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# Composite Adaptability Index

## A framework for urban transportation resilience to urban flooding

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### Abstract

This article explores the development of a Composite Adaptability Index (CAI), a framework that assesses the adaptability of urban transportation systems in response to climate change, particularly urban flooding. As Asian cities are facing the increasing risk of climate change impacts, the need for resilient transportation infrastructure is crucial. It is important to implement adaptation policies to improve the system's resilience and develop monitoring and evaluation measures to assess their effectiveness. The CAI relies on the main pillars of Environmental, Social, and Economic and sub-pillars of Exposure, Resilience, and Susceptibility. To understand the practical application of the CAI, a case study of Bengaluru, India, which is highly vulnerable to urban flooding, is presented. Results suggest that a policy bundle of land use and infrastructure instruments is extremely advantageous to increase system resilience. Compared to the other policy bundles and the Business-As-Usual scenario, the high CAI value of a bundle of land use and infrastructure instruments indicates its ability to improve the system's resilience. By adopting CAI, policymakers can proactively prepare the transportation system for climate challenges.

### Introduction

Climate change has been a focal point of discussion in dialogues worldwide, including the United Nations Framework Convention on Climate Change (UNFCCC), the Kyoto Protocol, and the Paris Agreement. Climate change and its impact is significantly felt across various sectors, majorly in critical infrastructures, including transportation. Asia has been undergoing rapid urbanisation and economic growth in recent decades, leading to uncontrolled migrations and heightened demand for infrastructure, especially transportation. Its heightened vulnerability to climate change risks and resulting economic losses (Kurth et al., 2020) has made it essential to prioritise system resili-

ence, especially in Asian countries, where many are particularly vulnerable to climate change. In India, metropolitan cities like Bengaluru, Mumbai, and Chennai are severely affected by annual floods, and low-lying cities such as Ho Chi Minh and Jakarta are vulnerable to sea-level rise. Bangladesh's unique geographical profile makes it highly susceptible to flooding, tidal inundation risks, and the accelerated melting of Himalayan glaciers.

While resilience is gaining popularity in research and policy, the significant disparity between developed and developing nations is prominent. (Pan et al., 2021). India is notably vulnerable to climate change, facing extreme weather events like cyclones and floods in increasing intensity and fre-

quency. The last few decades have seen unpredictable season changes and increased rainfall, leading to urban floodings threatening transportation systems. Uncontrolled urbanisation and unplanned developments have further complicated the matter with cities struggling to meet the socio-economic demands in these extreme conditions.

As the situation continues to deteriorate, particularly in developing countries like India, the urgency of adapting transportation systems becomes increasingly clear. Resilience is a big part of this step. Referred to as the "ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner" by the United Nations Office of the Special Representative of the Secretary-General for Disaster Risk Reduction, resilience principles can help fragile systems become more stable and flexible. By prioritising resilience in transportation planning, countries can better prepare for the adverse effects of climate change, ensuring their networks remain robust and reliable amidst environmental changes.

To tackle climate change issues effectively, it is important to focus on the interconnection between adaptation and resilience strategies. Adaptation is the process that involves making changes to adjust to new conditions through modified practices and redesigning structures. Adaptation contributes to building resilience so that climate change impacts can be reduced or modified. While countries have identified and recognised the importance of adaptation and prepared national adaptation strategies, no recognised matrix or methodology exists to measure their effectiveness.

Measurement and evaluation of adaptation projects and programs leads to effective communication and public engagement, informed planning and

decision-making, solid justification of adaptation expenditures, accountability, governance, and management. The lack of monitoring and evaluation frameworks could be attributed to the challenges due to uncertainty and complexity, context specificity, lack of comparable indicators and resources, and the long-term horizon involved in collecting reasonable results.

This article is inspired by the work done by Dr. Harsha Vajjarapu as part of his thesis titled, "Evaluating Climate Change Mitigation & Adaptation Potential of Sustainable Urban Transport Measures in India" at the Indian Institute of Science (IISc), Bengaluru, and presents the development of an innovative index named the Composite Adaptability Index. The Composite Adaptability Index (CAI) is a context-specific framework developed to evaluate the adaptability of an urban city's transportation system against floods. The index is developed based on the Environmental, Social, and

Economic pillars and considers the relationship between adaptation, exposure, susceptibility, and resilience. (Vajjarapu & Verma, 2021).

