted Network of Intersections Segment for Site A

4.3.2 Step 2 – Site Alternative with Criteria Total Score

This step incorporates the weighted product calculation by using the total scores to obtain the results for each site ranking. These uninterrupted two-way and interrupted examples show the criteria that were selected and the total score for site A (Figures 14 and 15) (Roes, 2026). The higher the total score, the more ideal it is for the ATMA system.

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 14. WPM Uninterrupted Two-Way Homogeneous Segment for Site A

4.3.3 Step 3 – Performance Criteria Score and Feasibility Total Score with Site Alternative Ranking

This final step computes the performance criteria score that is based on the total score by taking the weighted value as the exponent. The next part is to compute the sum of the criteria root to obtain the three-site alternative rankings. This uninterrupted example displays the established ranking with the best feasibility outcome that resulted in site B (Table 2) (Roes, 2026). For the interrupted network of interactions, for example, resulting in site C being most ideal for deployment (Figure 15) (Roes, 2026).

Table 2. WPM Uninterrupted Two-Way 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**

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 15. WPM Interrupted Network of Intersections Segment for Site Alternative Ranking

4.4. PROMETHEE Method

This method uses outranking alternatives by pairwise comparisons (Tzeng & Huang, 2011). The outranking evaluates which criteria are preferred over the others. This method also uses positive and negative rankings that further accomplish the preferred ranking system. The output is structured similarly to the previous methods, with a site alternative ranking system for identifying the optimal feasibility score for ATMA deployment.

4.4.1 Step 1 – Background Information and Total Score

This step allows users to input the key background information that includes specific criteria and weighted values. The total score is then computed by the initial criteria and the scoring range (0-100) to gather the normalization (Figures 16 and 17) (Roes, 2026).

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 16. PROMETHEE Uninterrupted Two-Way Homogeneous Segment for Site A

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 17. PROMETHEE Interrupted Network of Intersections for Site A

4.4.2 Step 2 – Performance Difference, Preference Function, Aggregated Preference

This step breaks down each computation with this method, starting with the performance difference that simply takes the difference between each site alternative. The preference function assigns a value of 0 or 1 to the performance difference. If the difference is greater than 0, the preference results in a value of 1, which is considered ideal. If the difference is less than or equal to 0, the preference results in a value of 0, which is considered not ideal (Tzeng & Huang, 2011). Next is the aggregated preference that examines how much the site alternatives are preferred over each other. By doing this, a preference ranges from 0 to 1, which indicates that closer to 1 is most ideal, and closer to 0 is less ideal (Tzeng & Huang, 2011). Figures 18 and 19 show the computations and derived results of the total score summary, performance difference, preference function, and the aggregated preference (Roes, 2026).

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 18. PROMETHEE Uninterrupted Two-Way Homogeneous Segment

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
$D_{A\text{-}B}$	40.0	-50.0	-100.0
$D_{A\text{-}C}$	60.0	-50.0	-100.0
$D_{B\text{-}A}$	-40.0	50.0	100.0
$D_{B\text{-}C}$	20.0	0.0	0.0
$D_{C\text{-}A}$	-60.0	50.0	100.0
$D_{C\text{-}B}$	-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 19. PROMETHEE Interrupted Network of Intersections Segment

4.4.3 Step 3 – Positive and Negative Flow with Net Flow Site Ranking

This final step examines and identifies the positive and negative flows by averaging the aggregated preference values. The positive and negative flows establish the dominance over other alternatives, and the degree to which an alternative is dominated (Tzeng & Huang, 2011). The net flow evaluates the balance of both positive and negative flows (Tzeng & Huang, 2011). The results of the net flow provide the site ranking system that compares which site is best. Thus, producing the outcome of the uninterrupted two-way and the interrupted examples, both result in site B being the most suitable for deployment (Figures 20 and 21) (Roes, 2026).

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 20. PROMETHEE Uninterrupted Two-Way Homogeneous Segment with Site Alternative Ranking

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 21. PROMETHEE Interrupted Network of Intersections Segment with Site Alternative Ranking

4.5. TOPSIS Method

This method uses the normalized and weighted criteria that examine the positive and negative, with the maximum and minimum values, to sort through the best ideal feasibility output. Similar to the previous methods, a site alternative ranking system is used to further determine this output.

4.5.1 Step 1 – Background Information and Total Score

The background information remains the same throughout each method and segment, depending on the different criteria inputs. The total score also reflects consistency by summing each criterion with the scoring rule (Figures 22 and 23) (Roes, 2026).

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 22. TOPSIS Uninterrupted Two-Way Homogeneous Segment for Site A

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 23. TOPSIS Interrupted Network of Intersections Segment for Site A

4.5.2 Step 2 – Criteria and Weighted Value Normalization, with Positive Ideal and Negative Ideal Criteria

This method normalizes the criteria and weighted values by utilizing the total score values. This normalization provides a baseline for balancing each criterion and weight. The positive and negative ideal criteria identify the best and worst values across all alternatives. Additionally, this assesses the minimum and maximum values for each normalized weighted value (Tzeng & Huang, 2011). Figures 24 and 25 represent each derived output that was based on the user input criteria in step 1 (Roes, 2026).

