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Prioritizing climate adaptation interventions for road infrastructure: An expert survey-based investigation of preferences and trade-offs

Aryasatya Adyatama [a,*], Srijith Balakrishnan [a,*], Beatrice Cassottana [b,c], Jan Anne Annema [a], Nazli Y. Aydin [a]

[a] Faculty of Technology, Policy and Management, Delft University of Technology, Delft, Netherlands
[b] Global Infrastructure Basel Foundation, Basel, Switzerland
[c] InfraRisk Pte. Ltd., Singapore

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ABSTRACT

Amid escalating climate risks and a widening adaptation finance gap, especially in low- and middle-income countries (LMICs), prioritizing adaptation measures for road infrastructure is essential for building sufficient resilience through both public and private adaptation financing. Despite the urgency of the issue, adaptation finance for infrastructure is often hampered by a lengthy and complex decision-making process that involves conflicting stakeholder interests. Existing taxonomies and benchmarks for adaptation finance typically focus on identifying optimal engineering solutions, often overlooking the numerous factors that influence these implementation decisions. To address this gap, this study develops an approach to understand stakeholders' and decision makers' preferences for road infrastructure adaptation measures using empirical evidence based on a global survey of 72 out of 129 respondents from industry, academia, and government. Multi-criteria decision analysis is applied using the Best-Worst Method (BWM) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Four relative importance criteria are assessed, namely, disaster risk reduction, maladaptation risk, adverse societal impact, and project cost, and rank 11 widely-adopted adaptation measures targeting intense precipitation and extreme heat. Results show preventive, cost-effective, and sustainable options, such as improved drainage systems, vegetation plans, and monitoring systems, are consistently favored over capital-intensive structural solutions like alternative road construction and road reallocation. Overall, the findings demonstrate a systematic approach that incorporates diverse stakeholder perspectives into road adaptation planning to enhance the transparency, legitimacy, and implementability of selected adaptation measures.

1. Introduction

Transport infrastructure systems, such as road networks, ports, and airports, play a vital role in the economy, forming the backbone of trade, commerce, and daily community activities (Espinet et al., 2016). The majority of road infrastructure is designed to withstand normal weather events. However, it often fails to account for the uncertainties of climate change-induced extreme events that fall outside the standard range (deAbreu et al., 2022). As a result, road networks experience structural degradation,

* Corresponding authors.
E-mail addresses: a.adyatama@tudelft.nl (A. Adyatama), s.balakrishnan@tudelft.nl (S. Balakrishnan), beatrice.cassottana@gmail.com (B. Cassottana), j.a.annema@tudelft.nl (J.A. Annema), n.y.aydin@tudelft.nl (N.Y. Aydin).

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reduced serviceability, and increased maintenance costs (Mushtaq et al., 2024). For example, during the 2022 floods in Pakistan, approximately 13,000 km of roads were washed off and access to markets, schools, and emergency services was cut off for 33 million people, underscoring how road infrastructure disruptions can rapidly escalate into severe socioeconomic losses (Paracha et al., 2023). Such catastrophic disasters must be anticipated, as climate change is expected to increase the frequency, duration, and severity of extreme weather events and slow-onset events. Beyond physical damages and loss of lives, these disruptions carry major financing implications, particularly for low- and middle-income countries, where the adaptation investment needs far exceed current capital flows. This widening adaptation finance gap increases the urgency for resource-efficient prioritization of resilience measures, as public budgets alone are insufficient to deliver climate-proof road systems (Casady et al., 2024).

Among the various climate-related stressors, intense precipitation and extreme heat have received the most attention due to their significant impacts on road infrastructure (deAbreu et al., 2022). Both stressors result in road deterioration, including the formation of cracks and potholes, thereby heightening the probability of traffic accidents (Chu et al., 2023). Empirical studies further indicate that intense precipitation can increase accident rates by 75% and injury rates by 45% (Koetse and Rietveld, 2009). To minimize the harmful impacts of climate change, road networks need to strengthen their climate resilience strategies (Singh et al., 2020). With a robust resilience intervention, the road network can maintain its functionality during climate-induced disruptions.

The existing literature discusses a wide range of climate adaptation strategies for road infrastructure. Most studies focus on the asset level, aiming to enhance the performance of individual measures within specific infrastructures (deAbreu et al., 2022). For instance, research has explored ways to increase the effectiveness of nature-based solutions (Cohen-Shacham et al., 2016) and to develop advanced materials capable of withstanding extreme temperatures (Kappou et al., 2022). While these studies provide valuable technical insights, they often overlook comparative evaluations that assess and rank adaptation options in road networks based on wide range of criteria that become relevant during decision making. Such assessments are challenging due to the limited amount of empirical longitudinal data and standardized evaluation frameworks for adaptation interventions (Haque, 2016). As a result, current road infrastructure adaptation research focuses on engineering-based assessment and offers limited guidance on comparative studies of different interventions based on key stakeholder preferences and tradeoffs (Achebe et al., 2021).

However, understanding the diverse views of key stakeholders is essential because they negotiate trade-offs and authorize the continuation of adaptation projects. For this, it requires a transparent and evidence-based justification of the weighting of economic, technical, and social criteria used to prioritize road adaptation measures before project execution. Moreover, integrating stakeholders' perspectives can help ensure that strategies are embedded in practice rather than remaining purely academic concepts (Cvitonovic et al., 2019). However, existing taxonomies and benchmarking frameworks rarely incorporate empirical evidence on stakeholder preferences (Keenan et al., 2019).

Involving stakeholders in decision-making is challenging because they often hold divergent views on the relative importance of adaptation criteria and measures (Siders and Pierce, 2021). For instance, business actors may emphasize maximizing the economic returns of interventions, whereas academic and community stakeholders often focus on ensuring fairness and equity in the distribution of benefits across neighborhoods. Therefore, prioritizing adaptation represents a classic "wicked problem" involving multiple actors, uncertainties, and competing goals (Wright et al., 2014). These different priorities further complicate the evaluation of adaptation options and highlight the need for a structured approach to consider stakeholder preferences and trade-offs to enhance the legitimacy of adaptation decisions (Reed, 2008). In summary, current research is missing empirical evidence on stakeholders' preferences and trade-offs in prioritizing climate adaptation interventions for road infrastructure.

To address this gap, this study conducted a global survey of 129 respondents from industry, academia, and government to examine explicit preferences and trade-offs in prioritizing climate adaptation interventions for road infrastructure. Specifically, the study aims to: (1) identify key prioritization criteria and widely adopted intervention alternatives, (2) quantify the importance weights of stakeholders' preferred adaptation criteria by estimating their relative importance, and (3) rank a list of preferred adaptation measures for road infrastructure under intense precipitation and extreme heat.

This study considers road assets broadly, without limiting the analysis to specific road functions, geographic contexts, case studies, project stages, or technical settings. It adopts a general road project perspective to support strategic applicability. This study helps stakeholders, such as investors in the pre-investment phase by providing screening-level guidelines as legitimation before detailed engineering and economic appraisal. Moreover, road agencies, planners, or consultants also benefit from understanding the comparative assessment between the most adopted adaptation measures, which acknowledge multidimensional criteria in a systematic, transparent, and evidence-based structure.

The rest of the paper is organized as follows: Section 2 reviews the existing literature on climate adaptation decision-making; Section 3 describes the methodology adopted in the study, including data collection and analytical approaches; Section 4 presents the key empirical findings; and Section 5 summarizes the main insights and policy implications.

2. Literature review

Road infrastructure remains insufficiently adapted to climate impacts, with 27% of the global network exposed to at least one climate-related hazard (Koks et al., 2019). As extreme precipitation and heatwaves become more severe, roads face accelerated pavement deterioration, heightened flooding and drainage risks, and reduced structural integrity (deAbreu et al., 2022). These trends underscore the need for adaptation measures for road infrastructure to maintain reliability under normal conditions and limit failure during extremes. This section reviews existing research on climate change adaptation for road infrastructure, examines trade-offs in decision-making, and highlights gaps in current knowledge. It establishes the foundation for developing a prioritization approach for climate adaptation.

2.1. Adaptive interventions for road infrastructure

Climate adaptation is the process of adjustment to climate effects to moderate the negative impacts and/or enhance the positive impacts of climate change (IPCC, 2014). Climate adaptation can also be viewed as a social response to change the way exposure units are affected by stimuli arising from climate change (Eisenack et al., 2012). Both definitions highlight a clear distinction between mitigation and adaptation, where mitigation seeks to reduce the causes of climate change, and adaptation focuses on minimizing its adverse impacts.

Road designers have incorporated adaptive interventions to withstand high precipitation and heatwaves. For example, vegetation plan to enhance rainwater absorption and provide shading to mitigate urban heat effects (Cohen-Shacham et al., 2016), developing localized power sources to decentralize energy systems within road networks (Gnatov et al., 2017), adopting heat-resistant roads to lower surface temperatures (Wang et al., 2022), enhancing road monitoring systems to provide information about road quality for maintenance purposes (Radopoulou and Brilakis, 2016), adjusting road elevation above anticipated flood levels (Mallick et al., 2014), constructing flood defenses to block or divert floodwaters (Serra-Llobet et al., 2021), improving flood pathway management to control and direct the flow of floodwaters (Yoosefdoost and Lubitz, 2022), improving drainage infrastructure to prevent water-logging (Emama et al., 2022), providing alternative routes as a contingency plan (El rashidy and Grant-Muller, 2014), rerouting vulnerable infrastructure to avoid hazard prone areas (Kaviani et al., 2017), and relocating roads away from current high-risk areas (Karamouz et al., 2019).

These adaptive interventions have been shown to enhance the climate resilience of road infrastructure. For adaptation to heatwaves, replacing conventional pavements with heat-resistant pavements in Marousi, Athens, lowered local air temperatures by 1.2–2.0 °C (Santamouris et al., 2012), roads with dense vegetative barriers recorded reductions of approximately 2.8 °C compared to treeless streets, thus improving pedestrian comfort (Sang et al., 2025). In cases of high precipitation, improper flood pathway management has been found to reverse water flow and increase floodplain exposure by 2.3 to 8.4% (Yasmin et al., 2022). Despite evidence on the benefits of individual adaptation interventions, limited research has compared and prioritized these options based on stakeholder preferences, hindering effective resource allocation.