### Composite adaptability index

You can think of the CAI as a progress report for the city's transportation system. Like how teachers assess the students through examinations, assignments, and seminars, the CAI index assesses the city's urban transportation network's adaptability to urban floods through various indicators. Similar to how blood pressure, pulse, and saturation level are indicators of the body's state of health, several indicators can be employed to determine the transportation system's performance. These indicators broadly fall under the three major pillars of adaptation - Environmental, Social, and Economic- the three sectors significantly affecting urban flooding and the sub-pillars of exposure, resilience, and susceptibility,

which will provide a deeper understanding of how the system interacts with urban flooding. While the Environmental pillar considers aspects of rainfall, the social pillar looks at how individuals' travel decisions change. The economic pillar considers the economic impacts of urban flooding.

Exposure refers to the elements that increase the exposure of transportation systems to urban flooding; resilience denotes the ability of the system to return to its original state after a flooding event, while susceptibility reflects the possibility that the system has a chance of getting flooded in the event of urban flooding. The CAI development follows a systematic approach that starts with indicator identification and normalisation and continues through prioritisation and index calculation. The Composite Adaptability Index (CAI) development process for urban transportation systems facing urban flooding involves several key steps, as shown in Fig 1 and explained below.

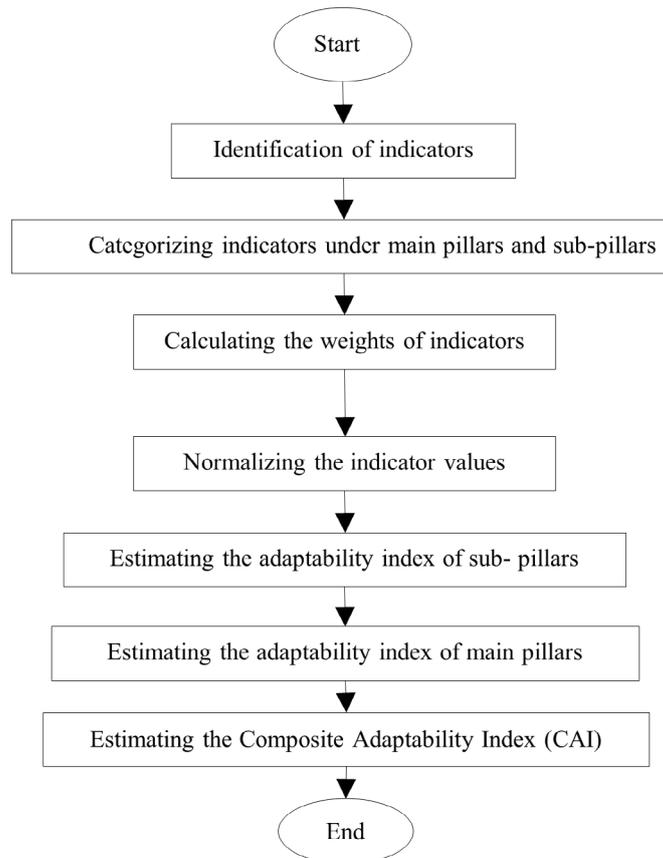


Figure 1: Development of Composite Adaptability Index (CAI)

(Source: Vajjarapu & Verma, 2021)

- 1. Identification of indicators:** For the development of the CAI, indicators under each of these main pillars and sub-pillars need to be identified.
- 2. Normalization of Data:** Normalization is carried out to ensure that indicator data collected on different scales can be compared meaningfully on a common scale. In simpler terms, normalisation ensures that apples are compared with apples and not oranges. Bringing all points to a common scale ensures their accurate evaluation and effective comparison without the influence of their differing measurement units.
- 3. Prioritization of Indicators:** To ensure a structured evaluation of the indicators and development of the index, indicators should be prioritised based on their importance in contributing to the system's adaptability. This process identifies the significance of each indicator about its sub-pillar and assigns a numerical value, the weight, representing this importance. By doing this step, the influence of various indicators on system adaptability can be determined.
- 4. Index Calculation:** The Composite Index calculation happens in three steps.

