

## MCDA-Based Decision Support Model for Advanced Warning Distance in Highway Maintenance

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### Abstract

This study develops a data-driven, risk-sensitive decision-support model. It determines optimal Advanced Warning Distances (AWD) for highway work zones, replacing fixed-value guidelines that ignore site-specific risks. Research integrates microscopic traffic simulation with a Hybrid Multi-Criteria Decision Analysis (MCDA) framework. Empirical data were collected from four and six - lane national highways in Thailand. The Surrogate Safety Assessment Model (SSAM) quantified near-miss conflicts (TTC = 1.3s). The Analytic Hierarchy Process (AHP) weighted key metrics: travel time (0.29), delay (0.35), and conflict frequency (0.36). Six MCDA techniques ranked the AWD configurations. Findings show that on six-lane highways, closing two right lanes requires an AWD over 1,075 meters; closing two left lanes works best below 575 meters. Four-lane highways with single-lane closures require a distance of 750 meters or less. All six MCDA algorithms showed high alignment. Sensitivity analysis confirmed conflict frequency as the most critical safety factor. This framework bridges a safety gap by replacing static guidelines with adaptive, context-specific metrics. It offers highway authorities a robust, evidence-based tool for designing customized traffic control strategies, thereby reducing crash risk and delays.

*Keywords:* Multi-Criteria Decision Analysis; Construction Management; Warning Distance; Highway Maintenance.

## 1. Introduction

Highway work zones are crucial for maintaining infrastructure, ensuring long-term functionality, and safety. These zones create temporary disturbances to stable traffic flows—such as localized lane closures, diversions, speed reductions, and geometric changes. Consequently, work zones are high-risk areas with increased conflicts and accident rates. They threaten both driver and worker safety [1, 2]. Administering these zones becomes more complex as traffic demand grows. Department of Highways (DOH) data show that Thailand's highways experienced 4.43% annual traffic growth from 2021 to 2025, especially on Highways No. 12 and No. 2 [3]. With about 46% of heavy vehicles, the risk of bottlenecks, delays, and dangerous vehicle intrusions increases [3, 4]. Such accidents put workers at risk and disrupt network operations, underscoring the need to enhance temporary traffic control, especially in Advance Warning Areas (AWAs) [4–6].

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Recent studies show that different traffic management measures, such as lane restrictions and carriageway deviations, yield varying reductions in capacity [7]. Poorly designed solutions lead to physical bottlenecks and severe capacity decline [8–10]. Evidence shows capacity loss depends on lane closure arrangements and whether the area is urban or regional. GPS probes and video studies reveal near-side lane closures (NSLC) drop capacity by about 15%. Run-around (RA) designs worsen capacity degradation to 46% [11].

Traffic operations during these transitions depend on driver reaction time and merging behavior [5, 12]. Prolonged reaction times under high cognitive demand slow traffic flow [13, 14]. Simulation indicates optimal macro-spatial planning—such as 1.5 km work zone spacing and 1.4 km minimum closure—can reduce congestion [8, 15]. Safety assessments have also shifted from historical accident data to proactive traffic conflict analysis, using metrics such as Time-to-Collision (TTC) and Post-Encroachment Time (PET) for near-miss incidents [16–18]. Studies find that warning and transition areas are highly risky due to short buffer distances, poor taper setups, and poor sightlines for traffic control devices [1, 5].

A driver's merging choice depends on road conditions and speed limits [12]. Microscopic safety modeling via binary logit analysis shows that early merges reduce the probability of rear-end crashes to 1.2%. In contrast, late merges near the taper are associated with a 4.0% crash probability [17]. Visible construction equipment encourages early merging [12]. The ideal AWA length requires balancing several factors [13]. Longer warning zones provide a safer stopping sight and greater comfort, but overly long zones increase driver stress and mental fatigue, as shown by EEG and fuzzy evaluations [14]. On multi-lane freeways, a 2,200-meter warning zone and a 160-meter transition taper reduce conflicts and maintain safety, efficiency, and manageable cognitive demand [14, 18].

Despite thorough past studies, some gaps remain. Previous methods focus on optimizing geometric parameters, such as work zone lengths for two-lane highways [19–21] or isolated crossover strategies [22]. They mainly address single operational controls, like variable speed limits [23]. As a result, conventional models emphasize isolated safety or performance measures and miss multi-criteria trade-offs in work zone management [6, 7]. International norms rely on uniform traffic patterns, leaving a gap in studies of emerging countries. In Thailand, traffic is highly heterogeneous. It features many vehicle types, motorcycles, low compliance, and unpredictable flows. Traditional methods rely on rigid technical standards that do not accommodate site-specific factors or incorporate organized expert judgment into decision-making [3, 11, 24].

This study presents a data-driven method combining microscopic traffic simulation with an advanced Multi-Criteria Decision-Making (MCDA) framework. Using a VISSIM-based simulation calibrated for mixed traffic in Thailand, the research explicitly captures conflict dynamics, delays, and capacity changes across work zone layouts. The Analytic Hierarchy Process (AHP) gathers engineering expertise and reveals trade-offs by assigning expert-weighted priorities. These priorities feed into several decision-support algorithms. The study evaluates alternative warning distances using Simple Additive Weighting (SAW), Weighted Aggregated Sum Product Assessment (WASPAS), TOPSIS, VIKOR, PROMETHEE, and EDAS methods.

This research introduces a context-sensitive, balanced decision-support system for Thai highway work zones. It offers four key contributions to transportation safety and traffic engineering. The study provides a dynamic, risk-based framework for setting advanced warning distances that go beyond static standards. It uses empirical driver risk perceptions, varied behaviors, and mixed traffic conditions in safety evaluations. The integrated, mathematically robust hybrid approach combines high-fidelity simulation with multi-algorithm MCDA to enable evidence-based traffic control design. These developments yield practical, context-specific policy recommendations to modernize work-zone regulations across diverse traffic environments.

## 2. Research Methods

Figure 1 delineates the research methodology, commencing with the formulation of a conceptual framework, followed by the collection of empirical data, and culminating in the creation of a microscopic traffic simulation model using VISSIM and the Surrogate Safety Assessment Model (SSAM). The model is subsequently calibrated and validated to replicate and assess lane-closure situations within the advance warning zone of construction and maintenance areas. The research subsequently utilizes the Analytic Hierarchy Process (AHP) to assess the relative weights of critical performance metrics, specifically travel time, delay, and the number of conflicts. The weights are subsequently used to identify the optimal option using distinct Multi-Criteria Decision Making (MCDM) methodologies, ensuring precise and reliable outcomes. The solutions obtained undergo thorough rank stability and sensitivity analyses. This systematic procedure ultimately converts technical study findings into decision-support instruments, actionable recommendations, and impactful policy implications for future traffic management.