2.2. Factor influencing climate adaptation decisions

Climate change-relevant decisions are defined as actions that have consequences for climate change, particularly through mitigation and adaptation (Orlove et al., 2020). Deciding how and when to adapt to climate change is inherently complex, involving multiple stakeholders, divergent problem framings, uncertainty, and competing objectives (Siders and Pierce, 2021). Prior research identifies several factors that shape adaptation decision-making and highlights five overarching criteria: effectiveness in reducing risk and vulnerability, enhancing social well-being, improving environmental quality, increasing economic benefits, and strengthening institutions (Owen, 2020). Effectiveness in risk reduction refers to the adaptive interventions outcomes, such as improved asset performance, timely implementation, and reduced exposure to climate-induced hazards (Haque, 2016). Another key consideration is the feasibility of implementation, as even highly effective measures may fail if they cannot be carried out in practice. Feasibility is typically assessed through cost justification, resource availability, institutional and legal compatibility, and sociocultural acceptability (Singh et al., 2020).

Alongside assessing potential benefits, it is important to consider the risk of failure or maladaptation, since adaptation planning often relies on imperfect information and involves significant uncertainty. Maladaptation arises when measures unintentionally increase vulnerability or exposure to climate hazards rather than reduce them (Schipper, 2020). For example, flood barriers in the Netherlands, although intended to protect against inundation, in some cases redirected water and increased flood risk in adjacent areas (Koelewijn et al., 2023). Social and environmental risks also warrant attention, including inequitable impacts or unintended ecological harm. For instance, a permeable pavement system is designed to reduce flood risk, but sometimes it can allow pollutants to infiltrate groundwater, potentially degrading local water quality (Oghorodje, 2024). Therefore, decision-makers require a comprehensive perspective that ensures adaptive infrastructure not only strengthens asset resilience but also minimizes technical risks and avoids unintended social consequences.

Those decision criteria are not always aligned; sometimes they conflict and involve complex trade-offs (Wiréhn et al., 2020). For example, vegetative barriers such as trees can effectively reduce heat stress by providing shade and cooling (McPherson et al., 1988). Yet they may also create unintended problems, such as weakening nearby road surfaces or reducing visibility for drivers (Shi et al., 2023; Van Treese II et al., 2017). Additional trees also require additional space and involve ongoing maintenance costs. Therefore, it is essential to capture these interrelated dimensions by acknowledging the emerging trade-offs among technical effectiveness, potential risks, social implications, and economic viability. Integrating these perspectives enables decision-makers to identify solutions that are contextually appropriate and sustainable over the long term.

2.3. Methods for climate adaptation decision analysis

Climate decision-making involves choices by individuals or groups that influence, or are influenced by, climate-related risks (Orlove et al., 2020). Decision support tools assist this process by analyzing data to clarify available options (Fernando and Baldelovar, 2022). Among these tools, cost–benefit analysis (CBA) is widely used to evaluate whether a project is worthwhile by comparing its monetized costs and benefits over a defined time horizon. For example, Hallegatte (2011) used CBA to evaluate flood protection options in New Orleans, and Dittrich et al. (2019) applied it to assess nature-based solutions (NbS) in a rural Scottish

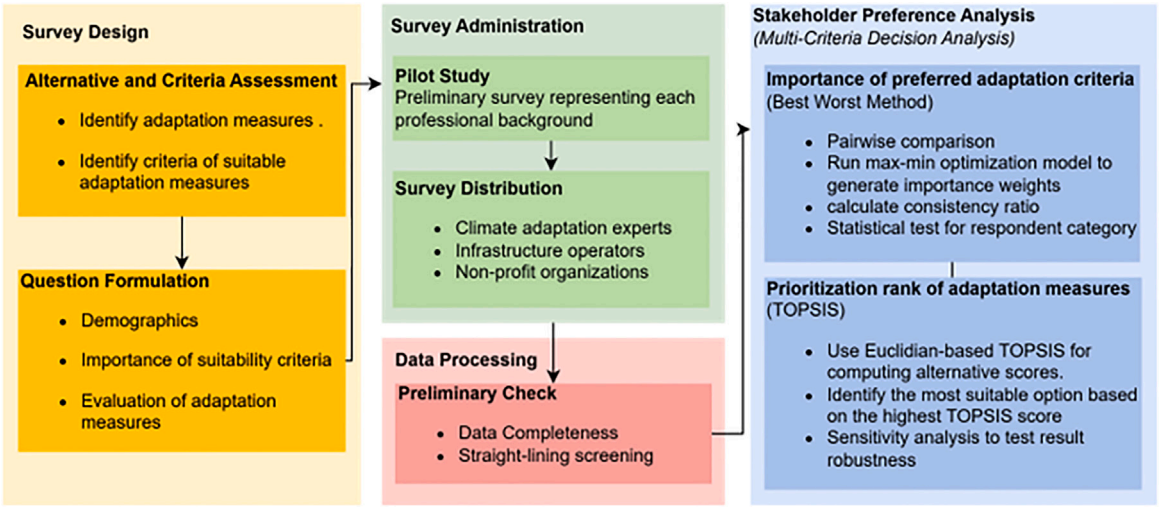


Fig. 1. Methodological framework and research steps.

basin. However, CBA is often criticized for overlooking non-monetary dimensions such as well-being, ecological integrity, and equity, and for its limited usefulness under deep uncertainty (Siders and Pierce, 2021; Hwang, 2016).

The other decision support approach is robust decision making (RDM), which identifies adaptation strategies that perform well across a wide range of uncertain climate futures (Bhave et al., 2016). Instead of optimizing for a single outcome, it tests strategies against multiple plausible scenarios to emphasize flexibility and robustness under deep uncertainty (Walker et al., 2013). For example, Lempert et al. (2020) applied robust decision making to Sacramento's regional transportation plan by stress-testing proposed strategies across thousands of plausible futures to identify scenarios that reveal which plans are most robust under deep uncertainty. Although valuable in highly uncertain contexts, its application is often limited by substantial data and computational demands (Shavazipour et al., 2021).

For decision-making and analysis, policymakers frequently adopt multi-criteria decision analysis (MCDA). This method identifies the most suitable alternatives by systematically evaluating multiple, often conflicting, criteria (Steuer, 1986). It is particularly suited to climate adaptation planning, where trade-offs occur among factors that differ in both dimension and unit. Previous studies have demonstrated MCDA method. For example, Arabameri et al. (2019) integrated technique for order of preference by similarity to ideal solution (TOPSIS) to develop flood hazard maps in Northern Iran, Maanan et al. (2018) assess coastal vulnerability by GIS-MCDA, and Rathnayaka et al. (2023) applied analytical hierarchical process (AHP) to prioritize adaptation measures across the electricity, transportation, and water infrastructure sectors. Overall, MCDA offers a transparent and flexible framework that accommodates both quantitative and qualitative criteria, incorporates stakeholder perspectives, and operates effectively under uncertainty. Despite its demonstrated applicability, existing MCDA studies rarely focus on road network-related adaptation measures under climate-induced stressors.

2.4. Gaps in the literature

Existing research on road resilience primarily focuses on evaluating individual adaptation measures, with limited empirical work comparing alternatives based on how stakeholders and decision-makers prefer and assess them. Adaptation decisions involve tradeoffs from social, economic, and technical feasibility perspectives. Yet, few studies explicitly investigate how stakeholders weigh these criteria and what kinds of trade-offs emerge when evaluating road adaptation measures. As a result, empirical evidence on stakeholder perspectives remains lacking. Addressing this gap requires a systematic, evidence-driven approach to how diverse stakeholders' preferences and trade-offs affect road adaptation assessment, which is essential for developing climate-resilient and sustainable road adaptation strategies.

3. Methodology

This study applied a structured survey to elicit stakeholder preferences and proposes an MCDA framework for evaluating climate change adaptation measures for road infrastructure. The methodology comprises four sequential steps as shown in Fig. 1. First, in the survey design stage, relevant adaptation options and preferred adaptation criteria were identified through a review of academic literature and established resilience taxonomies, and were used to formulate survey questions covering demographics, the perceived importance of criteria, and evaluations of adaptation options. Second, the data administration stage involved conducting a pilot survey that represented different professional backgrounds, followed by a wider distribution to experts through various channels, including professional networks and social media. Third, the data processing stage ensured response quality through a preliminary

Table 1
Adaptive interventions for road infrastructure.

ID	Intervention	Definition used for the survey
M-01	Vegetation plans	Integration of natural elements such as trees and vegetative barriers along roadways to reduce heat, manage runoff, and enhance environmental quality.
M-02	Localized power sources	Deployment of microgrids within road networks to maintain power supply during extreme weather events and reduce dependence on centralized grids.
M-03	Heat resistant road surface	Use of cool pavement technologies that lower road surface temperatures and mitigate heat accumulation.
M-04	Road monitoring systems	Continuous monitoring of road conditions to ensure functionality, detect damage, and support timely maintenance.
M-05	Adjustment of road height	Elevating road levels to prevent inundation and maintain access during flooding.
M-06	Road flood defenses	Installation of protective structures such as floodwalls, dikes, water-absorbing barriers, or gravity dams to block or redirect floodwaters.
M-07	Flood pathways management	Engineering of channels, pathways, or flow systems to direct floodwater away from roadways and prevent water accumulation.
M-08	Drainage system improvement	Enhancement of drainage networks to effectively collect and discharge excess surface water and reduce flood risk.
M-09	Alternative road	Development of additional routes to ensure transportation continuity during extreme events or road closures.
M-10	Road rerouting	Adjustment of road alignments to bypass flood-prone or hazardous areas.
M-11	Road reallocation	Relocation of roads entirely away from areas with high disaster exposure to ensure long-term resilience.

check comprised data completeness and straight-lining screening.. Finally, the stakeholder preference analysis stage applied MCDA techniques. The best-worst method (BWM) was used to determine the importance weights of suitability criteria based on pairwise comparisons, followed by a max–min optimization model and consistency check. TOPSIS was then used to rank adaptation measures by integrating respondents' evaluations with the derived weights.

3.1. Survey design

3.1.1. Selection of adaptation alternatives and evaluation criteria

The research began by identifying climate adaptation alternatives for road infrastructure and subsequently establishing the criteria for prioritizing these measures. The alternatives and criteria were derived from academic literature and recent grey literature, including the Climate Bonds Resilience Taxonomy published by the Climate Bonds Initiative (CBRT, 2024). The CBRT was chosen because it offers a publicly accessible and structured framework for defining climate change adaptation measures. CBRT is projected to be an important part of the financial toolkit used by financial professionals to make investment decisions related to sustainability (BNP Paribas, 2024).

This study identified 11 alternatives of climate adaptation measures in road construction, as detailed in Table 1. These measures are comparable because they share a strategic role in reducing climate-related disruption and damage, particularly from intense precipitation and extreme heat. Although they differ in form and scale, this study evaluates them at a strategic screening level rather than through project-specific technical design.