#### 4.1 Adaptability index of sub-pillars

The adaptability index of sub-pillars is calculated by combining the normal value of the indicators with their assigned weight. Each indicator value is first adjusted to a common scale, and then its importance is factored in through its weight. The result is a weighted sum that reflects the overall adaptability of the sub-pillars. The mathematical formula for the same is given in Eqn [1].

$$AI_{sp} = \sum_{i=1}^n [NVI_i * WI_i], \quad [1]$$

where,

sp – Sub-pillars of adaptability  
 NVI – Normalized Value of Indicator  
 WI – Global Weight of Indicators

#### 4.2 Adaptability index of main pillars

Examining the sub-pillars and their relation to the system's adaptability reveals that resilience positive-

ly influences adaptability; in other words, resilient systems are more adaptable, while exposure and susceptibility negatively impact adaptability. Considering these relationships, Eqn [2] was developed to determine the adaptability index of the main pillars of adaptation.

$$AI_{mp} = \sum \frac{[R_{sp} + (1 - E_{sp}) + (1 - S_{sp})]}{3}, \quad [2]$$

where,

mp – Main Pillars of Adaptability  
 R – Normalized Resilience  
 E – Normalized Exposure  
 S – Normalized Susceptibility

If the main pillar is entirely resilient to urban flooding with no exposure or susceptibility, then Eqn [2] gives the adaptation index of the main pillar as 1 with  $R_{sp} = 1$ ,  $E_{sp} = 0$ , and  $S_{sp} = 0$ .

#### 4.3 Calculation of Composite Adaptability Index (CAI)

Finally, the composite adaptability index for the entire urban transportation system is obtained from Eqn [3] as,

$$CAI_{system} = \frac{\sum AI_{mp}}{3} \quad [3]$$

The value of the composite adaptability index varies from 0 to 1, with 0 being the worst adaptability and 1 being the best adaptability.

### Case study

The developed composite adaptability index was applied to the Bangalore Metropolitan Region (BMR), covering over 8005 sq. km. One of the fastest-growing metropolises in India, Bengaluru has a population of 12 million (World Population Review, 2020). With its population expected to reach 18 and 33 million in 2030 and 2050, respectively, Bengaluru presents an exciting challenge, with the city grappling with the demands of rapid urbanisation. These demographic shifts are reflected in city traffic congestion, air pollution, and changing land use patterns. The rise in impervious surfaces and the loss of wetlands and vegetation have significantly contributed to frequent urban floods (Ramachandra, 2017). Effect measures are urgently required to mitigate the issue.

**Adaptation Policies:** The study formulated adaptation policies through a comprehensive literature review, stakeholder interaction, and Intergovernmental Panel on Climate Change (IPCC) definition, additionally drawing inspiration from Western countries. Through the Delphi method, the most relevant adaptation policies were identified. A widely used technique, the Delphi method, is a way to get opinions from experts by asking them questions anonymously. They answer, see a summary of everyone's thoughts, and update their answers. The Delphi method filtered nine potential adaptation policies down to six. Identifying that policies are more effective when implemented in a package, the six policies were bundled to enhance each other in achieving better resilience. The study formulated three policy bundles to tackle urban flooding in Bengaluru and to restore the city to a business-as-usual (BAU) scenario without flooding.

Each policy bundle is composed of different policy instruments; Bundle 1 contains land use and infrastructure instruments, while Bundle 2 constitutes policies related to land use and information (traffic management). Bundle 3 integrates infrastructure and information instruments. These bundles were then critically analysed to assess their combined impact on improving system resilience, particularly in reducing flood levels. To evaluate their effectiveness, scenario analysis was conducted considering three cases: the BAU no-flooding scenario, the BAU flooding scenario, and various adaptation policy scenarios. The Composite Adaptability Index was employed to determine the policy bundles' effectiveness in improving the system's adaptability.

**Indicators selection:** Indicators for the analysis were identified under the three main pillars: Environmental, Social, and Economic. Multiple urban transportation-related indicators were also incorporated for the index estimation. Vehicle Kilometers Travelled (VKT), Vehicle Hours Travelled (VHT), Average speed of the vehicle (ASV), Cancelled trips (CT), and Average Trip Length (ATL) were the transportation indicators used in the study.