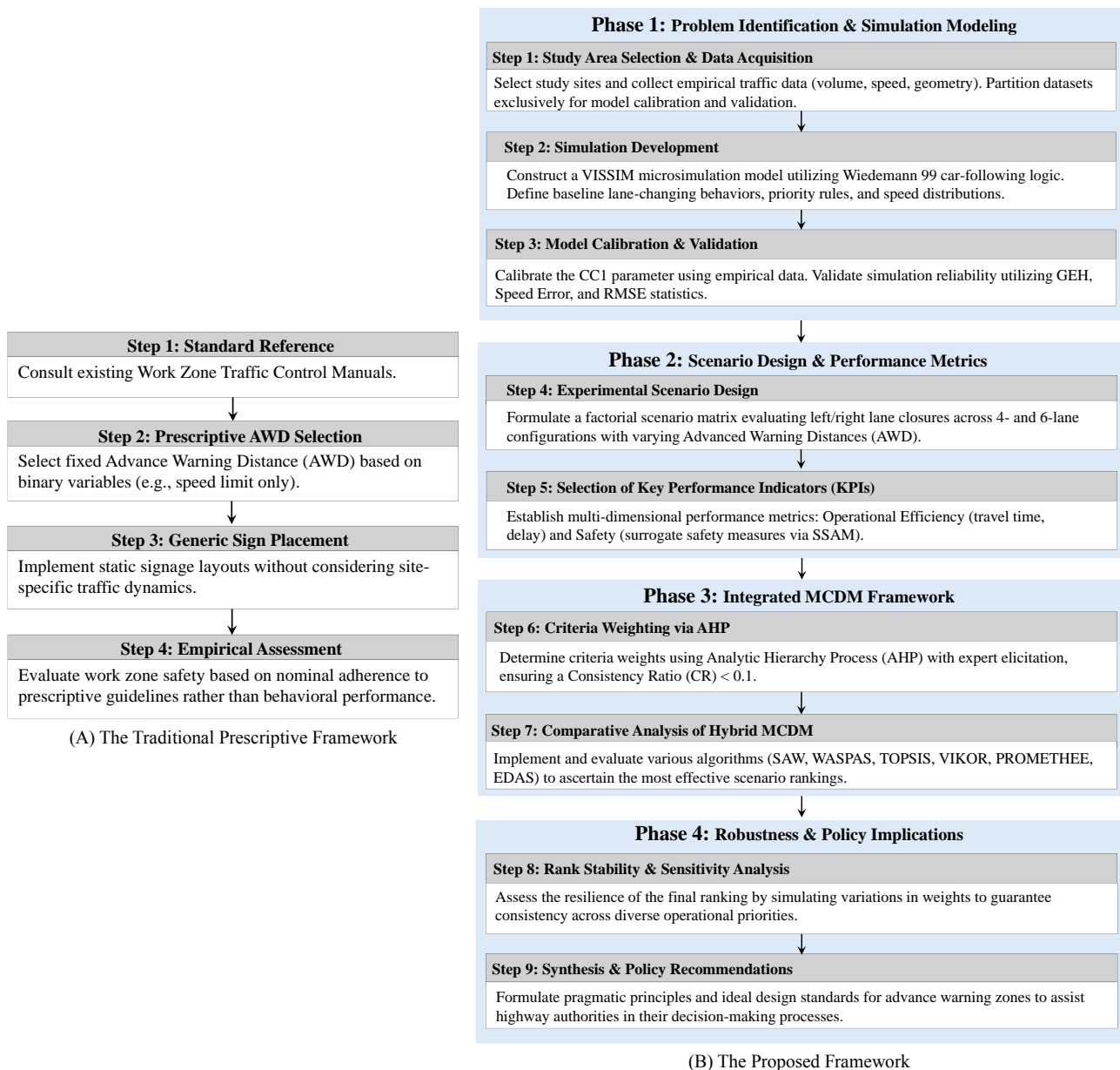


Figure 1. Research schematic framework

## 2.1. Study Area

This study selected a multilane highway as the study area to investigate the impact of driving behavior on highways with lane closures or traffic management. The selected study corridors were chosen for their substantial traffic demand and interregional connectivity, reflecting typical operating conditions on Thailand’s primary highways (Figure 2). In addition, the multilane configuration is consistent with the country’s primary highway network, where major corridors commonly operate with four to six traffic lanes and are widely distributed across Thailand. Due to their high traffic volumes, lane closures associated with maintenance activities on these primary highways can result in considerable traffic disruptions and increased crash risk. Therefore, the selected corridors provide a practical representation of the national highway system and support the broader applicability of the study findings. A representative section of this highway was selected: a four-lane section (two lanes in each direction with a raised median) on Highway No. 12, between Phrom Nimit and Huai Sida, Northeast Region, Thailand. From kilometer 568+000 to kilometer 571+000 (heading from Khon Kaen towards Chiang Yuen District), the study area has a total length of approximately 3 kilometers (covering the simulated road construction and rehabilitation area and a 1,000-meter stretch before entering the simulated area). The road has two traffic lanes per direction, each 3.5 meters wide, with a 2.50-meter-wide shoulder and a section with six traffic lanes (three lanes per direction with a depressed median) on Highway No. 2, Udon Thani –Nam Suai section, from km 468+000 to km 471+000 (heading from Udon Thani to Nong Khai). The study area has a total length of approximately 3 kilometers (covering the simulated road construction and rehabilitation area and a 1,000-meter distance before entering the simulation area). There are 3 traffic lanes per direction, each 3.5 meters wide, with a 2.50-meter-wide shoulder.

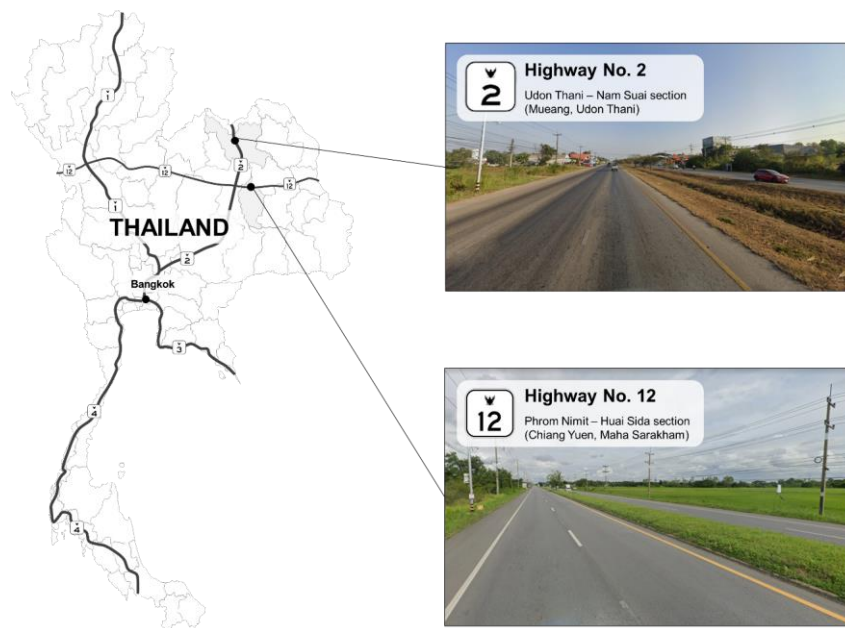


Figure 2. Study locations

## 2.2. Development of Traffic Microsimulation Model

### 2.2.1. Traffic Microsimulation

Microsimulation of traffic is based on car-following and lane-changing models that simulate the driving behavior of individual vehicles. The behavior of the vehicle ahead, such as acceleration, deceleration, or stopping, directly affects the vehicles following [25, 26]. The release of vehicles into the traffic network typically relies on a statistical random process (stochastic process) at predetermined time intervals and depends on the distribution of travel destinations [27]. Microscale models can accurately model individual vehicle behavior and are suitable for analyzing complex traffic problems, such as intelligent traffic light control systems and the impact of various events. They can display results in both two-dimensional and three-dimensional formats [28]. Furthermore, it is also suitable for studying individual driving behavior and vehicle dynamics. For this study, PTV VISSIM was applied for analysis. PTV VISSIM is a widely recognized tool in traffic and transportation engineering for its ability to simulate complex scenarios and deliver reliable results. It is also a widely used software in numerous research projects [29]. The VISSIM program consists of two main parts: the Traffic Simulator, which simulates traffic flow using car-following and lane-changing principles, and the Signal State Generator, which controls and determines traffic light conditions. These components work together to create and evaluate traffic conditions [30].

### 2.2.2. Data Collection for Model Development, Calibration, and Validation

This study conducted the collection of three main parts of basic data to be used in the creation, calibration, and validation of the VISSIM microscopic traffic simulation model, as detailed below:

#### *Geometric Data*

Executed a field survey to gather geometric component data of the roadways, encompassing the quantity and width of traffic lanes and shoulders, the configuration of medians, connecting features, and U-turn locations. Aerial imagery from Google Maps served as the backdrop for constructing the model's road network.

#### *Mid-Block Traffic Volume*

Traffic data were collected from closed-circuit television (CCTV) cameras under two conditions: heavy traffic during the evening peak and off-peak hours. These datasets were subsequently used to calibrate and validate the model. Vehicle classification was conducted in accordance with the Department of Highways [31] standards, with traffic divided into six categories: motorcycles (MC), passenger cars (PC), medium/small buses (MB), medium trucks (MT), heavy buses (HB), and heavy trucks (HT).

#### *Free Flow Speed*

Spot speeds were assessed utilizing a radar speed gun to ascertain the desired speed distributions. Measurements were performed under low-flow conditions (flow rate was below 500–1,000 veh/h/lane) between 06:00 and 07:00. Only lead vehicles that were not obstructed by other traffic were sampled. The data were categorized by lane and by the six identical vehicle classifications utilized in the volume survey.

### 2.2.3. Base Model

To accurately reflect the physical characteristics in a microsimulation environment, the PTV Vissim network was developed using high-fidelity field data—including lane counts, lane widths, shoulders, and medians—supplemented by aerial imagery for spatial precision. The infrastructure was modeled using links to define roadway geometry and traffic direction, while connectors were utilized to establish turning movements and lane-changing maneuvers. To replicate stochastic driving behavior under free-flow conditions, desired speed distributions were assigned to each vehicle class based on field-observed speed profiles, specifically incorporating the 15th, 50th, and 85th percentile speeds. Furthermore, traffic demand was calibrated by inputting vehicle volumes, origin-destination matrices, and vehicle compositions. Finally, Reduced Speed Areas (RSAs) were strategically placed to simulate realistic deceleration behavior in response to road geometry or warning zones, ensuring that simulated speeds align with observed driver reactions in restricted areas (Figure 3).

