ADAPTATION TO CLIMATE CHANGE IN THE TRANSPORT SECTOR – PRINCIPLES THAT LEAD TO A SUSTAINABLE MODEL

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Abstract. This study explores the urgent need for adaptation of the transport infrastructure in Bulgaria to the rapidly changing climatic conditions. Climate change requires rethinking approaches to the design and management of transport systems to improve their sustainability and functionality. An analysis of climate risks and the direct impact of climate change on transport systems is included. The development pays attention to the integration of current scientific research and data into the design and construction processes, proposing the adaptation of existing norms and procedures to meet the expectations of rising temperatures and more frequent extreme climate events. The importance of using sustainable materials and design improvements to increase the sustainability of transport facilities is highlighted. In addition, the need to implement innovative technological solutions to enrich the process of planning and project implementation is considered. A key aspect is the integration of a multidisciplinary approach in analysis and planning, involving specialists from different fields to formulate comprehensive and sustainable solutions. The aim is to create a comprehensive strategy that covers all aspects of transport infrastructure adaptation, from initial design to implementation and maintenance, protecting socio-economic interests and increasing the safety and reliability of transport systems in climate-challenged conditions.

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1. CLIMATE CHANGE AND SECTORAL VULNERABILITY

Over the past few decades, the countries of the European Union have confronted the escalating challenges of global warming and rapid climate change. To avert catastrophic consequences and reverse adverse trends, they have redirected their focus toward significant restructuring and reforms across various sectors. The transport sector, in particular, given its vital role in ensuring economic and social stability, must urgently adapt to these evolving conditions. However, accomplishing these goals is a complex and lengthy process that cannot be achieved quickly.

According to the accepted general definition, vulnerability for a transport system means its susceptibility to various types of stress factors, i.e., external and internal influences that may disrupt its normal functioning and efficiency. In the case of climate change, such a stressor can be an extreme weather event, a climate-induced risk, a sustained climate impact, etc.

Several recent studies offer practical insights into strengthening transport system resilience. Din et al. [1] show that sustainable transport, aided by climate technologies and electric rail, can reduce emissions, based on data from China. Rathnayaka et al. [2], in a Sri Lankan case study, stress the prioritization of adaptation measures using expert input and the AHP method—highlighting asset management, evacuation planning, and nature-based solutions. Melkonyan et al. [3] report low preparedness in Germany's logistics sector and propose a transformation framework for climate-resilient operations. These findings are relevant for shaping adaptation strategies in Bulgaria.

1.1 Adaptation to climate change and transport infrastructure

Adaptation of the transport sector to climate change is becoming increasingly important due to increasing climatic events. This means the sector must adapt to changing climate conditions and use different parameters to evaluate and plan its measures.

Adaptation to climate change is a process by which people, communities, organizations, and governments take measures to cope with the consequences of these changes. The main objective is to reduce the vulnerability and increase the resilience of the transport system to current and future climate conditions. This requires a comprehensive and flexible approach that can adapt to changing conditions and ensure the long-term resilience of the transport system against climate risks.

1.2 National Strategy for Adaptation to Climate Change and Action Plan for the Bulgarian Transport Sector

In early 2019, Bulgaria, completely recognizing the challenges posed by climate change, created the "National Strategy for Adaptation to Climate Change and an Action Plan" (NSACC) [4] with the help of specialists from the World Bank. This procedure is driven by the creation of the administrative record "Adaptation to Climate Change—Transport Sector Assessment" [5].

A new approach to transport infrastructure is needed, based on the principles of sustainable development of the transport sector in Bulgaria, but its development and implementation have been delayed by the complex situation in recent years. The collision of three significant crises has quickly led to severe upheavals in transport construction, especially in road construction. The problems began in early 2020 with COVID-19 and continue to this day. While Bulgaria experienced an irreversible delay in implementing the NSACC, the European Commission renewed the strategy for the member countries in 2021 with a long-term perspective until 2050 [6].