Building on the screening framework proposed in CBRT (2024), we then evaluated those road adaptation options using four criteria. The original (CBRT, 2024) framework specifies three considerations for climate-adaptation investments: (1) the extent to which a measure makes a substantial contribution to climate resilience by reducing exposure or vulnerability to climate hazards; (2) the degree to which maladaptation risks are adequately managed; and (3) consistency with wider sustainability objectives, ensuring that the measure does not generate significant harm to other systems or societal groups. This study translated the above considerations into a set of criteria for assessing the stakeholder preferences for road infrastructure adaptation as follows: effectiveness in reducing disaster risk (DRR), likelihood of maladaptation (MA), and potential for adverse societal impacts (ASI). To complement these and reflect the economic feasibility of adaptation alternatives, we added a fourth criterion capturing the project cost (PC) of each adaptation measure. The explanation of each selected criterion and its context, which is considered in this study, is illustrated in Table 2.

3.1.2. Structure and content of the survey

The survey consisted of three sections, each with a distinct objective. The first section focused on the respondents' demographics to map their background. Some of the demographic questions that were included are as follows: "What is your primary professional background? (Practitioner/Academic/Government Official/Others)"; "Do you have academic/professional experience in road projects? (Yes/No)"; "If yes, what is your role? (Operations and Engineering/Management Support/Researcher)"; "Where do you come from?"; and "How many years of professional experience do you have? (<1 year/1–5 years/5–10 years/10–15 years/>15 years)".

Table 2
Criteria of preferred climate adaptation measure.

Criteria	Definition	Context within this study
Disaster Risk Reduction (DRR)	Possibilities to minimize vulnerabilities and disaster risks throughout society, to avoid or limit the adverse impacts of hazards (United Nation, 2004).	Ensures that selected adaptation measures effectively minimize the impacts of climate change-induced hazards
Maladaptation (MA)	Action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems (Barnett and O'Neill, 2010)	Captures the risk of unintended consequences of adaptation measures that may exacerbate climate-induced hazards rather than reduce them.
Adverse Societal Impacts (ASI)	Negative consequences that adaptation measures may have on the broader environment and society, and it is aligned with the "Do No Significant Harm" principle under the EU Regulation 2020/852 (European Parliament, 2020)	Consider potential negative consequences beyond climate-induced hazard, such as social and ecological impacts in the neighborhood
Project Cost (PC)	Total expenditure required for planning, designing, constructing, and maintaining adaptation measures (Rathnayaka et al., 2023).	Acknowledge the cost of implementation since limited financial resources and institutional barriers may pose major challenges to executing the adaptation option

Table 3
Outline of the survey with sample questions.

Section	Objective	Sample questions
A. Respondent background	Capture respondents' professional, socioeconomic and demographic background	1. What is your professional field? 2. How many years of experience do you have in road infrastructure projects? 3. Which country or region do you currently work in?
B. Stakeholder preferences of climate adaptation evaluation criteria	Determine the perceived relative importance of each criterion	1. How important is it for a measure to have an effective disaster risk reduction? 2. How important is it for a measure to have a low likelihood of unintended effects (maladaptation)? 3. How important is it for a measure to have a low likelihood of adverse societal impacts? 4. How important is it for a measure to have a low project cost?
C. Stakeholder preferences of climate adaptation alternatives	Assess preference of each adaptation measure against all criteria	1. How effective is [alternative] in reducing disaster risk? 2. What is the likelihood of unintended effects from [alternative]? 3. What is the likelihood of adverse societal impacts from [alternative]? 4. What is the typical project cost associated with implementing [alternative]?

In the second section, respondents were asked to rate each of the four preferred adaptation measure criteria individually. Each criterion was accompanied by a definition, an example, and an illustration to support consistent understanding. Ratings were provided on a scale of 1 to 9, where 1 represented the least important and 9 represented the most important. Equal scores were not permitted to ensure differentiation among criteria. For example, for the 'disaster risk reduction' criterion, defined as 'the ability to reduce climate change–induced hazards and/or increase the infrastructure's adaptive capacity', respondents were asked: "How important is it for a measure to have an effective disaster risk reduction?" They then assigned a score between 1 and 9. Similar questions, with tailored definitions and visual examples, were presented for the other three criteria: maladaptation risk, societal impact, and project cost.

In the third section, respondents were asked to evaluate each of the 11 adaptation measures against the four preferred adaptation criteria. To assist consistent understanding, every measure was accompanied by a brief description explaining its function and relevance in reducing climate impacts. Respondents rated each criterion on a 1–5 scale, where 1 represented the lowest level of the criterion (e.g., low effectiveness, low likelihood of unintended effects or adverse societal impacts, or low cost) and 5 represented the highest level. For example, for the intervention 'implementation of vegetation plans', respondents were presented with a description outlining how roadside trees can reduce heat stress through shading and evapotranspiration. They were then asked the following questions: "How effective are vegetation plans in reducing disaster risk? (1 = low effectiveness, 5 = high effectiveness)"; "What is the likelihood of unintended effects from vegetation plans? (1 = low likelihood, 5 = high likelihood)"; "What is the likelihood of adverse societal impacts? (1 = low likelihood, 5 = high likelihood)"; and "What is the typical project cost for implementing vegetation plans? (1 = low cost, 5 = high cost)". Respondents provided individual scores for each criterion based on their own judgment. This question structure was repeated for all 11 adaptation measures, with tailored descriptions to support comprehension and ensure that assessments were grounded in the intended scope of each alternative.

An overview of the survey structure together with examples of question formats is provided in Table 3. The full set of questions is provided in the Appendix A. The original survey can be accessed at bit.ly/CCARoadSurvey.

3.2. Survey administration

A pilot study was conducted in January - February 2025 to refine and enhance the survey's quality with active participation from university students and researchers. The finalized survey was distributed via the Qualtrics platform between February-March 2025

with the purposive sampling approach, targeting professionals with relevant expertise across industry, academia, and government to capture multi-perspectives among key stakeholders. Purposive sampling approach is becoming increasingly popular for multi-criteria decision analysis research in various infrastructure planning and management domains (Apostolopoulos and Liargovas, 2016; Belay et al., 2022). Practitioners contributed insights from infrastructure operations, engineering, and maintenance; government officials represented policy development and implementation roles; and academics provided scientific and long-term perspectives on resilience and climate change.

Respondents were eligible to participate if they had professional, academic, or policy-related engagement with infrastructure management and operations, transport engineering, climate adaptation, or related fields. No minimum road project experience threshold was imposed, as the study intentionally sought perspectives from both experienced and inexperienced participants to also understand how experience moderate the preferences to various types of adaptation alternatives. Experienced respondents were those who have been actively involved in road infrastructure projects, including planning, construction, operation, or maintenance activities. Respondents without direct experience were individuals with expertise in infrastructure, climate change adaptation, or related topics, even though they had no direct exposure to road projects. Their external perspectives help reduce discipline-specific bias by incorporating other relevant expertise within the decision-making process.

Experienced respondents are represented by diverse professional roles in road projects, categorized as follows: (1) operations and engineering, including contractors, construction engineers, maintenance teams, surveyors, and other field-related professionals; (2) managers and operators, including asset owners, financial and human resources personnel, consultants, and investors; and (3) researchers, including individuals from academic institutions or research organizations. Expert status was determined through self-reported professional background and role based on their primary affiliation.

The survey was distributed via direct email, social media, and partnerships with private-sector entities involved in road infrastructure projects. Several measures were taken to mitigate selection bias. First, recruitment was carried out through multiple independent channels to avoid overreliance on a single professional network. Second, clear inclusion criteria were established to ensure that respondents' profiles aligned with the requirements of this research. Third, the survey was targeting multiple stakeholder groups to broaden respondent diversity and reduce the risk of a narrowly concentrated sample.

3.3. Survey data processing and filtering

The survey was accessed by 129 individuals, of whom 72 completed the survey by filling section A (respondent background), B (preferred criteria), and C (preferred alternatives), resulting in a completed response rate of 56%. Among the analyzed responses, 67% (48 respondents) were from Asia, 26% (19 respondents) from Europe, and the remaining 7% (5 respondents) from the Americas, Africa, and Australia. Since geographical location was not a variable in this study, this distribution was considered acceptable.

The processing and filtering of survey responses involved two stages: preliminary checks before analysis and BWM consistency checks for Section B. The preliminary checks assessed data completeness and screened for straight-lining, where respondents assigned identical scores across all items. In Section B, 42 of the 129 responses were excluded, while the remaining 87 responses were subjected to the BWM consistency check. In Section C, 72 responses met the completeness requirements and were used to produce the prioritization ranking, whose robustness was subsequently tested through sensitivity analysis.

The second stage involved the BWM consistency check embedded in the BWM methodology. The remaining 87 completed responses were assessed using the input-based Consistency Ratio (CR) defined by Liang et al. (2020), which is the accepted consistency indicator for linear BWM. This resulted in a final valid sample of 62 responses for BWM-based criteria weighting, as explained in detail in Appendix B. The respondent flow diagram is illustrated in Fig. 2. The difference in sample sizes between Section B and Section C (62 vs. 72) reflects the use of separate validity criteria between consistency in BWM pairwise comparisons and completeness in TOPSIS alternative scoring. Therefore, a respondent could fail the consistency requirement in Section B while still providing valid and complete responses in Section C.

The 62 respondents for Section B consists of academics 47% (29 respondents), practitioners 35% (22 respondents), and government officials 18% (11 respondents). Respondents varied in their experience with road projects: 35% (22 respondents) had road project experience and 65% (40 respondents) reported having no prior experience. Among the 22 experienced respondents, 55% (12 respondents) were from operations and engineering roles, 27% (6 respondents) from management support teams, and 18% (4 respondents) from research positions.

Meanwhile, for Section C, valid responses included 44% (32 respondents) from academia, 33% (24 responses) from practitioners, and 22% (16 respondents) from government officials. The sample showed a relatively balanced distribution between experienced 42% (30 respondents) and non-experienced 58% (42 respondents) participants. Among the 30 experienced respondents, 43% (13 respondents) from management support, 40% (12 respondents) were from operations and engineering roles, and 17% (5 respondents) from research roles. A summary of respondent demographics is presented in Table 4.