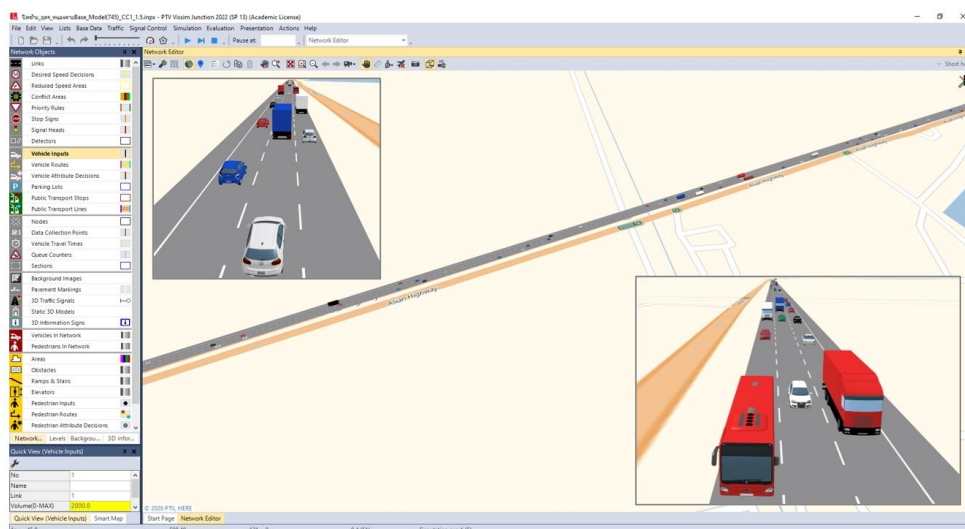


Figure 3. PTV Vissim base model

### 2.2.4. Model Calibration and Validation

The calibration of car-following behavior in this study was conducted using the Wiedemann 99 model. Given its high sensitivity and direct impact on roadway capacity, CC1 (headway time) was selected as the primary adjustment parameter. Optimization was achieved through an iterative calibration and validation process involving more than 11 simulation runs [32, 33]. The number of simulation replications was determined based on statistical considerations, including the standard error of the mean, standard deviation, and sample size ( $n$ ) [34]. These multiple runs were performed to account for the stochastic nature of microsimulation and to reduce random variability in the simulation outputs.

The iterative process aimed to identify the parameter settings that produced the closest agreement between simulated and observed traffic conditions, while the other parameters (CC0 and CC2–CC9) were kept at their recommended default values. To ensure that the model accurately replicated the observed field conditions, several statistical thresholds were applied. Traffic volume was evaluated using the GEH statistic. Speed was assessed according to the Florida Department of Transportation [35] validation threshold, which specifies an acceptable error margin within  $\pm 16$  km/h. Error distribution was evaluated using a threshold requiring more than 85% of data points to fall within a  $\pm 20\%$  error range, with a target Root Mean Square Error (RMSE) between 10 and 15, as suggested by Lu et al. [36].

The analytical results indicate that the simulation models for both the four-lane highway (Route 12) and the six-lane highway (Route 2) exhibit high predictive accuracy and successfully satisfy all established calibration thresholds. The modeling process used two distinct datasets: the first for model calibration and the second for independent validation. Overall, the six-lane highway model demonstrated marginally superior performance, yielding average GEH values of 0.28 and 0.18, along with mean speed deviations of 4.22 and 5.01 km/h for the calibration and validation phases, respectively. In comparison, the four-lane highway model produced corresponding GEH values of 0.37 and 0.29, with mean speed deviations of 1.75 and 3.86 km/h.

Because these error values are substantially lower than the maximum allowable thresholds, the parameter calibration can be considered highly appropriate. Consequently, the model serves as a robust and reliable proxy for traffic conditions within the study areas. Detailed calibration and validation results are summarized in Tables 1 and 2.

**Table 1. Model calibration results**

Highway No. 12, Phrom Nimit – Huai Sida section											
Vehicle type	Average Speed (km/h)						Traffic volume (veh/h)				
	Observed	Model	Threshold			Passed/Failed	Observed	Model	Threshold		Passed/Failed
			Diff. ( $\pm 16$ km/h)	%Diff. ( $\pm 20$ %)	RMSE (<10-15)				Diff.	GEH (< 5)	
MC	64.29	62.70	1.59	-2.48	2.27	Passed	95	101	6	0.61	Passed
PC	82.31	79.42	2.9	-3.52	2.91	Passed	765	750	15	0.55	Passed
MB	54	49.73	4.27	-7.9	5.82	Passed	2	2	0	0	Passed
MT	60.54	59.62	0.92	-1.52	2.03	Passed	27	31	4	0.74	Passed
HB	78.33	77.67	0.66	-0.85	2.15	Passed	2	2	0	0	Passed
HT	58.73	58.57	0.16	-0.27	1.23	Passed	46	48	2	0.29	Passed

Highway No. 2, Udon Thani – Nam Suai section											
Vehicle type	Average Speed (km/h)						Traffic volume (veh/h)				
	Observed	Model	Threshold			Passed/Failed	Observed	Model	Threshold		Passed/Failed
			Diff. ( $\pm 16$ km/h)	%Diff. ( $\pm 20$ %)	RMSE (<10-15)				Diff.	GEH (< 5)	
MC	63.24	62.07	1.16	-1.84	1.52	Passed	138	137	1	0.09	Passed
PC	84.96	77.98	6.98	-8.22	2.91	Passed	992	985	7	0.22	Passed
MB	67.85	58.78	9.07	-15.43	9.23	Passed	4	4	0	0.00	Passed
MT	69.04	66.04	3	-4.34	2.03	Passed	34	34	0	0.00	Passed
HB	83	79	4	-4.81	2.15	Passed	10	8	2	0.67	Passed
HT	57.18	56.06	1.12	-1.95	1.23	Passed	120	128	8	0.72	Passed

**Table 2. Model validation results**

Highway No. 12, Phrom Nimit – Huai Sida section											
Vehicle type	Average Speed (km/h)						Traffic Volume (veh/h)				
	Observed	Model	Threshold			Passed/Failed	Observed	Model	Threshold		Passed/Failed
			Diff. ( $\pm 16$ km/h)	%Diff. ( $\pm 20$ %)	RMSE (<10-15)				Diff.	GEH (< 5)	
MC	68.15	62.30	5.85	-9.39	2.11	Passed	316	321	5	0.28	Passed
PC	79.01	75.85	3.16	-4.17	9.14	Passed	923	915	8	0.26	Passed
MB	56.70	49.81	6.89	-13.83	4.51	Passed	9	8	1	0.34	Passed
MT	66.52	65.18	1.34	-2.06	5.88	Passed	9	9	0	0.00	Passed
HB	82.75	77.67	5.08	-6.54	2.15	Passed	1	1	0	0.00	Passed
HT	56.91	56.06	0.85	-1.52	0.69	Passed	21	25	4	0.83	Passed

Highway No. 2, Udon Thani – Nam Suai section											
Vehicle type	Average Speed (km/h)						Traffic Volume (veh/h)				
	Observed	Model	Threshold			Passed/Failed	Observed	Model	Threshold		Passed/Failed
			Diff. ( $\pm 16$ km/h)	%Diff. ( $\pm 20$ %)	RMSE (<10-15)				Diff.	GEH (< 5)	
MC	67.04	62.07	4.97	-8.01	1.52	Passed	301	298	3	0.17	Passed
PC	85.37	79.42	5.95	-7.49	2.91	Passed	1281	1281	0	0.00	Passed
MB	66.91	58.78	8.13	-13.83	9.23	Passed	8	8	0	0.00	Passed
MT	63.41	59.62	3.79	-6.36	2.03	Passed	30	32	2	0.36	Passed
HB	84.81	78.40	6.41	-8.18	7.88	Passed	6	7	1	0.39	Passed
HT	59.21	58.4	0.81	-1.39	1.23	Passed	55	54	1	0.14	Passed

**2.3. Application of Traffic Microsimulation Model**

The base model, calibrated and validated per established standards, is employed to develop a management model for advanced warning regions in construction and rehabilitation zones under diverse conditions. The model's findings are assessed through simulations of construction and rehabilitation area models.