1.3 Global problems for the applicability of the adopted strategy regarding the transport infrastructure of Bulgaria

Firstly, Bulgaria's transport sector faces a significant drawback because, between 2019 and 2023, the report on climate change adaptation [5] remains the sole document that assesses and provides recommendations for the necessary actions to adequately respond, prevent, and manage the operation of transport infrastructure in anticipation of future extreme climatic events at a national level.

In second place, Bulgaria's transport infrastructure, especially the road infrastructure, has massively deteriorated performance indicators regarding durability, continuity, and safety. This makes it a risky infrastructure with increased sensitivity to the negative effects of climate events.

Thirdly, there is a complete lack of strategic practices for forecasting and risk prevention based on climate models and the accumulation and exchange of information under programs such as "Copernicus" [7].

2. PROJECT "IMPACT OF CLIMATE CHANGE ON THE TRANSPORT INFRASTRUCTURE IN BULGARIA – CONCEPTUAL APPROACH TO ASSESS THE POTENTIAL IMPACT ON ACHIEVING SUSTAINABILITY AND SAFETY OF ELEMENTS OF THE TRANSPORT SECTOR."

The project BN 286/2023 was implemented at the Center for Scientific Research and Design of UACEG in 2023. The research aims to develop a comprehensive methodological approach for evaluating and determining the applicability of measures to adapt Bulgaria's transport infrastructure to changing climatic conditions. This includes identifying vulnerable components of the transport system, analyzing the impact of climate change on these components, and developing strategies to reduce risks while increasing the adaptability and resilience of transport infrastructure. The study is centered on a specific region in Bulgaria, utilizing parametric analysis, neural network modeling, and GIS-based analysis to assess specific climate impacts and their effects on the operational performance of the transport infrastructure.

2.1 Analysis of climate data – a methodological approach

Climate data collection is a vital process that underpins our understanding of climate change and forms the foundation for research, analysis, and the development of adaptation strategies. However, this process is only effective if it produces high-quality data that can be utilized to accurately project climate risks for transport infrastructure. Several significant limitations and shortcomings have been identified, which impede the implementation of a dynamic methodological approach that relies on the continuous renewal of the data collection process. The most important challenges that need to be addressed or mitigated include:

- Limited spatial coverage: In some instances, climate data is restricted to a small number of weather stations or specific regions, resulting in gaps where no data is available, leaving the climate dynamics of these areas unknown.
- Inadequate data duration: Long-term data is essential for the analysis of climate trends and changes over time. A lack of extended historical data can hinder the ability to conduct thorough analysis and make accurate forecasts.
- Measurement errors and inaccuracies: All measuring instruments and methodologies have inherent errors and inaccuracies, which can introduce noise into the data and potentially obscure the true climate conditions.
- Lack of standardization: Various weather stations and data sources use different methods and tools, which can make it difficult to compare and analyse the data effectively.
- Heterogeneous data sources: Climate data is gathered from a range of sources, including weather stations, satellite observations, and climate models. The diversity in data formats and collection methods can complicate the process of integrating this information.
- Unexpected data gaps: Occasionally, data sets may contain unforeseen gaps or omissions, which can pose additional challenges for analysis and forecasting efforts.

Addressing these limitations is crucial to ensure that climate data collection supports the accurate projection of climate risks and the effective adaptation of transport infrastructure to evolving climate conditions.

In summary, climate data should be sourced from diverse platforms, including climate stations, satellites, sensors, floating platforms, aerosondes, global databases, and other resources suitable for climate forecasting models. Comprehensive and current information on climatic conditions is essential as it provides the foundation for several critical activities:

- Forecasting and planning: Accurate data allows us to predict climate risks and plan the necessary changes and improvements in infrastructure to meet future challenges.
- Vulnerability assessment: With reliable climate data, we can assess vulnerability and the sensitivity of the road network and transport facilities to climate change, ensuring that the right parameters are taken into account during the investment process.
- Improving safety: Climate risk data is critical to developing more effective road safety strategies, including early warning systems and disaster prevention measures.
- Optimizing resources: Future climate information can help us optimize resource use, especially maintenance costs, ensuring more efficient and sustainable operations.