3.4. Evaluation of stakeholder preferences and prioritization of alternatives

Multi-criteria decision analysis (MCDA) provides a structured method of identifying and prioritizing suitable alternatives where decisions must balance multiple, and often conflicting, objectives (Steuer, 1986). This makes MCDA particularly suitable for climate adaptation planning, where trade-offs occur between effectiveness, risks, social acceptability, and financial feasibility. Incorporating stakeholder perspectives within MCDA further supports inclusive decision-making and strengthens the legitimacy of adaptation choices (Adger et al., 2005). To capture these trade-offs and elicit stakeholder priorities, we adopted a two-step MCDA procedure.

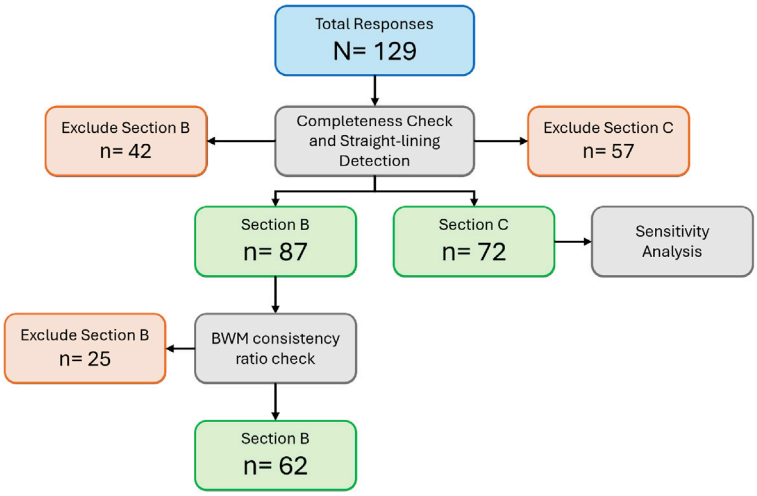


Fig. 2. Respondent flow diagram.

Table 4
Summary of survey respondents.

Category	Subcategory	Number of responses on Section B (criteria)	Number of responses on Section C (alternatives)
Profession	Practitioner	22	24
	Academics	29	32
	Government officials	11	16
Region	Asia	37	48
	Europe	22	19
	America, Australia, and Africa	3	5
Level of experience	Experienced	22	30
	Not experienced	40	42
Role	Operations and engineering	12	12
	Managers and operators	6	13
	Researchers	4	5
Year of experience	<1 year	5	7
	1–5 years	11	17
	>5 years	6	6

First, stakeholder importance preferences for adaptation criteria were quantified; second, adaptation alternatives were ranked according to those preferences. Accordingly, two complementary MCDA techniques were employed: (a) the Best–Worst Method (BWM) to derive weights for stakeholder-valued criteria, and (b) the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to prioritize adaptation measures using those weights. The combination of BWM and TOPSIS is commonly used in MCDA studies (Gidiagba et al., 2023; Lo et al., 2018; Yucesan et al., 2019) to translate stakeholder preference data into an overall prioritization of road adaptation measures in more efficient, consistent, and reliable decision-making framework (Trivedi et al., 2024).

First, we used the linear BWM (Rezaei, 2016) to derive the relative importance of the four evaluation criteria. BWM is chosen because it provides a structured way to derive criteria weights from stakeholder judgments while limiting the number of comparisons required from respondents, which helps reduce survey burden. Respondents were asked to indicate which criterion they considered most important and which they deemed least important, based on a 1–9 importance rating scale. The criterion with the lowest rating was considered the least important, while the criterion with the highest rating was considered the most important. They then compared the best criterion against the remaining criteria, and each remaining criterion against the worst. These responses formed the basis of a max–min optimization model, which we solved to obtain a normalized weighting vector for the criteria. The optimization problem is expressed as:

$$\min \max_i \left\{ \left| w_B - a_{Bi} w_i \right|, \left| w_i - a_{iW} w_W \right| \right\} \tag{1}$$

subject to:

$$\sum_{i=1}^{n} w_i = 1, \qquad w_i \geq 0. \tag{2}$$

where w_i denotes the weight of criterion i, w_B and w_W represent, respectively, the weights of the best and worst criteria, a_{Bi} is the respondent-provided preference value of the best criterion over criterion i, a_{iW} is the respondent-provided preference value of criterion i over the worst criterion, and n is the total number of criteria considered. Then, we calculated the input-based Consistency Ratio (Liang et al., 2020) to identify and exclude inconsistent responses, as described in Appendix B. The optimization model and consistency check were implemented in Microsoft Excel using the Solver add-in. To account for respondent heterogeneity, this study conducted statistical tests to assess differences in criteria importance weights across groups defined by profession, experience level, and role. A permutation-based multivariate analysis of variance was applied after transforming the weights using the isometric log-ratio transformation, as the weights are compositional and therefore not independent.

In the second phase, we applied the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to rank the adaptation alternatives. Responses from the Likert survey were aggregated using the arithmetic mean before TOPSIS normalization and weighting. The arithmetic mean was used because Likert-scale data can be treated as approximately interval-level when aggregated, and responses across a set of items are commonly summarized using the mean or sum (Harpe, 2015).

Then, the Euclidean distances between each alternative's criterion scores and both the ideal and the non-ideal solutions were calculated. The ideal and non-ideal solutions differ across criteria. For effectiveness in disaster risk reduction, the measure with the highest value is considered the ideal option, while the measure with the lowest value represents the non-ideal solution. In contrast, for likelihood of maladaptation, adverse societal impacts, and project cost, the lowest values correspond to the ideal solution, whereas the highest values denote the non-ideal solution. Based on this definition, the Euclidean distances between an alternative and the ideal and the non-ideal solutions for the four categories are calculated (denoted by d_{iB} and d_{iW}, respectively).

The relative closeness of each alternative to identify the performance score was calculated as:

$$s_{iw} = \frac{d_{iW}}{d_{iW} + d_{iB}}, \qquad 0 \le s_{iw} \le 1, \tag{3}$$

where s_{iw} denotes the performance score of alternative i under the weighted criteria set w, d_{iB} represents the Euclidean distance of alternative i from the ideal solution (i.e., the best attainable performance across all criteria), d_{iW} represents the Euclidean distance of alternative i from the non-ideal solution (i.e., the worst attainable performance across all criteria), and the resulting score s_{iW} ranges between 0 and 1, with values closer to 1 indicating alternatives that more closely resemble the ideal solution. Higher values indicate a stronger preference. This process resulted in a comparative prioritization of the 11 adaptation measures, enabling us to evaluate which options stakeholders viewed as most suitable for enhancing road infrastructure resilience under climate-induced stressors. The full TOPSIS procedure is described in Appendix C.

3.4.1. Sensitivity analysis

Sensitivity analyses were conducted to test the robustness of the prioritization results by examining how changes in criterion weights influence the overall TOPSIS scores (Hennink, 2024). Eight scenarios were developed by varying the criterion weights based on the standard deviation of the original BWM-derived weights, as shown in Appendix D. This approach captures the natural variability in stakeholder responses. When the weight of criterion i was reassigned to a new value w_{new}, the weights of all remaining criteria $j \neq i$ were recalculated to preserve the total weight sum of one, as follows:

$$S_{\text{orig}} = 1 - w_i \tag{4}$$

$$w'_j = \left(\frac{w_j}{S_{\text{orig}}} \right) \times (1 - w_{\text{new}}) \tag{5}$$

where w_i denotes the original weight of criterion i, w_j represents the original weight of any other criterion j, and w'_j is the corresponding new weight after adjustment. The term w_{new} is the newly assigned weight for criterion i, while S_{orig} refers to the sum of the original weights of all remaining criteria. This formulation ensured that the remaining total weight $(1 - w_{\text{new}})$ is redistributed proportionally among the other criteria, thereby maintaining the requirement that the total of all criterion weights equals one.

The robustness of the TOPSIS results was tested by comparing the baseline ranking with the rankings obtained under the eight sensitivity scenarios using Kendall's tau rank correlation coefficient. If the results showed a high level of ordinal agreement across scenarios, indicating that changes in criterion weights did not substantially alter the prioritization of adaptation measures. This suggests that the TOPSIS results are stable under plausible variations in the BWM-derived criterion weights.

4. Result and discussion

This section presents findings from the global stakeholder survey, including the relative importance of adaptation criteria and the ranking of road infrastructure adaptation options.

4.1. Most experts prefer long-term benefits and risk reduction over project costs

The result shows that disaster risk reduction (DRR), maladaptation likelihood (MA), adverse societal impact (ASI) received relatively similar levels of importance in evaluating suitable adaptation measures, whereas project cost (PC) was assigned a lower weight. The final importance weight of DRR, MA, ASI, and PC are 0.28, 0.27, 0.27, and 0.18, respectively, as illustrated in Fig. 3. Then, a non-parametric bootstrap with 95% percentile confidence intervals procedure (Efron and Tibshirani, 1993) applied to

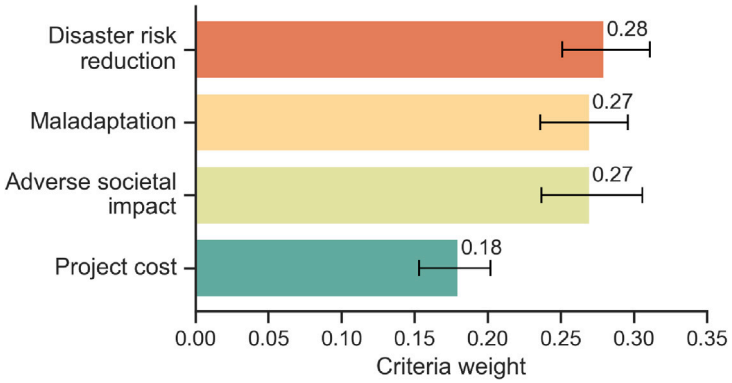


Fig. 3. Overall criteria weights derived using BWM (aggregating all the expert responses) and their 95% confidence intervals.