### 2.3.1. Work Zone Configurations on Multi-lane Highways

This research employs a calibrated and validated base model to simulate construction and maintenance area patterns in accordance with the Traffic Control Device Manual [37] on a rural road with a speed restriction of 90 km/h. To evaluate the effectiveness of different work zone configurations, two principal case studies were examined. In the first case, a single-lane closure was implemented on a four-lane highway (left/right). The setup had a complete Advance Warning Area, which included the shoulder taper of 575 m, a Transition Area (Taper Length, L) of 195 m, a Longitudinal Buffer Space of 150 m, an Activity Area (Work Space) of 500 m, a Downstream Buffer of 30 m, a Downstream Taper of 30 m, and a Termination Area of 70 m, as illustrated in Figures 4-a and 4-b. In the second case, a double-lane closure was applied on a six-lane highway (left/right). The complete Advance Warning Area was established at 745 m, employing a sequential lane closure technique ( $L = 195$  m, succeeded by a tangent distance of  $L/2 = 97.5$  m prior to the second taper of  $L/2$ ). Additional parameters comprised a longitudinal buffer of 150 meters, a workspace of 500 meters, and a terminating area of 70 meters. The corresponding layouts are presented in Figures 4-c and 4-d, while the VISSIM scenario models are shown in Figure 5.

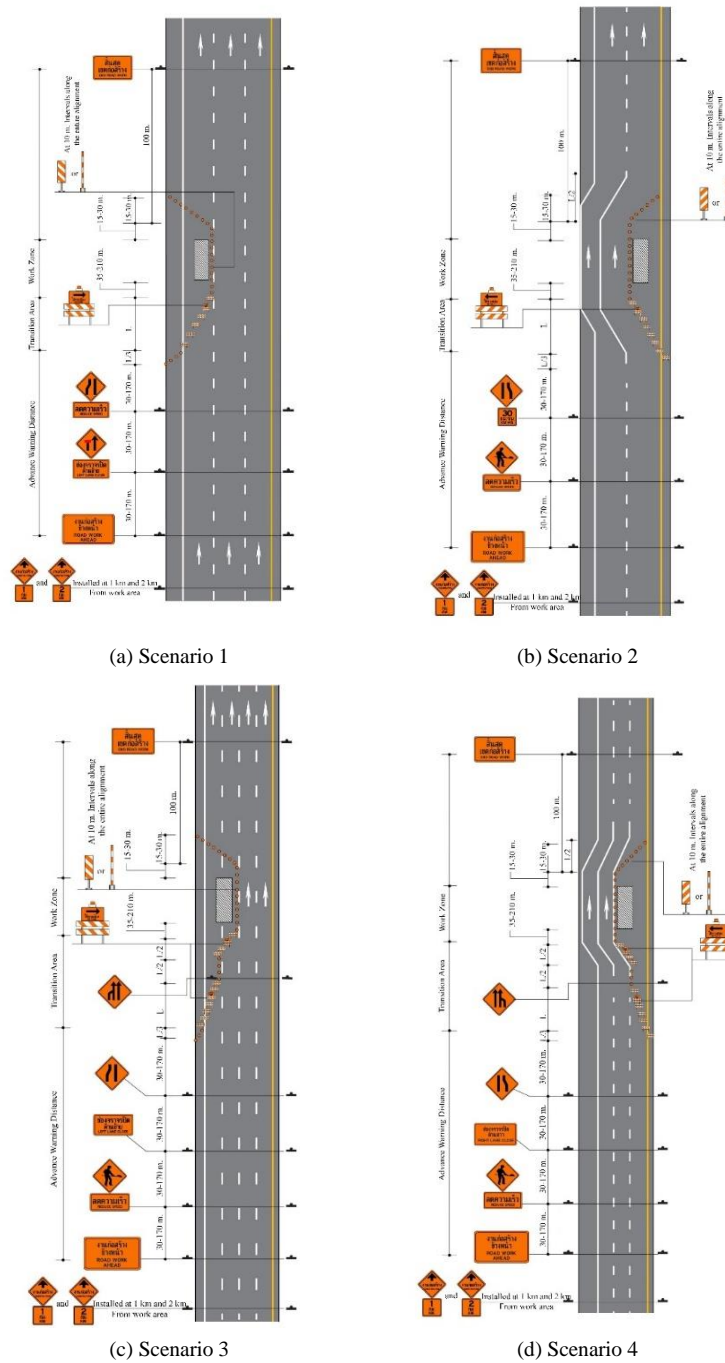
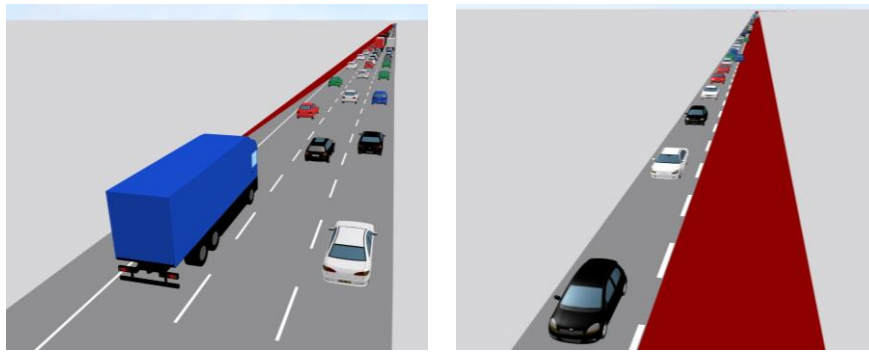
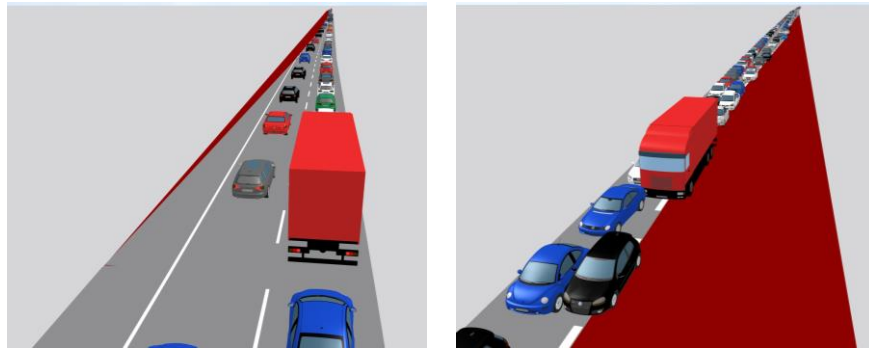


Figure 4. Construction and rehabilitation site modeling: (a) area with 1 left lane for multi-lane highways, (b) area with 1 right lane for multi-lane highways, (c) area with 2 left lanes for multi-lane highways, and (d) area with 2 right lanes for multi-lane highways [37].



(a) Highway No. 2, Udon Thani – Nam Suai section.



(b) Highway No. 12, section Phrom Nimit – Huai Sida.

Figure 5. PTV VISSIM scenario models

**2.3.2. Examination of Advance Warning Area Length**

This study examines the effects of altering the duration of the advance notice area in construction zones, categorized into two categories as follows.

*Traffic Operational Performance*

Assessed using measures including travel time and control delay, quantified at the upstream boundary of the advanced warning area. The sensitivity study entailed increasing the warning area length by 60 m increments (from 575 m to 815 m) for single-lane closures and by 80 m increments (from 745 m to 1,065 m) for double-lane closures.

*Traffic Conflict Analysis Utilizing SSAM*

The Surrogate Safety Assessment Model (SSAM) was utilized to assess safety by analyzing pre-collision conflict data. A Time to Collision (TTC) threshold of 1.3 seconds was adopted following previous SSAM studies, as it falls within the commonly used range (1.0–1.5 s) for identifying critical traffic conflicts [38, 39]. As illustrated in Figure 6, lower TTC values combined with higher conflict speeds are associated with greater conflict severity, and a TTC value of 1.3 s lies within the transition region between moderate- and high-risk conflicts, making it suitable for identifying critical traffic interactions [40]. The analysis focused solely on lane-changing (side-swipe) and rear-end conflicts, excluding crossing and head-on collisions due to the highway's split design (Figure 7).