2.2 Collection of data on crisis events and their impact on transport infrastructure

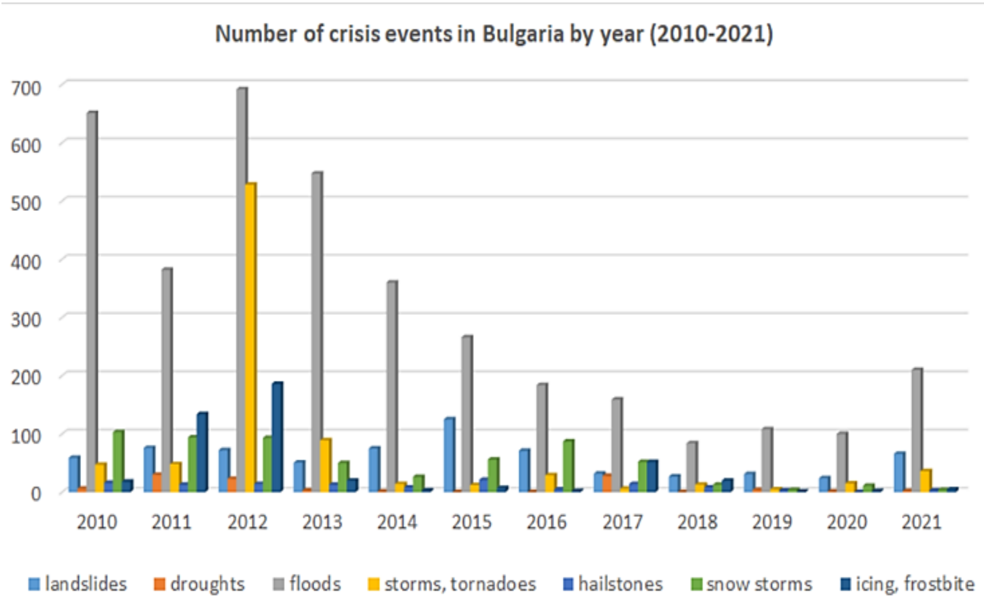

Fig. 1. Summary of data from the NSI on the number of crisis events by type in Bulgaria by year for the period 2010–2021 [8].

Concerning the institutional framework responsible for providing this data, it has been identified that there are no nationally administered databases specifically tracking climate-related road infrastructure crises. This lack of data management severely hinders the application of methodological models and prevents responsible institutions from developing long-term strategies. Consequently, this results in a low adaptive capacity within the sector. Figure 1 presents a summary of data from the National Statistical Institute (NSI) on crisis events, categorized by type and year, for the period 2020-2021 [8].

It is crucial to recognize that data collection is the foundational step upon which all other aspects of adaptation rely. Given the delays in implementing previous recommendations, it is now essential to initiate a discussion and organize the systematic collection of databases, including climate data and information on the condition of transport infrastructure. The goal is to build a solid foundation for detailed planning within a medium-term framework (5–7 years) and to create opportunities for effective adaptation strategies. Without improving data collection practices to ensure they are sufficiently open and accessible for use in processing, refining algorithms, and enhancing climate models, it will be impossible to develop a robust methodology for analyzing and preventing climate-related events in the transport sector.

2.3 Analysis of the main adaptation measures

The national documents on climate change adaptation (CCA) in the transport sector [4, 5] offer a mix of effective and impractical recommendations when it comes to their real-world applicability.

One of the strengths of these documents lies in the thorough examination of sector-specific challenges and the corresponding recommendations that have been developed. If effectively implemented, these recommendations could pave the way for increased adaptability and better-coordinated activities within the transport sector. This should, in turn, result in Bulgaria's transport infrastructure being more secure and capable of providing enhanced services over the medium to long term.

However, there are two key areas where the recommendations fall short and require significant improvement:

- Widening the scope: There is an urgent need to expand the range of components considered under the CCA framework beyond what has been proposed in [5].
- Revising unfeasible recommendations: Some of the adaptability recommendations are currently unworkable within the existing standards and regulatory frameworks. These either need to be removed or restructured to ensure they can be realistically implemented.