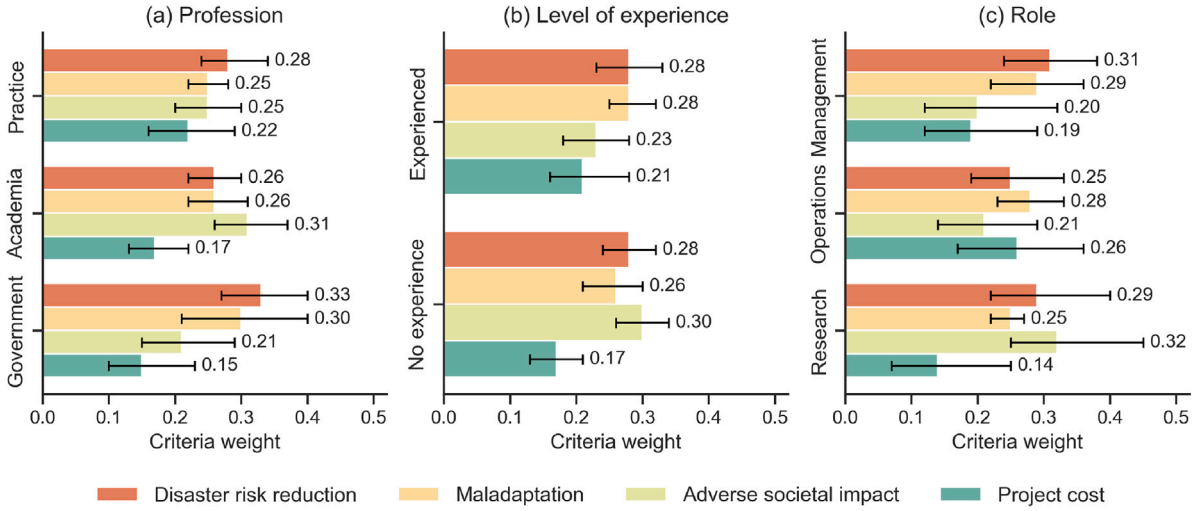


Fig. 4. Criteria importance weight across, professional background, level of experience, and domain role and their 95% confidence intervals.

quantify the confidence intervals. Intervals for project cost [0.153, 0.219] did not overlap with those for DRR [0.251, 0.311], MA [0.236,0.296] ASI [0.237, 0.306], confirming that the relatively lower weight assigned to cost reflects a consistent stakeholder preference rather than sampling variability.

Although financial considerations remain relevant, respondents perceive them as less critical than the broader objectives of effective disaster risk reduction, minimizing maladaptation, and avoiding negative societal impacts. This finding is consistent with the study by Benson and Twigg (2007), which highlights how incorporating economic analysis into disaster risk reduction planning can justify interventions with higher upfront costs by demonstrating their long-term benefits for risk reduction and societal well-being. Overall, these stakeholder preferences suggest a tendency to favor long-term, sustainable adaptation strategies over short-term cost savings that could undermine infrastructure and regional resilience.

Next, we examined how the relative importance of the four preferred adaptation criteria differs across professional backgrounds, levels of domain experience, and domain roles. To account for the compositional nature of the data, criteria weights were transformed using an isometric log ratio (ILR) method. A PERMANOVA test applied to these transformed values indicated no significant differences in the overall weighting profiles across stakeholder groups within each category. These findings confirm the robustness of the aggregate weights used for road adaptation prioritization. However, as shown in Fig. 4, the comparison reveals both areas of convergence and meaningful variation of criteria weights within respondent groups. Across all categories (except for experts with experience in operations), project cost consistently received the lowest weight, ranging from 0.14 among researchers to 0.22, indicating broad agreement that short-term financial considerations are secondary to performance and risk-related dimensions when evaluating adaptation measures. This uniform ranking indicates a broad stakeholder preference for emphasizing the technical and risk-related dimensions of adaptation over immediate financial considerations, aligning with prior work highlighting the primacy of public safety and long-term resilience in adaptation planning (Palliyaguru et al., 2010; Adger et al., 2005).

Divergent preferences emerge between professional categories (Fig. 4a). Practitioners exhibit the most balanced weighting across criteria (DRR = 0.28; MA = 0.25; ASI = 0.25; PC = 0.22), suggesting that their decision-making reflects a holistic consideration

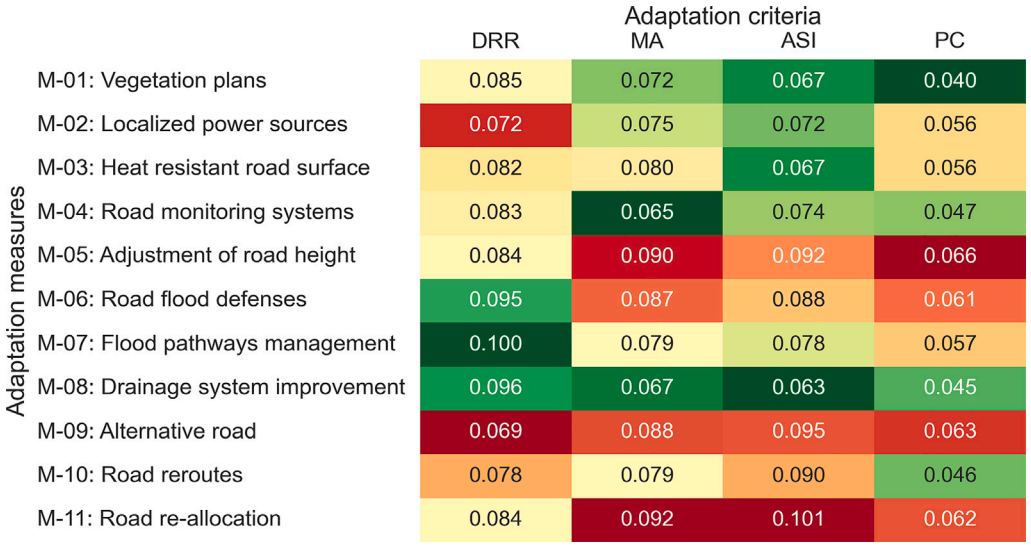


Fig. 5. Derived TOPSIS scores for adaptation measures (DRR: disaster risk reduction; MA: maladaptation; ASI: adverse societal impact; PC: project cost). Red indicates closer to the worst level; green indicates closer to the best level.

of performance, societal outcomes, and practical constraints. Academic respondents assign the greatest importance to adverse societal impact (0.31), followed by DRR and MA (both 0.26), a pattern consistent with the growing academic focus on equity and distributional implications in adaptation processes (Cannon et al., 2023). Government respondents place the highest weight on disaster risk reduction (0.33) and maladaptation risk (0.30), reflecting their institutional responsibility to mitigate hazards and avoid unintended negative consequences, while assigning substantially lower importance to cost (0.15).

Differences between experienced and non-experienced respondents further illustrate how familiarity with infrastructure projects shapes prioritization (Fig. 4b). Experienced individuals assign the highest weights to disaster risk reduction and maladaptation (both 0.28), followed by adverse societal impact (0.22) and project cost (0.21). Their prioritization reflects an emphasis on performance and risk mitigation commonly observed among practitioners with hands-on exposure to infrastructure management. By contrast, respondents without relevant experience place a greater emphasis on adverse societal impact (0.30), suggesting that individuals outside the domain tend to foreground social considerations when evaluating adaptation interventions.

Variation across domain roles reinforces these distinctions (Fig. 4c). Respondents in operations management prioritize DRR (0.31) and MA (0.29), reflecting their focus on operational continuity and system reliability. Those in operations place comparatively greater weight on project cost (0.26), likely due to their involvement in budgeting, maintenance, and implementation logistics. Researchers assign the highest importance to adverse societal impact (0.32), mirroring academic perspectives that emphasize social equity and community-level effects of adaptation initiatives.

The above patterns demonstrate that stakeholder preferences for criteria for evaluating road infrastructure adaptation alternatives are shaped by a combination of professional context, experiential knowledge, and organizational responsibilities. While disaster risk reduction and maladaptation risk consistently emerge as high-priority considerations, the relative importance assigned to societal impacts and cost varies across groups.

4.2. Preventive and less-invasive measures show strong preference across adaptation criteria

After deriving the criteria weights, we applied TOPSIS method to evaluate the relative performance of each adaptation measure under the four criteria using the survey responses. The corresponding TOPSIS scores are presented in Fig. 5. These scores reflect each measure's proximity to the ideal solution: higher values indicate stronger performance in DRR, while lower values indicate more desirable outcomes for MA, ASI, and PC, for which the objective is minimization.

Across the adaptation criteria, several patterns emerge. Measures that are preventive, incremental, or operational in nature tend to achieve more favorable scores. For instance, drainage system improvement (M-08) and flood pathways management (M-07) perform highest in terms of DRR (0.096 and 0.100), while also maintaining relatively low maladaptation and societal impact scores. Vegetation plans (M-01) similarly show a balanced scoring across criteria, combining moderate DRR performance (0.085) with some of the lowest project cost values (0.040). These results indicate that stakeholders perceive such measures as effective, low-risk, and financially viable.

On the other hand, large-scale structural modifications and grey infrastructure, such as adjustment of road height (M-05), alternative roads (M-09), and reallocation (M-11), tend to exhibit higher scores for maladaptation, societal impact, or cost. For instance, M-05 recorded the highest project cost score (0.066), while M-11 shows the highest ASI score (0.101), reflecting concerns that such interventions may introduce disruption or require significant resources that outweigh the benefits. Although these

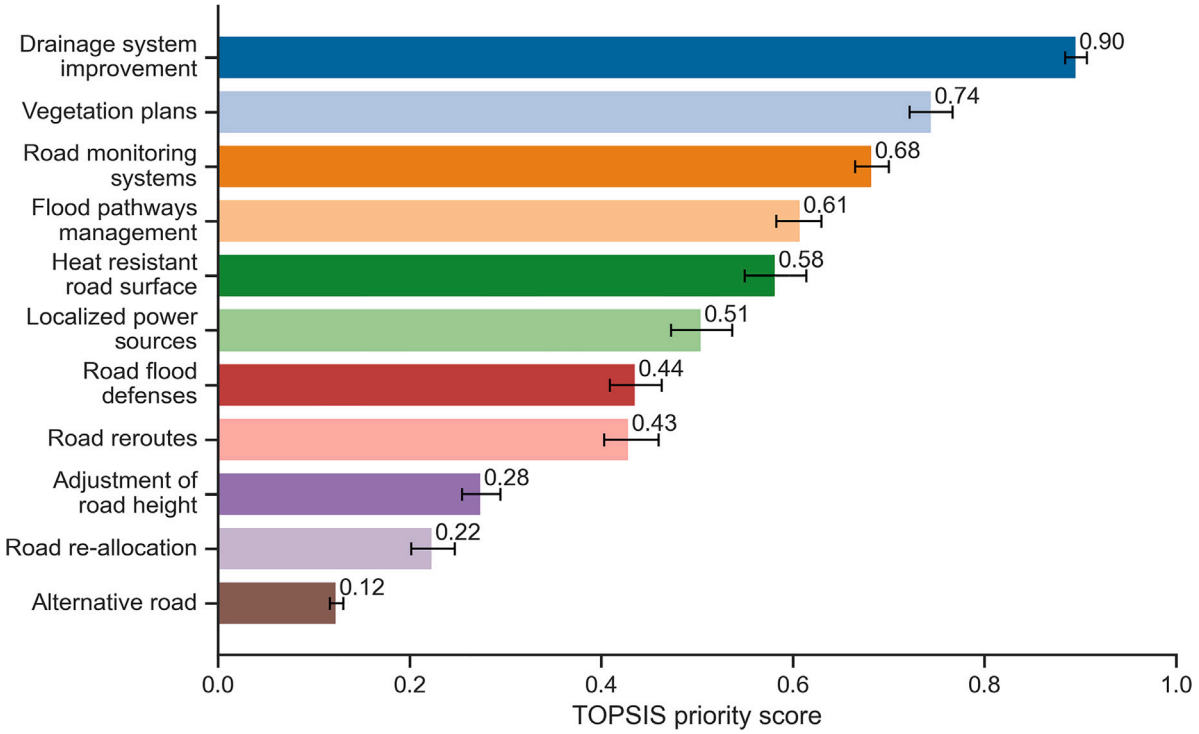


Fig. 6. Overall TOPSIS scores and 95% confidence intervals of various transport infrastructure adaptation alternatives.

interventions perform reasonably well on DRR, their higher values on the other criteria suggest trade-offs that reduce their overall suitability.