**Scenario analysis:** The values for the indicators selected above depend on the policies and vary across the policy bundles. Each of the policies affects different stages of planning a trip: determining where a trip starts and ends (Trip generation), determining how many people will travel from one place to another (Trip Distribution), choosing the method of transportation, such as car, bus, or train (Mode choice), and selecting the route to take (Trip Assignment). When combined, these steps are termed as the ‘traditional four-step model’ in transportation planning and are widely accepted for analysis. By using TransCAD, a transportation plan-

ning software with GIS and transportation modelling capabilities integrated with the four-step model, the three scenarios were analysed: BAU- no flooding, BAU- flooding, and Adaptation policy scenarios for years 2030 and 2050, and indicator values were extracted or estimated. (Vajjarapu et al., 2020)

**Normalising and weighing:** Since each indicator has different units, it is essential to apply data normalisation to bring them to a standard unit. Due to its simplicity, the min-max method is employed in this study, where it scales the data to fall within a range of 0 to 1. This helps transform the data to make it easier to compare and analyse.

$$NVI = \frac{(actual\ value - minimum\ value)}{(maximum\ value - minimum\ value)}$$

where,  
 NVI – Normalized value of the indicators  
 Actual value – Indicator value obtained from the model  
 Maximum and minimum value – Estimated Maximum and minimum values of indicators.

After normalising, the Analytical Hierarchy Process (AHP), a multi-criteria decision-making approach based on pair-wise comparison, developed by Saaty in the 1970s (Saaty, 1987) was used to achieve weights of the indica-

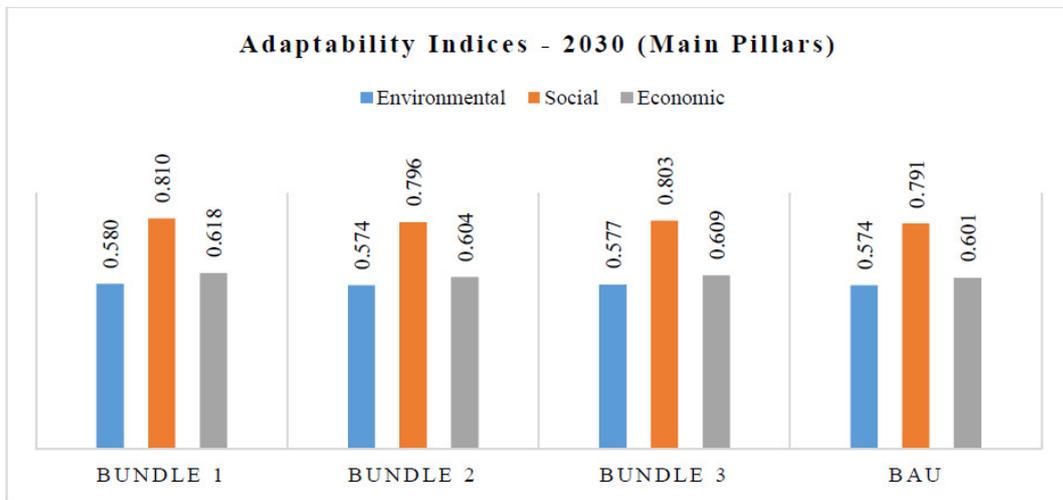


Figure 2: Adaptability Indices of Main Pillars for the year 2030

(Source: Vajjarapu & Verma, 2021)

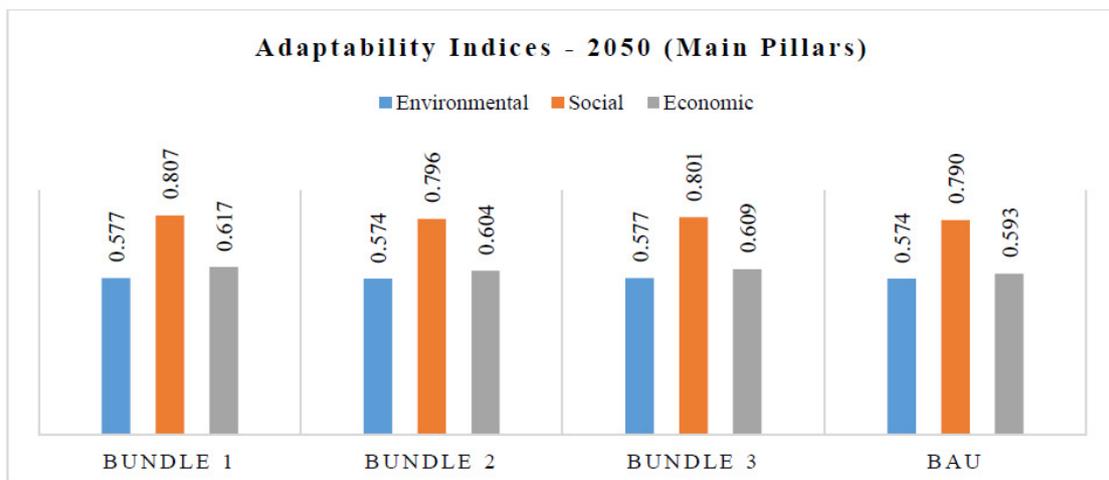


Figure 3: Adaptability indices of main pillars for the year 2050

(Source: Vajjarapu & Verma, 2021)