3. RECOMMENDATION TO INCREASE THE SCOPE OF THE ELEMENTS UNDER THE CCA REGARDING TRANSPORT INFRASTRUCTURE

3.1 Expansion of recommended climate risks as significant with effects on transport infrastructure

The evaluation of the transport sector outlined in [5], along with scientific monitoring of the sensitivity of Bulgaria's transport infrastructure [9, 10], helps identify the most significant climate-related risks: extreme temperatures (high and low), heavy rainfall and storms, snowfall and blizzards, and combined effects of two or more of these factors. This underlines the need to include more climate elements and dynamics than are currently considered in [5]. Furthermore, climate events in [5] are not classified according to the reactivity of specific infrastructure components (roads, railways, transport facilities). Instead, the initial classification should be based on durability—an example for Bulgaria is summarized in Table 1.

Table 1. Types of climate events, their impacts, and risks

Types of climate events	Climate impacts (direct climate variable)	Climate impacts (secondary climate variable) and their risks
Extreme weather events	Extreme weather events Extremely high temperatures Extremely low temperatures Storms - wind impact Storms - wave action Precipitation of an extreme nature Floods (of a precipitation nature) Blizzards (snowstorms) Hail	Rising water levels in rivers Rise in groundwater (water saturation) Fogs Freezing rain
Climate events with gradually increasing impact	Permanently high temperatures Permanently low temperatures Droughts Continuous rainfall Snowfall (increase) Temperature amplitude Warmer winters – snowfall (decreasing)	Geological risks (erosion, abrasion) Sea level rise Geological risks (landslides, collapses)

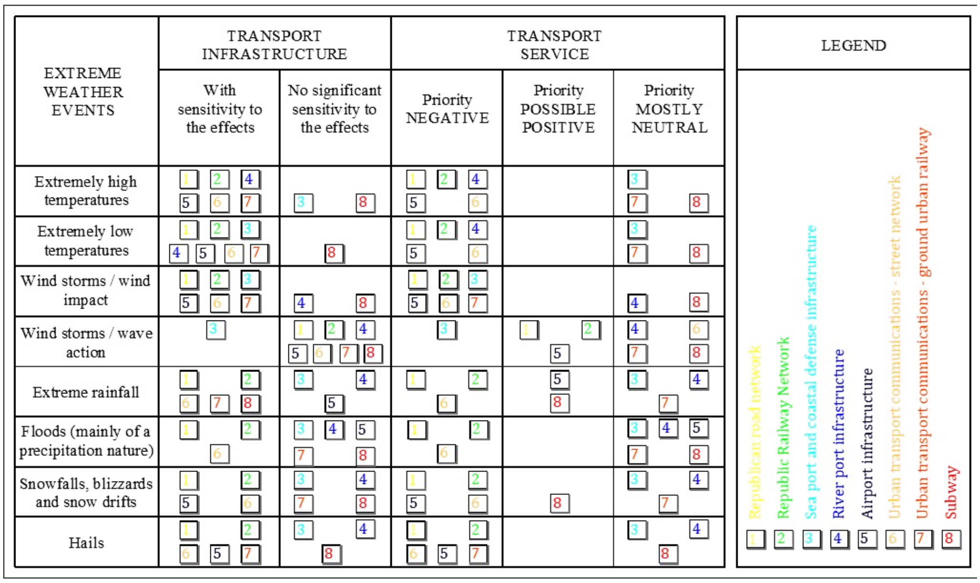

Fig. 2. Climatic impacts (direct climate variable) on the transport infrastructure of Bulgaria - affected elements of the Transport sector.