The results also show that technology-enabled interventions, such as road monitoring systems (M-04) and localized power sources (M-02), perform moderately across DRR while exhibiting low scores for intended effects and societal impacts. These measures can enhance preparedness and response of road infrastructure projects against extreme events and thus enhance system resilience without requiring major physical modifications. In summary, experts tend to favor cost-effective, less-invasive measures that provide satisfactory risk reduction with limited negative effects, while demonstrating cautious optimism towards capital-intensive structural interventions and grey infrastructure development.

Next, the TOPSIS scores were aggregated for the 11 adaptation measures using the methodology described in Section 3.4. The aggregate TOPSIS scores with the Bootstrap 95% percentile confidence intervals and the ranking of alternatives based on them are presented in Fig. 6. These scores integrate criterion weights derived from the BWM analysis, and this reflect stakeholder preferences across effectiveness, maladaptation risk, societal impact, and cost and rank stability was high across all bootstrap iterations.

Consistently, the results indicate a preference for non-invasive, preventive, and incremental interventions over large-scale capex-intensive modifications and constructions. Drainage system improvement emerged as the most suitable adaptation measure with an aggregate score of 0.90, followed by vegetation plans (0.74), road monitoring systems (0.68), and flood pathways management (0.61). These measures share several characteristics: they enhance disaster risk reduction, pose relatively low maladaptation and societal risks, and require comparatively modest financial investment. Their high scores suggests that stakeholders value interventions that can be integrated into existing infrastructure with minimal disruption while delivering tangible improvements in resilience against flooding and extreme heat.

In contrast, structural measures, such as road rerouting, adjustment of road height, road reallocation, and construction of alternative roads rank among the least preferred options. These interventions tend to incur higher costs and carry greater potential for maladaptation and adverse societal impacts. Construction in marginal or hazard-prone areas can inadvertently increase long-term exposure to climate risks. Moreover, these measures typically require significant land acquisition, which may lead to displacement, livelihood disruption, and land-use conflicts. High implementation and maintenance costs further reduce their feasibility, making them less attractive compared to cost-effective and preventive alternatives such as drainage improvement and vegetation planning. These findings are consistent with previous studies highlighting that pre-disaster and early-warning strategies often yield higher resilience returns per unit of investment compared to reactive, infrastructure-heavy solutions (Mechler et al., 2014; Benson and Twigg, 2007).

We also examined whether the prioritization of adaptation measures varied across professional backgrounds and levels of domain experience. As shown in Fig. 7, the TOPSIS-based ranking of road transport adaptation alternatives indicates a strong consensus among all respondent groups, even though, their criteria weights showed significant variations. Drainage system improvement,

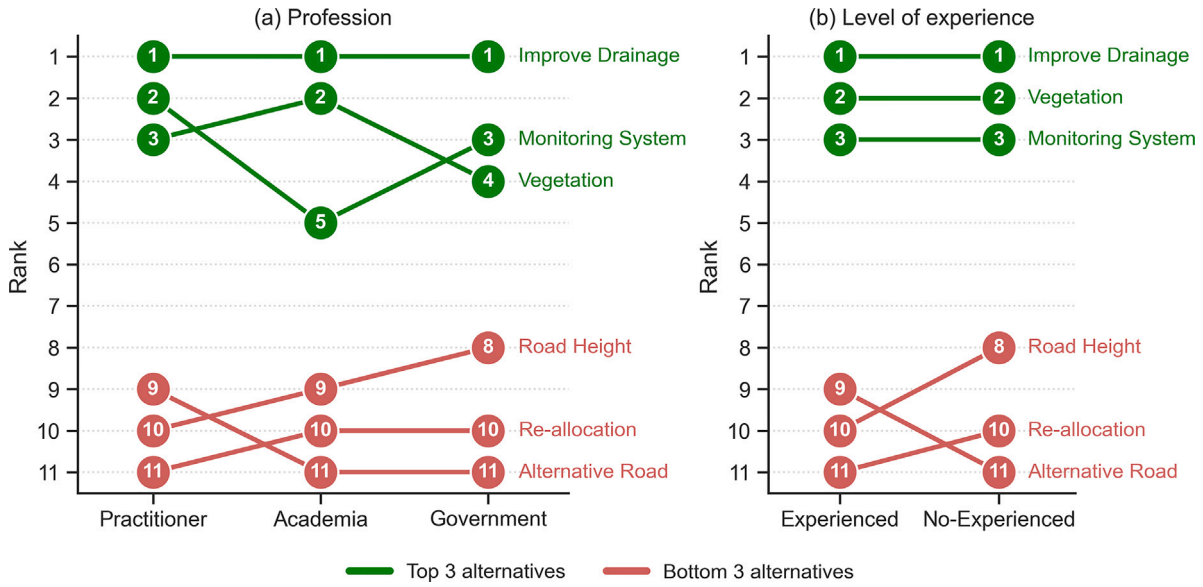


Fig. 7. Preference to top- and bottom 3 alternatives based on TOPSIS across professional and experience categories.

vegetation plans, and road monitoring systems were consistently preferred among top choices across professional categories (Fig. 7a). By contrast, adjustment of road height, road reallocation, and alternative roads were ranked as the least preferred options. This suggests that the overall rankings are consistent in preferences across professional groups. The preferences for alternatives are also similar among groups with different levels of domain experience (Fig. 7b).

Academics, government officials, and non-experienced respondents identified alternative roads as the least favorable adaptation option. On the other hand, practitioners and experienced respondents ranked road reallocation as the least preferred measure. The above divergence likely reflects that these two groups of participants value feasibility and desirability differently.

This is possibly because practitioners and experienced respondents, who are more familiar with the implementation challenges and high costs of large-scale relocation projects, may view road reallocation as less feasible. Conversely, academics and less experienced participants tend to evaluate from a conceptual or societal perspective, perceiving alternative roads as less effective due to their limited contribution to long-term risk reduction and potential to displace existing vulnerabilities rather than solve them.

4.2.1. Rankings of most of the adaptation alternatives are robust

In order to test the robustness of the overall rankings of adaptation alternatives derived using TOPSIS (Fig. 6), we performed several scenario-based sensitivity analyses. Eight scenarios were considered by varying criteria weights, accounting for uncertainties in both expert judgment and weighting assumptions. Each scenario represents a ± one standard-deviation adjustment applied to a single criterion. For example, in Scenario DRR+, the weight of disaster risk reduction is increased by one standard deviation, whereas in Scenario DRR− it is decreased by the same amount. The remaining weight is redistributed proportionally across the other criteria according to the BWM-derived weight structure. The same procedure is applied to the other criteria: Scenarios MA+ and MA− adjust the maladaptation weight by ± one standard deviation, ASI+ and ASI− adjust adverse societal impact, and PC+ and PC− adjust project cost. Fig. 8 shows the ranking of adaptation measures under the eight scenarios.

As evident in the results, the overall ranking is highly stable across scenarios, especially those at the top and bottom. Improving the drainage system, consistently identified as the most preferred adaptation measures, maintained its top position throughout. For the Top 3, there was a change in the second and third rankings under the DRR− scenario, while the rankings remained unchanged in the other scenarios. Conversely, reallocation, alternative road, and road height adjustment remain consistently ranked as the least suitable options. The observed variability among mid-tier alternatives, such as flood pathway management, heat-resistant road surfaces, localized power sources, and road flood defenses, and road reroutes suggests that these options are more sensitive to changes in relative criteria weights.

The robustness of the TOPSIS results was further assessed using Kendall's tau rank correlation by comparing the ranking from each sensitivity scenario with the baseline BWM-based ranking. This indicates strong ordinal agreement between the baseline and scenario rankings, with Kendall's tau coefficients exceeding 0.800 and ranging from 0.85 to 1.00, as explained in detail in Appendix D. Therefore, the TOPSIS prioritization can be considered robust under the tested variations in criterion weights.