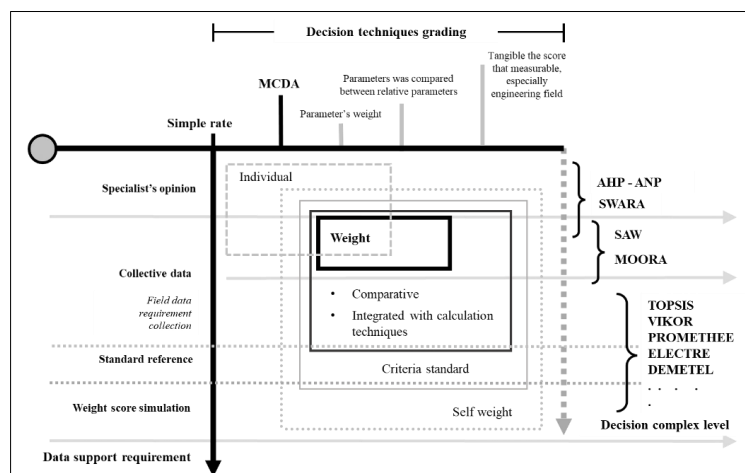


Figure 6. Grounded principal of Multi-Criteria Decision Analysis and Schematic chart of MCDA

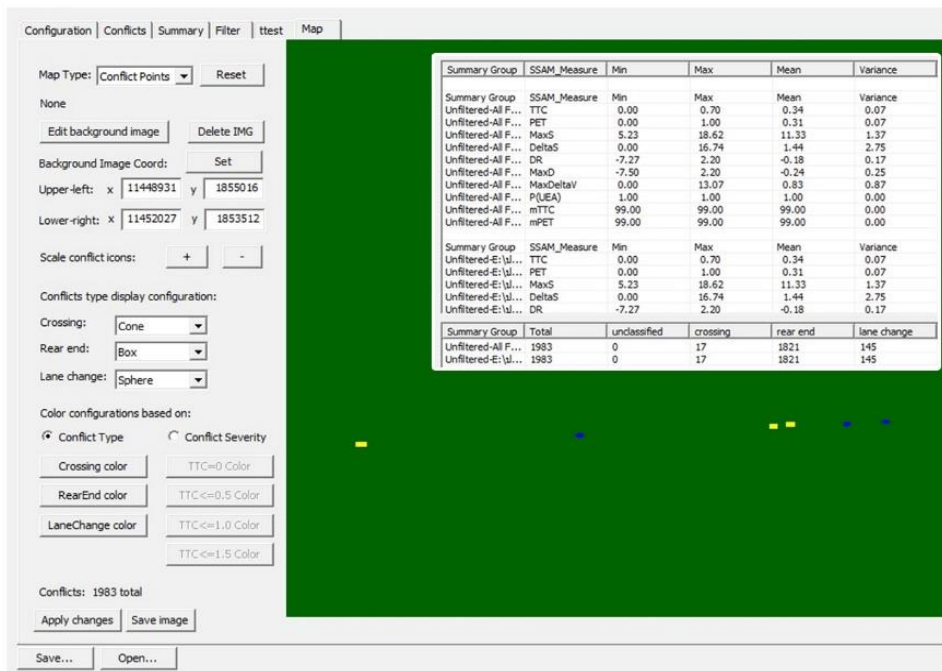


Figure 7. The traffic conflict analysis results from the SSAM program

2.4. Calculation of Scores Using SAW, WASPAS, TOPSIS, VIKOR, PROMETHEE and EDAS Methods BASED on AHP

This study focuses on factors derived from microsimulation results across three criteria: total travel time (s), network delays (km/h), and number of conflicts. The MCDA cluster was classified into 3 groups. First, the "Simple" and "Low-Data" group (SAW, WSM, WPM): Suitable for uncomplicated problems, emphasizing speed and ease of explanation to frontline operators. Secondly, the "Medium" group (TOPSIS, VIKOR, EDAS): Popular tools that strike a balance between mathematical accuracy and ease of interpretation. Suitable for KPI measurement processes or general project selection. Lastly, the "Complex" and "High-Data" group (ANP, ELECTRE, PROMETHEE): Used when decision-making problems involve high risk, highly conflicting criteria, or the need to prevent "maximum regret" at the organizational strategic level. The grounded principle of MCDA is shown in Figure 7. The MCDA was combined with a decision tree and a set of descriptors comprising the variables, the criteria weights, and the weight variations [41]. Previously, numerous studies [42-44] have focused on assessing the consistency of various multi-criteria decision-making (MCDA) methods, including SAW, WASPAS, TOPSIS, VIKOR, PROMETHEE, and EDAS (as illustrated in Table 3). These methods are the primary techniques utilized in this study. The framework of this study was extended to explain the effect of decision weights on other emerging alternatives. The results suggest an approach for prioritizing and selecting a simplified intersection model based on data acquisition via a simulation model and decision-making through actual practice. Table 4 provides a detailed comparison examination of the technical attributes and mathematical formulations for several MCDA approaches, including SAW, WASPAS, TOPSIS, VIKOR, PROMETHEE, and EDAS. This synthesis outlines particular techniques for criterion weighing, data standardization, and sensitivity analysis, emphasizing the unique aggregation mechanisms characteristic of each method.

Table 3. Comprehensive the capability of MCDA

Method	Theoretical Foundation	Computational Procedure	Key Distinctions (Critical Parameters)	References
SAW	Based on Additive Utility Theory, assuming linear compensation between criteria.	Aggregates normalized scores through a weighted linear sum to derive a final preference value.	N.A.	[45, 46]
WASPAS	A Hybrid Model integrating the Weighted Sum Model (WSM) and Weighted Product Model (WPM).	Employs a joint criterion of additive and multiplicative synthesis to enhance ranking stability.	$\lambda$ (Jointness Parameter): Optimizes the influence between WSM and WPM to increase the robustness of the decision.	[47-49]
TOPSIS	Grounded in the Compromise Principle, where the best alternative has the shortest geometric distance to the ideal.	Calculates Euclidean distances to both Positive-Ideal (PIS) and Negative-Ideal Solutions (NIS).	Relative Closeness Coefficient: Evaluates alternatives based on their relative proximity to the optimal performance boundaries.	[50-52]
PROMETHEE	Based on Outranking Relations, focusing on the intensity of preference between pairs of alternatives.	Utilizes specific Preference Functions to quantify the degree of dominance one alternative has over another.	Preference Functions & Thresholds (p,q): Manages uncertainty and indifference zones in decision-making processes.	[53, 54]
VIKOR	Focuses on reaching a Compromise Solution in the presence of conflicting criteria and non-commensurable units.	Determines a compromise ranking by minimizing the individual regret and maximizing group utility.	$v$ (Weight of Decision Strategy): Balances the trade-off between "majority rule" and "minimum individual regret."	[55-57]
EDAS	Evaluates alternatives based on their Distance from an Average Solution (AV) rather than ideal points.	Calculates the Positive (PDA) and Negative Distance from Average (NDA) to determine an appraisal score.	Average-centric Evaluation: Highly effective for datasets with significant outliers, as it utilizes the mean performance as a benchmark.	[58, 59]

**Table 4. Comparison of the SAW, WASPAS, TOPSIS, VIKOR, PROMETHEE and EDAS Methods**

MCDA Technique	Criteria/Sub-criteria	Weighting	Data Normalization	Distance-based	Compare Best/Worst	Compare to Average	Pairwise Comparison	Sensitivity Analysis
SAW	Yes	Yes	Linear	No	Yes	No	No	Limited
WASPAS	Yes	Yes	Linear	No	Yes	No	No	Moderate
TOPSIS	Yes	Yes	Vector	Yes	Yes	No	No	Moderate
VIKOR	Yes	Yes	Linear	Yes	Yes	No	No	High
PROMETHEE	Yes	Yes	None*	No	Yes	No	Yes	High
EDAS	Yes	Yes	None	Yes	No	Yes	No	High

\*PROMETHEE does not require explicit normalization, as it relies on preference functions.