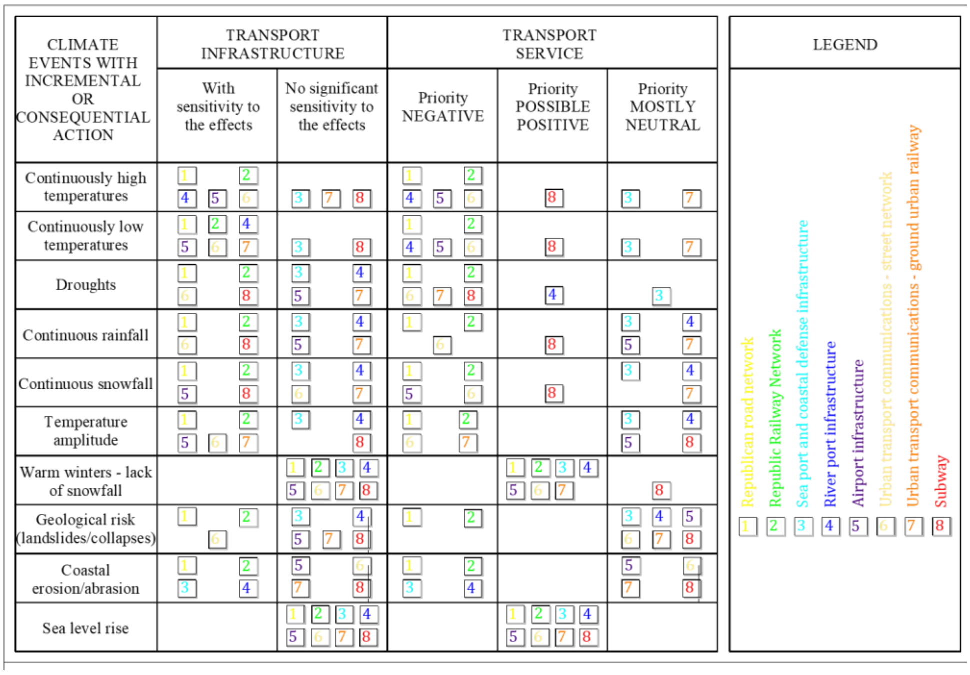

Fig. 3. Climatic impacts (secondary climate variable) on Bulgaria's transport infrastructure affected elements of the transport sector.

NOTE: The analysis is summarized for the types of transport infrastructure and the transport facilities to them in Figs. 2 and 3.

Extreme climatic events are mainly characterized by a level of stress, which is measured by the intensity and/or frequency of recurrence over time. Climate risks associated with lasting impacts can be assessed in the transport sector by determining average values to set a range of risks. Based on the type of impact, two classifications can be made: 1) with a gradual increase in pressure or with a sudden, stressful nature (Fig. 2), and 2) with a direct or secondary nature of the event (Figs. 2 and 3).

3.2 Summary of climate change impacts on transport infrastructure - data modification and optimization proposal

A comprehensive review of the operational processes in the transport infrastructure, as well as their interrelationship with the findings and recommendations in [4, 5], was made. The results have been restructured and illustrated in Figs. 2 and 3, which categorize the significance of different climatic events across key segments of Bulgaria's transport sector. These figures offer a clearer understanding of how climate change affects various components and propose enhancements to the data presented in [5].

4. RECOMMENDATION FOR A METHODOLOGICAL APPROACH TO BUILDING INSTITUTIONAL CAPACITY FOR CCA

This research recommendation is based on the fact that in [5], it is recommended to work in the direction of institutional connectivity and action on CCA. Unfortunately, due to the particularities of the management and significant deficiencies in the systems, it is impossible to directly apply experience to other European countries. On the other hand, this affects the feasibility of each measure and recommendation regarding the transport sector because it leads to regulatory documents that are not compatible. Thus, in practice, there is no unified system of legal and by-law standardization, which can be supplemented by CCA.

The lack of institutional capacity logically leads to the practical impossibility of adapting design, maintenance, and operation norms. The reason for this is the significant inconsistency in the implementation of the analyzed processes at the national level, where the compilation and publication of the documentation for investment projects is the responsibility of multiple institutions. In addition, the preparation of norms, regulations, and standards is assigned to completely independent technical (expert) commissions, which work without coordination among themselves. At the national level, there is no obligation or instructions according to which individual units are required to harmonize their legal acts in a single, common system. This leads to the inapplicability of many of the adaptation measures recommended in [5], which makes it difficult to introduce the principles of climate change adaptation (CCA) in these processes.