5. Conclusion

Road infrastructure faces increasing stresses from intensifying climate hazards and a widening finance gap, particularly in low- and middle-income countries. Against this backdrop, greater transparency in how adaptation options are evaluated and compared

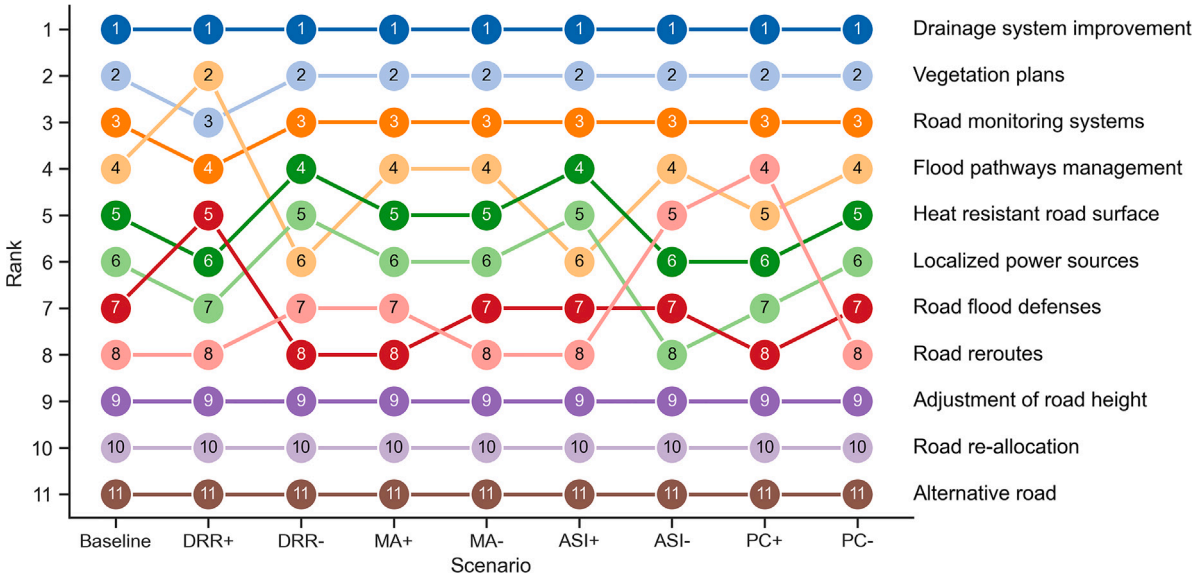


Fig. 8. Sensitivity of priority ranks of adaptation alternatives under deviation from baseline weights.

across diverse stakeholders becomes essential for guiding public investment and strengthening the credibility of adaptation projects for private sector financing. This study addresses the persistent gap by using empirical evidence to reveal stakeholder preferences and tradeoffs that underpin adaptation finance decision-making processes, particularly in the context of road infrastructure exposed to climate stresses, such as, extreme precipitation and heat stress.

Drawing on a global survey of 129 experts from industry, academia, and government, we applied the Best-Worst Method to assess the relative importance of four key evaluation criteria and then employed TOPSIS to rank 11 widely adopted road infrastructure adaptation measures. Across respondents, disaster risk reduction effectiveness, maladaptation risks, and adverse societal impact emerged as nearly equally important criteria, whereas, project cost was consistently assigned the lowest weight. This pattern reflects a broader agreement that long-term resilience and societal concerns matter at least as much as financial considerations when evaluating adaptation projects. Although project cost received a lower weight in this sample, this does not imply that cost is unimportant in real-world decision-making, particularly in LMICs where fiscal and budgetary constraints are often substantial.

The integrated MCDA results revealed clear and robust preferences for preventive and non-structural measures for transport infrastructure adaptation: improved drainage systems, vegetation plans, and monitoring systems consistently ranked highest across professional groups, experience levels and sensitivity scenarios. These interventions were considered to provide high disaster risk reduction effectiveness with limited maladaptation and societal disruption, and they require comparatively moderate financial outlays. Conversely, capital-intensive structural measures, such as alternative roads, major elevation adjustments, and road reallocation, ranked lowest, as these options may shift exposure to new locations and lead to new risks rather than addressing underlying vulnerabilities. Their reliance on additional land, potential for public resistance, and high construction and maintenance costs further limit their attractiveness. Sensitivity analyses further confirmed the robustness of these rankings, underscoring the reliability of stakeholder preferences in guiding adaptation investment decisions. The results represent the perceived priorities of the surveyed respondents and should be interpreted as screening-level guidance rather than universal prescriptions. Higher-ranked measures do not necessarily imply the best solution in practice, but they indicate stakeholder prioritization preferences. These preferences should be combined with site-specific engineering assessments, hydrological analysis, pavement design considerations, and cost–benefit analysis before implementation decisions are made.

By integrating expert judgment with multi-criteria evaluation, this study provides evidence-driven insights into how adaptation measures for road infrastructure are assessed, compared, and prioritized across stakeholders. The proposed approach is a replicable empirical approach for eliciting stakeholder preferences and investigating trade-offs among adaptation options which can be applied to other climate adaptation measures as well as other critical infrastructure systems exposed to climate shocks. The findings also highlight the strategic importance of emphasizing preventive, scalable, and socially acceptable interventions over capital-intensive grey infrastructure, especially where financial resources are constrained.

5.1. Limitation and future research

While the study provides valuable strategic-level insights, three limitations should be considered and addressed in future research:

1. The global scope of the survey provides universal perspectives but limits the development of locally targeted adaptation strategies. Effective adaptation ultimately depends on local knowledge, institutional capacity, and regional and spatial

characteristics. Accordingly, the region was not used as a stratification variable because the study aimed to capture overall stakeholder judgments rather than compare region-specific priorities. Future research could examine how adaptation priorities vary across different geographic contexts.

2. Although the study relied on expert judgment, expertise was based on self-reported background, which may introduce variation in expertise levels. Future studies could apply more explicit expert selection criteria or compare responses across different expertise groups.
3. The results are method-dependent, as different MCDA methods, weighting schemes, or normalization procedures may produce different prioritization outcomes. Future research could test the robustness of the findings using alternative MCDA approaches and methodological assumptions.

In general, this study serves as a preliminary foundation for further research that deepens the prioritization analysis within specific contexts, incorporating criteria that reflect local constraints and opportunities. Moreover, extending this approach to other critical infrastructure sectors, such as energy, water, and urban systems, would provide a more comprehensive understanding of cross-sectoral adaptation priorities and interdependencies.

CRediT authorship contribution statement

Aryasatya Adyatama: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Srijith Balakrishnan:** Writing – original draft, Visualization, Supervision, Formal analysis, Data curation. **Beatrice Cassottana:** Writing – review & editing, Supervision, Conceptualization. **Jan Anne Annema:** Writing – review & editing, Supervision. **Nazli Y. Aydin:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Full questionnaire

A.1. Survey introduction

Extreme weather events (EWE) are more intense, leading to catastrophic damage to critical infrastructures, including road networks. EWE triggers road deterioration (e.g., rutting, cracking, potholes) and significantly increases road traffic accidents. Moreover, insufficient road infrastructure to withstand EWE exacerbates natural disaster impacts such as flooding and landslides. To address this problem, road authorities need to adjust their infrastructure capacity to climate change effects, which is called the Climate Change Adaptation (CCA) Measures. This study aims to help decision-makers prioritize CCA measures based on specified criteria that were introduced by the Climate Bond Resilience Taxonomy (CBRT). The survey is divided into three sections:

A. Respondent background
B. Stakeholder preferences of climate adaptation evaluation criteria
C. Stakeholder preferences of climate adaptation alternatives

A.2. Section A: Respondent background

1. What is your professional background?

☐ Practitioner or industry	☐ Academic or university	☐ Government official
☐ Others (Please specify): _____		

2. Where do you come from?

☐ Asia	☐ Europe	☐ North America	☐ South America
☐ Africa	☐ Australia		

3. Do you have academic/professional experience in road projects?

☐ Yes	☐ No

4. What is your role in the projects?

☐ Management office	☐ Construction engineer	☐ Operations team or contractors
☐ Asset owner	☐ Researcher	☐ Others (Please specify): _____

5. How many years of academic/professional experience do you have in road projects?

☐ <1 year	☐ 1–5 years	☐ 5–10 years	☐ 10–15 years
☐ >15 years			

A.3. Section B: Stakeholder preferences of climate adaptation evaluation criteria

- Instructions: Please assess the importance of the four Climate Change Adaptation criteria in determining the most suitable measures for road infrastructure.
- Use a scale from 1 to 9, where 1 represents the least important criterion and 9 represents the most important one.
- Equal scores are not permitted.

1. Disaster Risk Reduction (DRR): The ability to reduce climate change-induced hazards and/or increase the infrastructure's adaptive capacity.
(Example: Flood risk can be minimized with permeable pavement because it allows water to infiltrate into the ground and decreases surface runoff during heavy rainfall. How important is it for a measure to have an effective DRR?)

Importance	Score								
Least Important (1) → Most Important (9)	1	2	3	4	5	6	7	8	9
Selection	☐	☐	☐	☐	☐	☐	☐	☐	☐

2. Unintended Effect (Maladaptation): The potential unexpected outcomes of adaptation measures that exacerbate the hazard.
(Example: Excessive infiltration from permeable pavement could lead to soil saturation leaving no space for air and increasing the flooding risk. How important is it for a measure to have a low likelihood of unintended effects (maladaptation)?)

Importance	Score								
Least Important (1) → Most Important (9)	1	2	3	4	5	6	7	8	9
Selection	☐	☐	☐	☐	☐	☐	☐	☐	☐

3. Adverse Societal Impact (ASI): The negative impacts of adaptation measures on the environment, society, and the economy.
(Example: Permeable pavement allows pollutants (oil, heavy metals, and chemicals) to seep into groundwater, harming local clean water supplies. How important is it for a measure to have a low likelihood of adverse societal impact?)

Importance	Score								
Least Important (1) → Most Important (9)	1	2	3	4	5	6	7	8	9
Selection	☐	☐	☐	☐	☐	☐	☐	☐	☐

4. Project Cost (PC): The total expenditure required to plan, design, construct, and maintain adapting measures.
(Example: Permeable pavement is typically 1.5 to 3 times more expensive than traditional asphalt or concrete pavement. How important is it for a measure to have a low project cost?)

Importance	Score								
Least Important (1) → Most Important (9)	1	2	3	4	5	6	7	8	9
Selection	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table A.5
Stakeholder preference assessment of road climate adaptation measures.

Climate adaptation measure	DRR (1–5)					MA (1–5)					ASI (1–5)					Cost (1–5)				
	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
1. Vegetation plans	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Localized power	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Road surface	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Monitoring system	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Road height	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Flood defenses	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Flood pathways	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Improve drainage system	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Alternative road	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Re-routing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Reallocation	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

A.4. Section C: Stakeholder preferences of climate adaptation alternatives

- Instructions: You will evaluate 11 road infrastructure measures for adapting to climate change based on your personal opinion and the four criteria from Section B.
- You need to select a score between 1 and 5 for each criterion for each measure.