MCDA Technique	Formula
SAW	$R_{ij} = x_{ij} / x_j^*$ , if the $j^{th}$ criteria is a benefit criterion, and $R_{ij} = x_j / -x_{ij}$ , if the $j^{th}$ is the cost criterion
WASPAS	$Q_i^{(1)} = \sum_{j=1}^n \bar{x}_{ij} w_j, Q_i^{(2)} = \prod_{j=1}^n (\bar{x}_{ij})^{w_j}, Q_i = \lambda \sum_{j=1}^n \bar{x}_{ij} w_j + (1 - \lambda) \prod_{j=1}^n (\bar{x}_{ij})^{w_j},$ $\bar{x}_{ij} = \begin{cases} \frac{x_{ij}}{\max x_{ij}} & \text{if } \max x_{ij} \text{ is preferable} \\ \frac{\min x_{ij}}{x_{ij}} & \text{if } \min x_{ij} \text{ is preferable} \end{cases}$ $\lambda = 0, 0.1, 0.2, \dots, 1.0$
TOPSIS	$R, r_{ij} = x_{ij} / \text{sq root}(\sum_{i=1}^m x_{ij}^2), S_i^* = \text{Sq root}(\text{sum of squares for } j = 1 \dots n) \text{ of } (V_{ij} - V_j^*), S_i^- = \text{Sq root}(\text{sum of squares for } j = 1 \dots n) \text{ of } (V_{ij} - V_j^-) \text{ as } C_i^* = S_i^- / (S_i^* + S_i^-)$
VIKOR	$L_{p,j} = \sum_{i=1}^n [w_i (f_i^* - f_{ij}) / (f_i^* - f_i^-)]^{1/p}, 1 < p < \infty; j = 1, 2, \dots, j$ $S_j = L_{p,j} = \sum_{i=1}^n w_i (f_i^* - f_{ij}) / (f_i^* - f_i^-), R_j = \max_j [\sum_{i=1}^n w_i (f_i^* - f_{ij}) / (f_i^* - f_i^-)]$ $Q_j = v (S_j - S^*) / (S^- - S^*) + (1 - v) (R_j - R^*) / (R^- - R^*); \text{ while } v \text{ is introduced as weight of strategy of } S_j \text{ and } R_j$
PROMETHEE	$P_j(i, i') = 0 \text{ if } R_{ij} R_{i'j}; P_j(i, i') = (R_{ij} - R_{i'j}) \text{ if } R_{ij} R_{i'j}$ $\phi^+(i) = \frac{1}{n-1} \sum_{i'=1}^n \pi(i, i'), i' \neq i; \phi^-(i) = \frac{1}{n-1} \sum_{i'=1}^n \pi(i', i), i' \neq i;$ $\pi(i, i') = \sum_{j=1}^m W_j \times P_j(i, i') / \sum_{j=1}^m W_j; \phi^+(i) = \phi^+(i) - \phi^-(i)$
EDAS	$AV = [AV_j]_{1 \times m}; AV_j = \frac{\sum_{i=1}^n x_{ij}}{n}; PDA = [PDA_{ij}]_{n \times m}; NDA = [NDA_{ij}]_{n \times m}$ If $j$ th criterion is beneficial; $PDA_{ij} = \frac{\max(0, (x_{ij} - AV_j))}{AV_j}; NDA_{ij} = \frac{\max(0, (AV_j - x_{ij}))}{AV_j}$ If $j$ th criterion is non-beneficial; $PDA_{ij} = \frac{\max(0, (AV_j - x_{ij}))}{AV_j}; NDA_{ij} = \frac{\max(0, (x_{ij} - AV_j))}{AV_j}$ $SP_i = \sum_{j=1}^m w_j PDA_{ij}; SN_i = \sum_{j=1}^m w_j NDA_{ij}; NSP_i = \frac{SP_i}{\max(SP_i)}; NSN_i = \frac{SN_i}{\max(SN_i)}$ $AS_i = \frac{1}{2} (NSP_i + NSN_i)$

### 3. Results and Discussion

#### 3.1. Results of AHP

A panel of experts in highway engineering, traffic safety, and construction management, all possessing significant practical experience in work zone operations, participated in the AHP analysis to ensure a comprehensive and robust assessment. The AHP results in Table 5 demonstrate that experts attributed the most significance to Number of conflicts (W = 0.3600), followed by Network delay (W = 0.3500) and Total trip time (W = 0.2900). The increased emphasis on disputes indicates that safety considerations were emphasized over operational success metrics. This discovery illustrates the traits of varied traffic conditions frequently seen in developing nations, where diverse vehicle types and inconsistent driving habits heighten the likelihood of traffic confrontations in work zones. Thus, reducing potential conflicts was deemed the paramount consideration in assessing work zone traffic management options. The consistency ratio (CR < 0.10) validates the dependability of the expert assessments. The details of the weight priorities assigned by the experts are listed in Table 5.

**Table 5. Weight priorities of indicators for decision-making on AHP**

Main criteria	Weights
C1: Total travel time	0.2900
C2: Network delay	0.3500
C3: Number of conflicts	0.3600

\*Consistency ratio (C.R.) analysis <0.10.

### 3.2. Results of Efficiency Indicator Analyses and MCDA

This section discusses the use of analytical outcomes derived from PTV VISSIM for the different sub-criteria based on which the simulation outcomes of the efficiency indicators were exported, as shown in Figure 8. The MCDA aspects provided a comprehensive visualization of decisions regarding the three indicator variables. First, the four best scenarios were as follows: 1. Scenario 1: 4-lane highway (left lane closed), 2. Scenario 2: 4-lane highway (right lane closed), 3. Scenario 3: 6-lane highway (left lane closed), and 4. Scenario 4: 6-lane highway (right lane closed). In evaluating the efficacy and robustness of process optimization strategies, theoretical postulates must be rigorously empirically validated. This section presents a comprehensive comparative analysis of five prominent Multi-Criteria Decision Analysis (MCDA) methodologies: Simple Additive Weighting (SAW), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), Weighted Aggregated Sum Product Assessment (WASPAS), VIŠeKriterijumska Optimizacija I Kompromisno Rešenje (VIKOR), and Evaluation based on Distance from Average Solution (EDAS). By deploying a dynamic microsimulation framework as a surrogate for complex sociotechnical processes, this study systematically investigates the algorithmic behavior, decision stability, and practical applicability of each method under varying degrees of systemic stress.

The sensitivity analysis of the EDAS scores demonstrates clear stability patterns among the four lane-closure scenarios (Figure 8). Scenario (c) displays the greatest stability, exhibiting just slight score fluctuations over the evaluated weight ranges, while Scenarios (a) and (b) reveal significant sensitivity. Conversely, Scenario (d) exhibits the highest variability, signifying a more pronounced impact of criteria-weight modifications on alternative performance. Significantly, score fluctuations become more evident as the conflict-point weight exceeds 55%, especially in Scenario (d). The findings indicate that left-lane closures on six-lane highways yield more reliable decision outcomes, while right-lane closures are more susceptible to variations in weighting and necessitate meticulous deliberation during decision-making.

The SAW method represents the effective warning distance as 825 meters for (a) 4-lane highway, closing 1 left lane; (b) 4-lane highway, closing 1 right lane, and 1,050 meters for (c) 6-lane highway, closing 2 left lanes; and (d) 6-lane highway, closing 2 right lanes. On the other hand, those WASPAS, VIKOR, PROMETHEE, and TOPSIS techniques are addressing the same trend that warns that in the long run, they are effective, in cases (a) 4-lane highway, closing 1 left lane; (b) 4-lane highway, closing 1 right lane. TOPSIS, PROMETHEE, and VIKOR insights indicate that the effective warning distance is 750 meters. In case of (c) 6-lane highway, closing 2 left lanes; and (d) 6-lane highway, closing 2 right lanes, the analysis suffers from the contrast of effective warning that TOPSIS and WASPAS, and concordance agreement with the (d) 6-lane highway, closing 2 right lanes cases that the effective distance is 750 meters. Without these cases, the effective warning distance in case the (c) 6-lane highway, closing 2 left lanes; and (d) 6-lane highway, closing 2 right lanes are prefer 1,050 meters are the effective warning distance. Moreover, the revised manuscript strengthens the interpretation of the MCDA results by explaining why PROMETHEE, EDAS, VIKOR, and TOPSIS showed greater ranking stability than SAW and WASPAS across varying weighting conditions. These additions improve the analytical depth of the study and strengthen the practical implications of the proposed decision-support framework.

To critically assess the sensitivity and rank-reversal vulnerabilities inherent in these MCDA techniques, the experimental design incorporates a multifaceted stress-testing paradigm. The simulation evaluates alternative spatial configurations ranging from 575 to 985 meters for a 4-lane highway with the left and right lanes closed, and operational conditions to critical capacity thresholds of 1,200 to 4,800 units per hour for a 6-lane highway with the left and right lanes closed. Furthermore, to ensure the methodological rigor of the decision outcomes, a multidimensional sensitivity analysis was conducted across 5 distinct weighting scenarios, as shown in the sensitivity analysis table. This deliberate perturbation of criterion weights accurately mimics the inherent uncertainty, dynamic constraints, and fluctuating stakeholder priorities commonly encountered in real-world process engineering. The subsequent subsections delineate the empirical findings, focusing specifically on the intersection between the mathematical architecture of the algorithms and practical process resilience. By tracking the performance trajectories and ranking stability of the alternatives across the simulated constraints, this analysis elucidates the specific operational conditions under which each MCDA method either thrives or exhibits critical vulnerabilities. Ultimately, the following results synthesize epistemological MCDA insights with applied operations research, providing an evidence-based roadmap for deploying appropriate decision-making frameworks to mitigate systemic bottlenecks, optimize buffer capacities, and drive continuous process improvement.