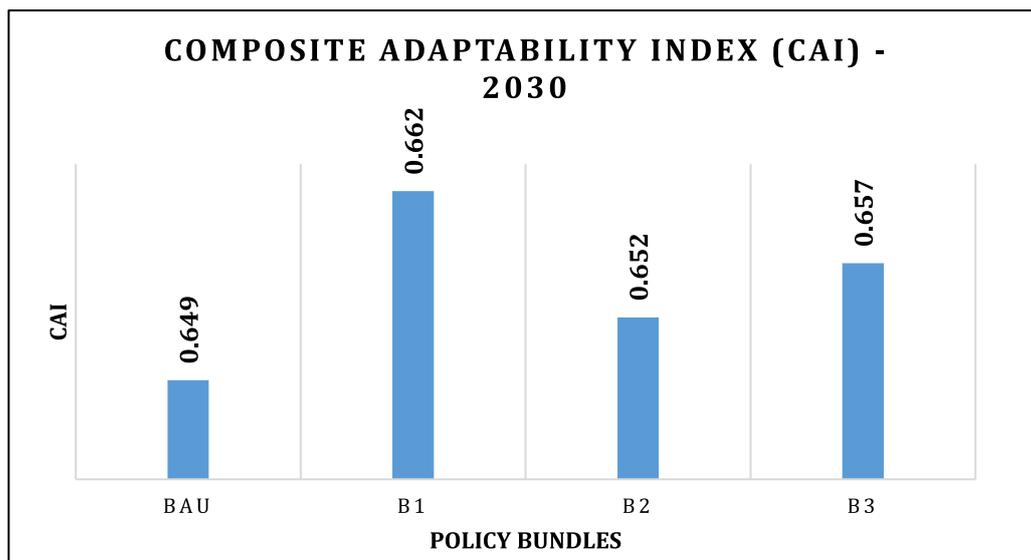


Figure 4: Composite Adaptability Indices for the year 2030

(Source: Vajjarapu & Verma, 2021)

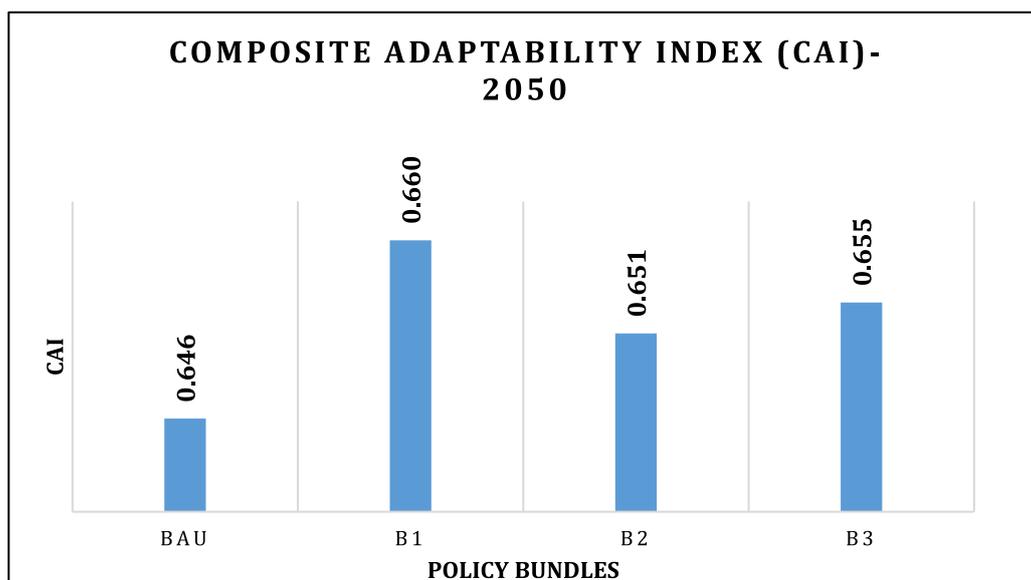


Figure 5: Composite Adaptability Indices for the year 2050

(Source: Vajjarapu & Verma, 2021) A comparison of the composite adaptability indices across the various policy bundles shows that bundle 1 achieves the best results. The higher CAI value of bundle 1, which combines land use and infrastructural instruments, underscores the importance of a well-informed resilience strategy that integrates these two sectors. This approach significantly increases the urban transportation systems' adaptability to urban floods and overall resilience.