In conclusion [5], building adaptation capacity in the sector requires intensive work in two main directions: 1) data collection and 2) knowledge and capacity building. These two tasks necessitate the development of a package of adaptation measures [5] in the following four groups of activities:

4.1 Updating and supplementing design standards

As mentioned in part I of Annex 2 of [5], the design standards for transport infrastructure have been created with a significant level of conservatism. This approach ensures their reliability when it comes to meeting the specified design parameters under typical operating conditions. However, these norms often include internal regulations from individual agencies, which were created without the requirement to align with national standards and are now outdated in their core provisions. Additionally, the normative documents are often separate and independent, lacking integration into a cohesive system of rules, which complicates the implementation of comprehensive solutions to address climate change impacts on transport infrastructure and its associated risk components. To address these accumulated shortcomings, the adaptation of normative documents should focus on three key elements of the regulatory framework in Bulgaria, as illustrated in Fig. 4.

4.2 Optimization of project preparation procedures

As outlined in part II of Annex 2 of [5], it is essential to develop regulations, instructions, or guides that incorporate climate change considerations for different types of transport within the range of each investment project. This process should take advantage of advancements in climate models and database creation and archiving technologies [10-12], as depicted in Fig. 4.

4.3 Revise, enhance, and expand the standards for managing and maintaining operations

Figure 4 presents the essential first steps required to tackle the considerable delay in updating this type of documentation. These steps include reviewing, revising, and enhancing the standards and processes for managing and maintaining operations (part III of Annex 2 of [5]).

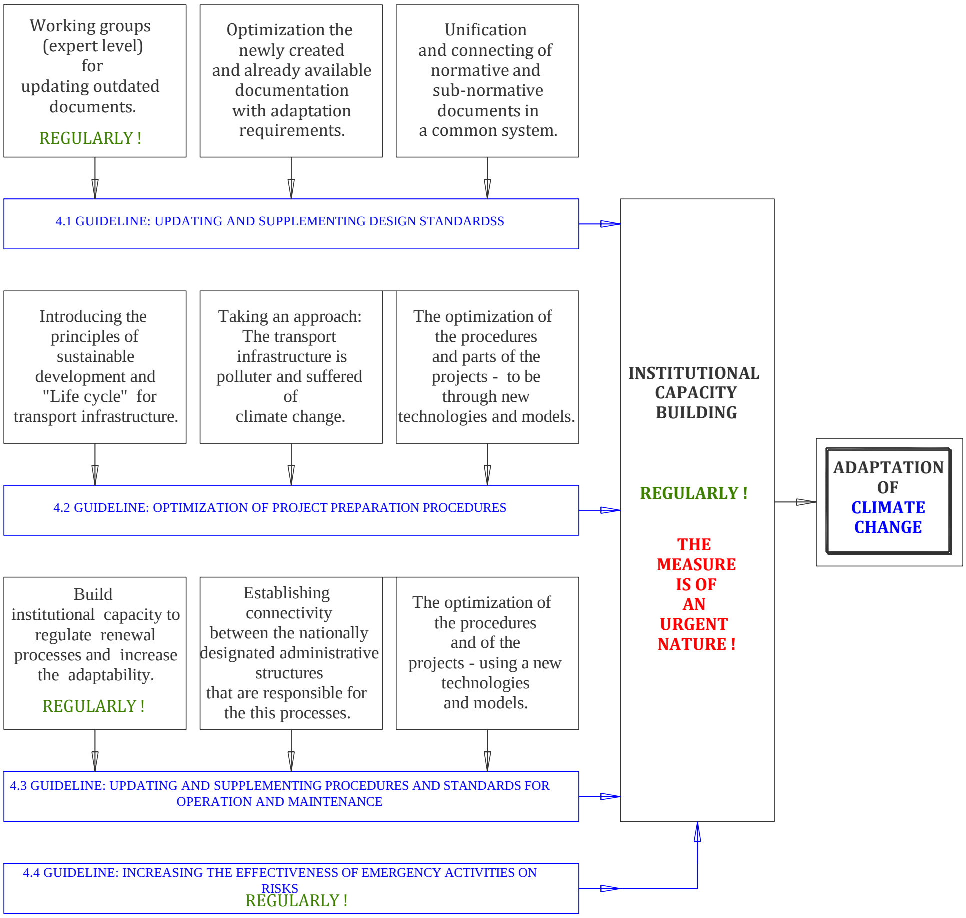

Fig. 4. A methodological approach to building institutional capacity.