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

Figure 24. TOPSIS Uninterrupted Two-Way Homogeneous Segment

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

Figure 25. TOPSIS Interrupted Network of Intersections Segment

4.5.3 Step 3 – Distance Measurements, Relative Closeness Ideal, and Final Output Ranking

The distance measurements compare the positive and negative ideal solutions from the previous step by looking at the distance between the best and the worst ATMA site feasibility (Tzeng & Huang, 2011). The relative closeness ideal produces the final ATMA deployment feasibility with the designated site ranking. For the uninterrupted and interrupted examples, the results concluded with site B as the most suitable for ATMA deployment (Figures 26 and 27) (Roes, 2026).

Distance Measurements for Ideal and Non-Ideal Criteria	
Site A (+)	0.068
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
A	53	Rank 2
B	83	Rank 1
C	35	Rank 3

Figure 26. TOPSIS Uninterrupted Two-Way Homogeneous Segment with Site Alternative Ranking

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		Site Ranking
A	22	Rank 3
B	84	Rank 1
C	78	Rank 2

Figure 27. TOPSIS Interrupted Network of Intersections Segment with Site Alternative Ranking

4.6. Method Comparison Results

The four methods used in the previous sections included examples that covered the uninterrupted two-way segment and the interrupted network of intersections segment. A summary of each example's output rankings for the uninterrupted two-way segment is displayed in Table 3 (Roes, 2026). Overall, the results show that site B is considered to be the best feasible outcome for ATMA deployment. This verifies that each method is consistent when inputting similar criteria for the final result. Determining which method to use depends on the user and their reason for using the tool.

Table 3. Example Output Ranking with Site Alternatives for each Method

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

4.7. Selection of Methods

The four approaches included in this MCDA tool allow users to adopt the most appropriate method for their specific characteristics. Each method is unique and best suited for a certain deployment scenario. For example, if the user wants to determine the best site alternative for piloting, the TOPSIS technique is recommended. The TOPSIS approach is ideal for comparing best- and worst-case scenarios. The PROMETHEE is ideally suited for complex decision-making, as it employs pairwise ranking and positive and negative net flow rankings. The WSM and WPM are ideal for making straightforward absolute and relative comparisons, respectively. For a quick understanding, TOPSIS and WSM are easiest to explain because both produce a single score that can be sorted across sites. In general, if the question is "which site should be piloted next quarter," TOPSIS provides a direct response. If we are interested in which site has no serious operational weakness for safe ATMA deployment. WPM may provide better insights. If we need to know why Site-1 outranked Site-2, and whether that would change if we cared more about traffic exposure, PROMETHEE would be a better choice.

Chapter 5 Conclusion

The research was conducted to identify key guidelines that were necessary for promoting a safer option for mobile zones that utilize ATMA systems. These guidelines were essential to develop the two decision-making tools for users (e.g., DOTs) to evaluate the best scenario that is economically feasible and operationally feasible to consider deployment. The decision-making process began with the BCA as the first stage tool to obtain a feasible BCR that exceeds 1.0. As long as the BCR shows economic feasibility, then the next stage of the tool can initiate the MCDA process that analyzes the route characteristics and segment criteria to check that the ATMA system can operate successfully. By doing this, essential methods (e.g., WSM, WPM, PROEMTHEE, TOPSIS) were used to make this tool assess the multi-criteria characteristics for each segment. Overall, the user has the ability to adjust criteria inputs, weight values, method selection, and input historical data for the MCDA and BCA tools.

Additional information on the details of each decision-making tool and the methods used, can be found in the following thesis: A multi-criteria decision support framework for autonomous truck-mounted attenuator deployment in mobile work zones accounting for economic and technical feasibility (Roes, 2026).

5.1. Decision-Making Tool Limitations

It is recognized and recommended that the BCA tool relies on expected and estimated values; therefore, proper data is essential for accurate BCR results. These input values pertain to TMA crash data and their designated costs within the corresponding state.

The MCDA tool depends on the user inputs for route characteristics and site conditions for deployment to prompt an accurate output. The four methods that were used in this tool can be difficult to select which to use, and it may rely on the user's objective of the tool and their familiarity with a particular method.

5.2. Future Research Recommendations

Since ATMA systems are still relatively new, additional economic variables, route characteristics, and segment conditions would be beneficial for enhancing both decision-making tools. Incorporating these new variables would optimize the accuracy of the economic and operational ATMA feasibility outcomes. Furthermore, conducting a queuing analysis for mobile work zones that use the ATMA system would be valuable to gain insight, especially for routes that pass through signalized intersections.

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