tors. AHP utilises the decision-maker's expertise and breaks down the decision problem into a hierarchy of easily comprehensible sub-problems, which can then be analysed independently. The participants are asked to compare the indicators in pairs and rank them accordingly based on their effect on adaptability. In the study, to determine the weights of the indicators, inputs

from 30 experts were considered. The experts included government officials, government officers from transport and urban planning, the meteorological department, disaster management, and professors from the Indian Institute of Science who are experts in Transportation Engineering. Once the results were calculated, a consistency ratio was used to ensure their reliabil-

ity, allowing necessary adjustments to enhance decision-making.

**Composite Adaptability Index:** Once the normalised indicator values and their weights were obtained, the adaptability indices for the sub-pillars and the main pillars were calculated for the years 2030 and 2050. Fig.2 and Fig.3 represent the adaptation indices of various policy bundles and busi-

ness-as-usual scenarios with flooding. Compared with the BAU scenario for both years, the adaptability indices for the main pillars are increasing across all policy bundles, indicating that implementing the adaptation policies improves the system's adaptability level. Furthermore, to compare the effectiveness of policy bundles and identify the one with higher benefits, the composite adaptability index of the system for all policy bundles and the BAU were calculated, and the results are presented in Fig 4 and Fig 5 for the years 2030 and 2050, respectively.

## Conclusion

The ever-present threat of climate change on the horizon and the demands for more and more infrastructure, particularly in the rapidly urbanising cities of Asia, have necessitated the incorporation of resilience strategies in long-term transportation planning. As climate-related risks become more frequent and intense across cities, the transportation system, one of the critical lifelines, is becoming severely vulnerable, especially in developing countries like India. While there are many adaptation policy initiatives to maintain the functionality and stability of the systems, the lack of a suitable measurement matrix reduces their acceptability.

This article presents the development of a Composite adaptability Index (CAI) an indicator-based approach that can be used to evaluate the adaptability of climate change adaptation strategies for the urban transportation sector, focusing on urban flood. The index is developed based on three main pillars – Environmental, Social, and Economic- and three sub-pillars or factors – Exposure, Susceptibility, and Resilience. Considering the relationship between adaptation and the three factors, a mathematical expression was developed for the index. The CAI offers a comprehensive approach by integrat-

ing various indicators across these pillars to understand how urban transportation systems can adapt to growing risks associated with climate change.

To highlight the practical application of the index, a case study of Bengaluru, one of India's fastest-growing cities, is also discussed in the article. Bengaluru faces frequent urban flooding due to unconstrained urbanisation and the loss of natural ecosystems. The CAI was applied to analyse the effectiveness of various policy bundles from infrastructural, land use, and traffic management instruments designed to reduce the effects of urban flooding on Bengaluru's transportation system. The Composite Adaptability Index developed in the study can be used to evaluate the effectiveness of adaptation policies. Though the application was restricted to adaptation strategies for Indian cities, the index is transferrable and can be used as an evaluation technique for adaptation policies. The model will act as a scientific tool for policymakers to make appropriate decisions in reducing the risk of flooding in urban areas.

Looking ahead, it is crucial for policymakers, researchers, and urban planners to adapt the CAI as a standard evaluation tool for adaptation policies. Through a holistic approach to urban resilience, it can be ensured that transportation systems are proactively designed to withstand future disturbances. The CAI applied in the Bengaluru case study was developed with a limited number of indicators; in the future, the CAI can be refined by incorporating more diverse indicators and testing its applicability across various contexts.

It is high time to integrate resilience into long-term transportation planning. By focusing on capacity building, stakeholder engagement, fund allocation, risk assessment, and stakeholder involvement, we can create robust and reliable transportation systems capable of withstanding disasters. Much as

a band-aid on a broken arm does not solve the issue, ensuring adaptation does not result in maladaptation is crucial. Tools like the Composite Adaptability Index will serve as vital support systems for these initiatives, enabling informed decision-making and enabling policymakers towards effective strategies. Through collaborative efforts and strategic planning, we can ensure that transportation systems remain adaptive and resilient.

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