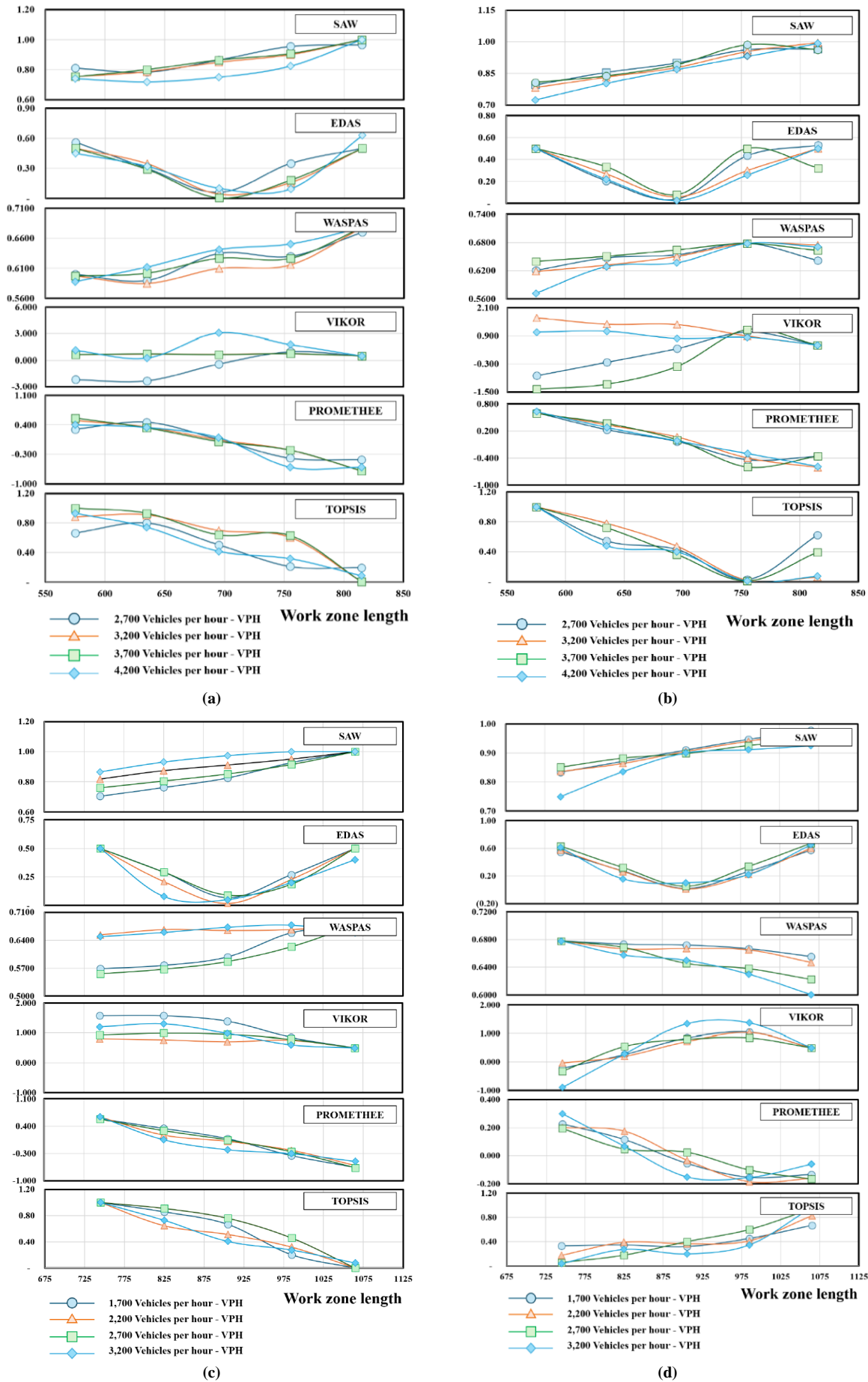


Figure 8. The prioritization length of the early warning area via 6 MCDA methods: (a) 4-lane highway, closing 1 left lane; (b) 4-lane highway, closing 1 right lane; (c) 6-lane highway, closing 2 left lanes; and (d) 6-lane highway, closing 2 right lanes

### 3.3. Sensitivity Analysis

Techniques and Conceptual Frameworks Identified in the Dataset: This dataset was used to evaluate the sensitivity analysis of six MCDA algorithms: SAW, TOPSIS, PROMETHEE, WASPAS, VIKOR, and EDAS under the following test structure (Figure 9):

- Traffic Volume Levels: The input volume is categorized into uncongested flow conditions (1200, 1700, 2200, 2700 vehicles/hour) and congested conditions (3200, 3300, 3800, 4200, 4300, 4800 vehicles/hour).
- Decision Alternatives: Spatial process design (distance) is divided into main groups, such as short-distance sets (575 m, 635 m, 695 m, 755 m) and long-distance sets (745 m, 825 m, 905 m, 985 m).
- Sensitivity Scenarios: Data was tested through 5 scenarios (Scenario 1 to Scenario 5), representing adjustments to the weights of the decision criteria at levels of 0.36, 0.45, 0.55, 0.65, and 0.75 to test the ranking robustness.

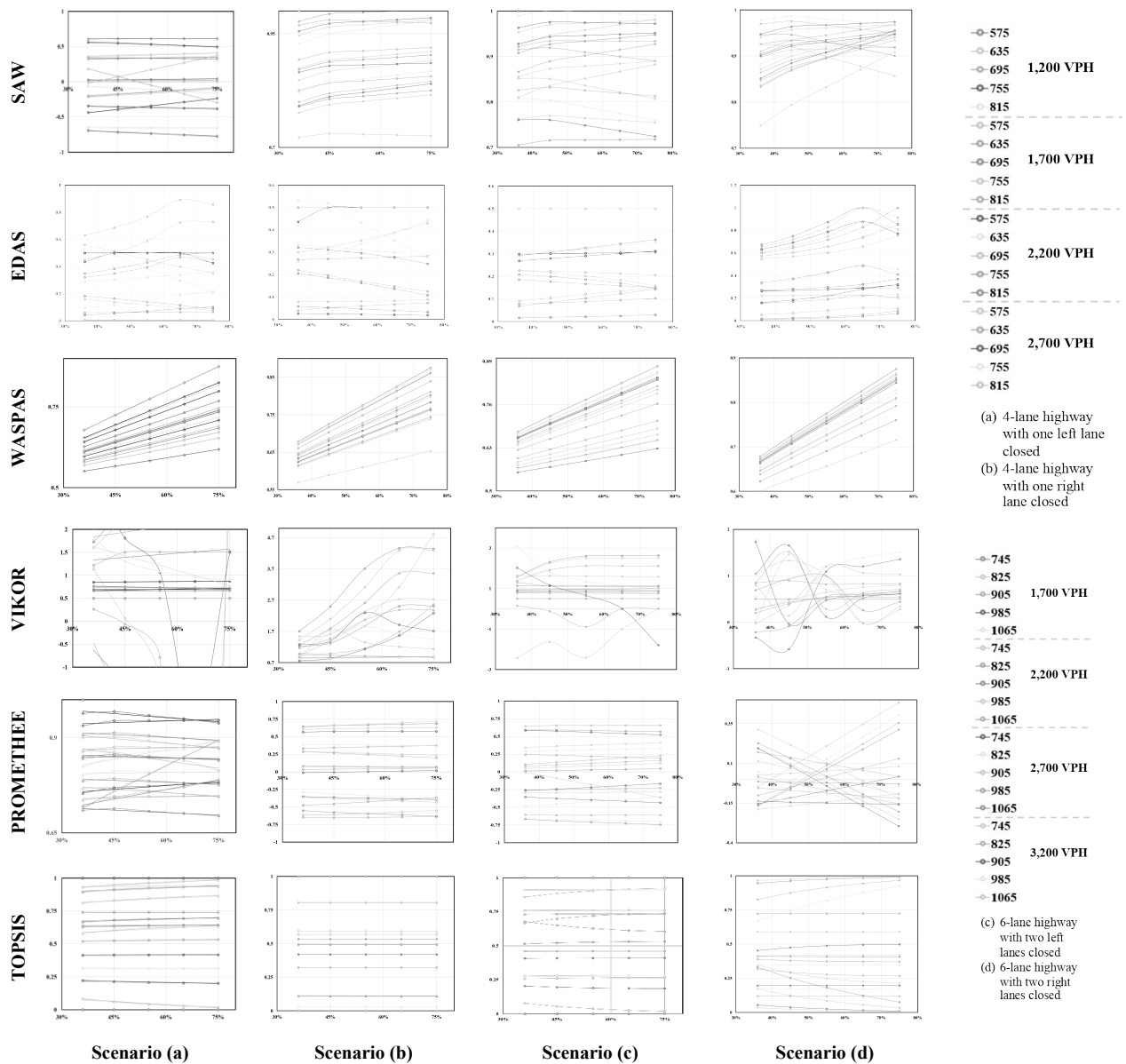


Figure 9. Comparative sensitivity analysis of ranking stability across six MCDM methods under four highway lane closure scenarios: (a) 4-lane highway with one left lane closed, (b) 4-lane highway with one right lane closed, (c) 6-lane highway with two left lanes closed, and (d) 6-lane highway with two right lanes closed.