A.4.1. Scoring scales

- Disaster Risk Reduction (DRR): (1: low effectiveness; 5: high effectiveness)
- Unintended Effect (MA): (1: low likelihood; 5: high likelihood)
- Adverse Societal Impact (ASI): (1: low likelihood; 5: high likelihood)
- Project Cost (PC): (1: low cost; 5: high cost)

A.4.2. Measures to be evaluated

1. *Vegetation plans:* Incorporating natural elements such as trees and other vegetative barriers along roadways. This effort mitigates heat stress by providing shade and cooling through evapotranspiration.
2. *Localized power:* Decentralizing energy systems within road networks. It reduces dependency on centralized grids and ensures operability during extreme weather events.
3. *Road surface:* Applying specialized materials, coatings, or technologies to road surfaces to withstand high temperatures and reduce heat absorption, minimizing damage like cracking, rutting, or softening during heatwaves.
4. *Monitoring system:* Implementing systems such as sensors and cameras to detect rising water levels and provide warnings to prevent accidents.
5. *Road Height:* Raising the elevation of roads or bridges to prevent submersion in flood-prone areas. It protects transportation routes from flood damage and ensures connectivity.
6. *Flood defenses:* Constructing barriers like embankments or flood walls to block or divert floodwaters, minimizing the risk of inundation.
7. *Flood pathways:* Designing systems to control and direct the flow of floodwaters, preventing water accumulation near roads and adjacent areas.
8. *Improve drainage system:* Enhancing drainage systems to handle heavy rainfall and quickly remove water from road surfaces.
9. *Alternative road:* Constructing additional roads as a contingency plan to ensure an uninterrupted transportation system during extreme events.
10. *Re-routing:* Modifying current road path to avoid areas prone to frequent flooding like coastal zones.
11. *Reallocation:* Moving current road infrastructure away from areas that are highly vulnerable to flooding.

A.4.3. Your assessment

See Table A.5.

Appendix B. BWM implementation details

B.1. Consistency ratio and exclusion rule

The internal consistency of each respondent's pairwise comparisons was assessed using the input-based Consistency Ratio (CR) defined by Liang et al. (2020):

$$\mathrm{CR} = \frac{\xi^*}{\mathrm{CI}(\alpha_{BW})} \tag{B.1}$$

Table B.1
Summary statistics of the BWM Consistency Ratio (CR) across respondents who completed Section B ($n = 87$).

Statistic	Value
Minimum	0.00
Maximum	0.21
Mean	0.10
Median	0.15
Standard deviation	0.09
Accepted (CR ≤ threshold)	62
Rejected (CR > threshold)	25

Table C.1
Raw decision matrix (arithmetic mean, $n = 72$).

ID	Alternative	DRR	MA	ASI	PC
M-01	Vegetation plans	3.639	2.556	2.347	2.736
M-02	Localized power sources	3.083	2.667	2.528	3.778
M-03	Heat resistant road surface	3.514	2.833	2.347	3.833
M-04	Road monitoring systems	3.583	2.306	2.597	3.222
M-05	Adjustment of road height	3.625	3.208	3.208	4.500
M-06	Road flood defenses	4.069	3.083	3.069	4.139
M-07	Flood pathways management	4.292	2.819	2.750	3.875
M-08	Drainage system improvement	4.125	2.361	2.222	3.083
M-09	Alternative road	2.958	3.125	3.333	4.306
M-10	Road reroutes	3.361	2.819	3.139	3.125
M-11	Road re-allocation	3.597	3.250	3.556	4.194
$\sqrt{\sum x_{ij}^2}$		12.09	9.41	9.49	12.44

where ξ^* is the optimal objective value of the linear BWM model and $\mathrm{CI}(\alpha_{BW})$ is the consistency index corresponding to the respondent's maximum pairwise preference score α_{BW}. The threshold is respondent-specific, ranging from 0.15 (when $\alpha_{BW} = 3$) to 0.25 (when $\alpha_{BW} = 7$) in this dataset. A response is accepted when CR ≤ threshold; responses with CR = 0 are perfectly consistent and require no threshold comparison.

Of the 87 respondents who completed Section B, 25 were excluded (CR > threshold), leaving 62 consistent responses for the BWM aggregation. Excluded responses do not contribute to the aggregate criterion weights used in the TOPSIS analysis. Summary statistics for CR are reported in Table B.1.

Appendix C. TOPSIS implementation details

This appendix documents the full TOPSIS pipeline applied to rank 11 road infrastructure climate adaptation measures across four criteria: disaster risk reduction (DRR, benefit),maladaptation likelihood (MA, cost), adverse societal impact (ASI, cost), and project cost (PC, cost). Individual ratings (scale 1–5) from $n = 72$ valid respondents were first aggregated using the arithmetic mean. Criterion weights were derived from BWM analysis of $n = 62$ consistent expert responses: $w_{\mathrm{DRR}} = 0.281$, $w_{\mathrm{MA}} = 0.265$, $w_{\mathrm{ASI}} = 0.271$, $w_{\mathrm{PC}} = 0.183$.

C.1. Raw decision matrix

Respondent ratings were aggregated using the arithmetic mean:

$$x_{ij} = \frac{1}{n}\sum_{k=1}^{n} r_{ijk} \tag{C.1}$$

where r_{ijk} is the rating of respondent k for alternative i on criterion j, and n is the number of respondents (see Table C.1).

C.2. Normalized and weighted decision matrix

Vector (Euclidean) normalization renders criteria dimensionless:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{C.2}$$

Weighted normalized values are then computed as: (see Table C.2).

$$v_{ij} = w_j \times r_{ij} \tag{C.3}$$

Table C.2
Normalized matrix r_{ij} and weighted normalized matrix v_{ij}.

ID	Alternative	Normalized (r_{ij})				Weighted normalized (v_{ij})			
		DRR	MA	ASI	PC	DRR	MA	ASI	PC
M-01	Vegetation plans	0.301	0.272	0.247	0.220	0.085	0.072	0.067	0.040
M-02	Localized power sources	0.255	0.283	0.266	0.304	0.072	0.075	0.072	0.056
M-03	Heat resistant road surface	0.291	0.301	0.247	0.308	0.082	0.080	0.067	0.056
M-04	Road monitoring systems	0.296	0.245	0.274	0.259	0.083	0.065	0.074	0.047
M-05	Adjustment of road height	0.300	0.341	0.338	0.362	0.084	0.090	0.092	0.066
M-06	Road flood defenses	0.337	0.328	0.324	0.333	0.095	0.087	0.088	0.061
M-07	Flood pathways management	0.355	0.300	0.290	0.312	0.100	0.079	0.078	0.057
M-08	Drainage system improvement	0.341	0.251	0.234	0.248	0.096	0.067	0.063	0.045
M-09	Alternative road	0.245	0.332	0.351	0.346	0.069	0.088	0.095	0.063
M-10	Road reroutes	0.278	0.300	0.331	0.251	0.078	0.079	0.090	0.046
M-11	Road re-allocation	0.298	0.345	0.375	0.337	0.084	0.092	0.101	0.062
Weight w_j		–	–	–	–	0.281	0.265	0.271	0.183

Table C.3
Ideal (V^+) and anti-ideal (V^-) solutions.

	DRR (benefit)	MA (cost)	ASI (cost)	PC (cost)
V^+	0.100 (M-07)	0.065 (M-04)	0.063 (M-08)	0.040 (M-01)
V^-	0.069 (M-09)	0.092 (M-11)	0.101 (M-11)	0.066 (M-05)

Table C.4
Distances, relative closeness, and final ranking.

Rank	Alternative	S^+	S^-	P
1	M-08 Drainage system improvement	0.01	0.06	0.90
2	M-01 Vegetation plans	0.02	0.05	0.74
3	M-04 Road monitoring systems	0.02	0.04	0.68
4	M-07 Flood pathways management	0.03	0.04	0.61
5	M-03 Heat-resistant road surface	0.03	0.04	0.58
6	M-02 Localized power sources	0.03	0.04	0.51
7	M-06 Road flood defenses	0.04	0.03	0.44
8	M-10 Road rerouting	0.04	0.03	0.43
9	M-05 Adjustment of road height	0.05	0.02	0.28
10	M-11 Road reallocation	0.05	0.02	0.22
11	M-09 Alternative road	0.06	0.01	0.12

C.3. Ideal and anti-ideal solutions

The ideal solution V^+ and anti-ideal solution V^- are determined per criterion type: (see Table C.3).

$$V_j^+ = \begin{cases} \max_i(v_{ij}) & \text{if } j \text{ is a benefit criterion (DRR)} \\ \min_i(v_{ij}) & \text{if } j \text{ is a cost criterion (MA, ASI, PC)} \end{cases} \tag{C.4}$$

$$V_j^- = \begin{cases} \min_i(v_{ij}) & \text{if } j \text{ is a benefit criterion (DRR)} \\ \max_i(v_{ij}) & \text{if } j \text{ is a cost criterion (MA, ASI, PC)} \end{cases} \tag{C.5}$$

C.4. Distances and relative closeness

The Euclidean distances from each alternative to V^+ and V^- are:

$$S_i^+ = \sqrt{\sum_{j=1}^{4}\left(v_{ij} - V_j^+\right)^2} \qquad S_i^- = \sqrt{\sum_{j=1}^{4}\left(v_{ij} - V_j^-\right)^2} \tag{C.6}$$

The relative closeness coefficient $P_i \in [0, 1]$ is:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{C.7}$$

Alternatives are ranked in descending order of P_i; a value closer to 1 indicates stronger similarity to the ideal solution. The TOPSIS result is shown below: (see Table C.4).

Table D.1
Criterion weights used in the baseline BWM result and sensitivity-analysis scenarios.

Criteria	BWM result	DRR+	DRR−	MA+	MA−	ASI+	ASI−	PC+	PC−
DRR	0.28	0.40	0.17	0.24	0.32	0.23	0.33	0.23	0.33
MA	0.27	0.22	0.31	0.38	0.15	0.22	0.31	0.22	0.31
ASI	0.27	0.23	0.31	0.23	0.31	0.41	0.14	0.22	0.32
PC	0.18	0.15	0.21	0.15	0.21	0.15	0.22	0.32	0.05

Table D.2
Kendall's Tau-b results across scenarios.

Scenario	Tau-b	p-value	Interpretation
DRR+	0.85	0.00	Strong agreement
DRR−	0.89	0.00	Strong agreement
MA+	0.96	0.00	Very strong agreement
MA−	1.00	0.00	Very strong agreement
ASI+	0.93	0.00	Very strong agreement
ASI−	0.85	0.00	Strong agreement
PC+	0.85	0.00	Strong agreement
PC−	1.00	0.00	Very strong agreement

Appendix D. Prioritization rank sensitivity analysis

The criterion-weight changes applied in each sensitivity-analysis scenario are shown below: (see Table D.1).

A further statistical test was conducted to assess the robustness of the TOPSIS model. The results show that all Kendall's tau coefficients exceeded 0.800, indicating strong ordinal agreement between the baseline ranking and the rankings generated under alternative weighting scenarios. Therefore, the TOPSIS-based prioritization can be considered robust under the tested variations in criterion weights (see Table D.2).

Data availability

The original survey instrument is available at bit.ly/CCARoadSurvey. The anonymized data supporting the findings of this study are available from the corresponding author upon reasonable request..

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