4.4 Increasing the effectiveness of emergency procedures and activities

This task is described in (part IV of Annex 2 of [5]) and demands a strategic framework that includes a criticality assessment and the development of crisis management plans. These plans must account for the dynamic nature of climatic events such as floods, geological hazards, wildfires, heavy snowfalls, and other related risks.

To strengthen the effectiveness of risk prevention within the CCA framework, it is crucial to concentrate on two main areas: 1) defining the level of service and 2) addressing the aftermath of a crisis event. The recommendations for better managing transport infrastructure processes can be organized based on the stages of an emergency's progression through three key phases:

- Warning phase: During this phase, the emphasis should be on creating a real-time communication system to enhance the effectiveness of early warning mechanisms.
- Crisis phase: During this phase, the challenges of managing a crisis event impacting transport infrastructure are significant, often taking on a nationwide scope. Research conducted as part of the scientific project “Impact of Climate Change on Transport Infrastructure in Bulgaria – A Conceptual Approach to Assessing Potential Impacts on Sustainability and Safety in the Transport Sector” highlighted that poor communication and disconnected databases among institutions lead to significant discrepancies in the evaluation of the same event’s severity and risk level.
- Post-crisis recovery phase: In this final stage, institutional capacity must ensure the creation of a unified database that tracks the resources allocated and the specific areas within the transport sector that were affected.
- This approach not only emphasizes the importance of coordinated efforts across different phases of a crisis but also underlines the need for a cohesive and unified response system that can effectively manage and mitigate the impacts of climate-related events on transport infrastructure

5. CONCLUSIONS AND RECOMMENDATIONS FOR BUILDING INSTITUTIONAL CAPACITY AT THE CCA

Adaptive capacity is developed when institutions create environments that allow stakeholders to prepare for and adapt to the risks, changes, and impacts of climate processes. To achieve this, significant restructuring and reorganization within the “Transport” sector are necessary.

Targeted actions at both the national and regional levels are essential to enhance several key elements that will define institutional roles in adapting the transport service to climate change. The critical elements that need optimization include:

- Creation of specialized sub-sectors: These sub-sectors should have direct responsibility for implementing climate change adaptation (CCA) practices.
- Regulatory and administrative reform: Existing regulations and management documentation governing the sector must be thoroughly reviewed and updated to support the adaptation process.
- Prioritization of delayed programs: Units responsible for CCA initiatives must prioritize addressing the delays identified in the national adaptation documents from 2019 [4, 5].
- Resolution of inter-institutional challenges: This can be achieved by adopting a principle of collaborative action, which involves two key activity groups:
- First group—structural adjustments: This involves aligning the scope and responsibilities of institutional management within the “Transport” sector with national

legislative frameworks, ensuring that these connections are formalized through regulatory acts.

- Second group—enhancing digital integration: To facilitate collaboration between institutions, a high degree of digital transformation is required. Implementing digital platforms will create universally accessible portals and connectivity hubs, enabling seamless information sharing across all involved entities.

Additionally, the adaptation element ”Increasing awareness,” proposed in [5], needs to be redefined. The current emphasis on surveys should shift towards compiling foundational documents, conducting in-depth analysis, and more. This change will not only reflect the level of institutional awareness but also contribute to the overall strategy and coordination of actions among institutions rather than simply illustrating their existing level of awareness. The system must include the compilation of documentation with the possibility of applying the CCA, the implementation of maintenance and operation activities that are already linked to adaptive performance indicators, and the performance of activities in the event of emergencies that have real-time information, the ability to early warning and the responsible institutions coordinate their activities simultaneously in the stages of the emergency situation.

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