In the EDAS analysis, the sensitivity analysis reveals distinct behavioral shifts across different criterion weight thresholds. Within the 40% to 60% range, multiple graphical intersections emerge among the mid-tier alternatives (scores ranging from 0.3 to 0.5), highlighting a high degree of sensitivity in which minor weight adjustments can easily alter secondary rankings. Notably, extreme sensitivity is evident in the alternative that initially performed best at lower weights; as the criterion's weight increases, its score significantly declines, leading to rank reversal and the loss of its optimal status. Despite this volatility among secondary options, the top-ranked alternative demonstrates strong

robustness in certain scenarios, remaining unaffected by weight variations. However, when the criterion weight exceeds 65%, even the leading alternatives begin to experience performance degradation and rank reversals. Overall, the graphical trends indicate that disproportionately emphasizing a single criterion severely compromises ranking stability and diminishes the relative efficiency of the best available options.

The sensitivity analysis, therefore, provides valuable insight into the robustness of the MCDA framework by identifying the conditions under which ranking outcomes remain stable or become vulnerable to change. In particular, the relatively stable performance of SAW, WASPAS, PROMETHEE, EDAS, VIKOR, and TOPSIS under moderate weight variations suggests that these methods are better suited to support strategic transportation decisions in complex work zone environments. SA – SAW, cannot represent the change of weight significantly, SA – WASPAS, cannot detect the change of weight that WASPAS are weak at representing. SA – VIKOR cannot define. SA - PROMETHEE, addressing the (d) 6-lane highway, closing 2 right lanes is significant, while the weight changes up to 55 percent approximately. SA – TOPSIS is clear that (a) a 4-lane highway, closing 1 left lane; (b) a 4-lane highway, closing 1 right lane, are stable to confirm the result mentioned above. Additionally, weight changes of approximately 40-45% are becoming crucial.

Although six MCDA methods were evaluated in this study, the discussion primarily focuses on PROMETHEE, EDAS, VIKOR, and TOPSIS because these methods demonstrated greater ranking stability and consistency across the sensitivity analysis scenarios. These approaches are mathematically more robust in handling conflicting criteria, trade-offs, and variations in criterion weights, particularly under high-stress traffic conditions. In contrast, SAW and WASPAS rely mainly on additive aggregation techniques, which are more sensitive to normalization effects and weight fluctuations. As a result, small changes in criterion weights can produce noticeable changes in rankings, especially among mid-ranked alternatives.

Furthermore, PROMETHEE, EDAS, VIKOR, and TOPSIS incorporate more advanced comparative mechanisms, such as distance-to-ideal solutions, outranking relationships, compromise ranking, and average-based evaluation, enabling better discrimination between alternatives under complex work zone conditions. Nevertheless, SAW and WASPAS still produced generally comparable ranking trends and remain useful due to their simplicity, computational efficiency, and ease of practical implementation. Therefore, they were retained in the comparative framework to provide a broader methodological perspective and to validate the overall consistency of the MCDA evaluation process. The sensitivity analysis demonstrates that ranking instability and rank reversals occur when criterion weights are substantially modified, particularly within the 45–65% weighting range.

#### 4. Conclusion

This study aims to propose a strategic decision-support model for determining the appropriate advanced warning distance for highway construction and maintenance work zones. The model integrates Multi-Criteria Decision Analysis (MCDA) techniques to systematically evaluate performance indicators across multiple dimensions, including safety, driver behavior, and traffic flow impacts under heterogeneous conditions. This research investigates the transportation behavior and logistical impacts of ongoing highway construction and maintenance projects, especially in developing economies, where road infrastructure serves as a critical foundation for transport mobility. Delays and inefficiencies in maintenance directly compromise both transport efficiency and public safety. To address these challenges, this study establishes a framework for investigating the optimal “effective length” of road maintenance work zones.

Using various MCDA techniques, the research evaluates four distinct scenarios to define clear warning-distance recommendations. The results ensure maximum safety and operational flow, with four key findings revealed. First, for multilane highways with two right lanes closed, a suitable warning distance exceeds 1,075 m. This differs from other scenarios, where a shorter distance of 575 m is preferred for two left-lane closures on multilane highways, while 750 m is preferred for one-lane maintenance on multilane highways. The longer warning distance required for right-lane closures may be associated with both driver behavior and traffic operational characteristics. On multilane highways in Thailand, the right lane is commonly used for overtaking and higher-speed travel. Consequently, vehicles approaching a right-lane closure may experience greater speed differentials and require additional time and distance to perceive, react, and safely execute lane-changing maneuvers. In contrast, left-lane closures generally involve lower speeds and fewer lane-changing conflicts. Therefore, geometric and traffic flow characteristics may contribute to the observed differences in warning-distance requirements.

Second, the comparative MCDA framework, which uses advanced technical methods, including numerical vector calculations and pairwise comparisons, incorporates SAW, WASPAS, PROMETHEE, EDAS, VIKOR, and TOPSIS. The SAW method identified effective distances of 825 m for four-lane highways with one lane closed and 1,050 m for six-lane highways with two lanes closed. In contrast, WASPAS, VIKOR, PROMETHEE, and TOPSIS tended to favor longer distances. For four-lane closures, TOPSIS, PROMETHEE, and VIKOR identified 750 m as the optimal distance. For six-lane closures, analytical contradictions emerged between TOPSIS and WASPAS, although agreement was reached on a 750 m distance specifically for the two-right-lane closure scenario. Otherwise, a warning distance of 1,050 m remained the preferred choice for both six-lane highway scenarios. The use of progressively complex analytical techniques enhances the granularity of the findings, thereby providing a robust empirical foundation for determining optimal safe advance warning thresholds.

Third, the sensitivity analysis showed that a 45%–50% change in weight becomes crucial for determining work zone management distances. Therefore, the critical issue lies in the number of conflicts (C3) parameter. The proposed research framework provides knowledge for addressing advanced regulatory needs in countries where road infrastructure is central to transport mobility. This evidence can support more effective regulation of highway construction and maintenance projects.

## 5. Abbreviation

$x_{ij}/x_j^*$	The calculate number when the $j^{\text{th}}$ criterion is a benefit criterion	$r_{ij} = x_j^-/x_{ij}$	The calculate number when the $j^{\text{th}}$ criterion is a cost criterion
$Q_i^{(1)}$	The total relative importance of alternative $i$ as per the WPM method	$R_{ij}$	Estimate the normalized decision matrix
$D_{ij}$	The weighted normalized decision matrix	$S_i^*$	The separation of each alternative (the positive-ideal one)
$S_i^-$	The separation of each alternative (the negative-ideal one)	$C_i^*$	The relative closeness to the ideal solution
$V_{ij}$	The weighted normalized value	$L_{p,j}$	Ranking is done based on the measure
$S_j$	The maximum group utility	$R_j$	The minimum individual regret of the opponent
$X_{ij}$	The performance measure of $i^{\text{th}}$ alternative with respect to $j^{\text{th}}$ criterion	$P_j(i, j_-)$	Preference function
$\pi(i, i)$	Aggregated preference function	“n”	The number of alternatives
$\phi(i)$	Used to rank all the alternatives	$AV_j$	The average solution of the $j$ -th criterion
PDA	The positive distance from the average solution	NDA	The negative distance from the average solution
$W_j$	The weight of the $j$ -th criterion	$SP_i$	The weighted sum of positive distances for the $i$ -th alternative
$SN_i$	The weighted sum of negative distances for the $i$ -th alternative	$NSP_i$	Normalized $SP_i$
$NSN_i$	Normalized $SN_i$	$AS_i$	The appraisal score for final ranking

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, N.N. and P.K.; methodology, W.P.; software, W.P., W.A., and W.C.; validation, W.P., W.A., P.K., and W.C.; formal analysis, W.P., T.C., and W.C.; investigation, W.P., W.A., W.C., and P.K.; resources, N.N., W.C., and P.K.; data curation, W.P.; writing—original draft preparation, W.P. and P.K.; writing—review and editing, W.P. and W.A.; visualization, W.P.; supervision, W.C. and P.K.; project administration, W.P. and P.K.; funding acquisition, N.N. and P.K. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available in the article.

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### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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