Climate change and its impact on long-term sustainability of the road infrastructure in Bulgaria

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Summary: *Climate changes are having an increasingly strong impact on the sustainability and safety of the road infrastructure in Bulgaria. This paper analyzes how changes in climatic conditions over the last three decades affect the condition and functioning of the road network. The aim is to identify critical factors and propose methodological guidelines for design and maintenance that include adaptive strategies to address climate risks. The work emphasizes the need for a complex multidisciplinary approach combining scientific research, strategic planning, and practical implementation.*

***Keywords**: CLIMATE CHANGE, ROAD INFRASTRUCTURE SUSTAINABILITY, LONG-TERM STRATEGIES, ROAD SAFETY, CLIMATE RISKS, MULTIDISCIPLINARY APPROACH, STRATEGIC PLANNING, ADAPTIVE MEASURES.*

1. Introduction

Climate changes are having an increasingly strong impact on the sustainability and safety of the road infrastructure in Bulgaria. The country is distinguished by specific geographical and climatic features – in a relatively small territory. There is a wide variety of relief, a wide temperature range, fluctuations in precipitation, and snow cover, which are essential factors for the operational efficiency of the road network.

In recent decades, the climatic conditions in Bulgaria have changed with great intensity [1]. This creates serious challenges for road infrastructure and requires new design and maintenance strategies. As climate change progresses, these challenges are expected to deepen and become more complex.

This article analyzes how changes in climatic conditions affect the condition and functioning of the road network in Bulgaria. The aim is to identify critical factors and propose methodological guidelines for design and maintenance that include adaptive strategies to address climate risks.

This analysis is conducted in the context of growing interest and concern for the future of the country's road infrastructure due to the need to adapt to the consequences of climate change. By bringing together scientific research, strategic planning, and practical implementation, it is possible to improve the resilience of the road network, reduce losses, and protect public safety.

2. Climatic changes in Bulgaria during the last three decades

The last three decades have seen a global increase in temperatures, which has significant consequences on various climate elements. They are discussed in detail in [1, 2]. Among these key changes are:

Increase in average temperature: In Bulgaria, as well as worldwide, the average annual temperature is increasing. This has important consequences for climate and the environment, including a greater frequency of extreme weather events. In places with a moderate continental climate, the increase in the average annual minimum temperature is about 1.1 ºC, and in the rest of the country – about 0.5 ºC [2]. Increases in minimum temperatures during the period 1991–2020 relative to 1961–1990 are greater in hilly regions compared to plains.

Seasonal changes: Climate change leads to shifting seasons and extended periods of extreme conditions. The biggest change is noticed in the summer, which is natural, while in the winter, the change is the smallest. The reasons for these seasonal changes are to be found mainly in the circulation conditions [3, 4]. In general, the summer is getting longer, and the winter season is getting shorter and warmer, which affects the snow cover and precipitation. In turn, less snowfall leads to a higher terrestrial albedo, which in turn leads to greater amounts of solar energy absorbed by the terrain, which is converted into heat and leads to an additional increase in surface air temperatures.

Intense rainfall and drought: In recent years, cases of intense rain in Bulgaria have become more frequent [5]. This happens most often in the summer period, but the cases of intense precipitation also begin to increase during the cold part of the year. They occur more often in the eastern half of the country and the southern regions. An increase in intense rainfall can lead to floods, landslides, collapses, and infrastructure damage. At the same time, prolonged periods of drought, especially in summer, and the reduction of water resources create a risk of fires.

3. Analysis of the impact of climate change on road infrastructure

Transport infrastructure and all modes of transport are vulnerable to climate change. The more important cases of sensitivity and the corresponding significance for road infrastructure can be summarized in the following cases:

3.1 Extremely high temperatures. Prolonged periods of high to peak temperatures

Among the environmental factors, the air temperature has the most significant influence on the temperature of the asphalt pavement. Positive temperature values affect the quality of the transport infrastructure and the service provided by it in three main cases – extreme values, a wide temperature range, and prolonged periods of high average day-night temperatures [6, 7]. Within these three groups, the following climate-induced risks for the transport system are distinguished for our country:

Influence of high temperatures on asphalt coatings:

• Temperature sensitivity of asphalt mixtures: Asphalt coatings are susceptible to temperature changes. At high temperatures, which can reach 70 ºC on the surface, standard (unmodified) asphalt coatings increase their plasticity (soften). This leads to a reduction in their carrying capacity and can lead to various types of damage, such as rutting, waves, shearing, and others.

• Modification of mixtures to improve their temperature characteristics: With additives in the composition of the asphalt mixture, the temperature of the surface can be lowered, usually in the range of about 60 ºC. This is also positive for the cases of prolonged periods with high average day-night temperatures, which prevents the asphalt concrete from cooling. However, this increases the cost of the material.

• Temperature amplitude and mechanical stresses: Large temperature amplitudes, especially when changing low – high-temperature values, can cause block, transverse, or longitudinal cracks due to mechanical stresses resulting from the expansion and contraction of asphalt concrete coatings.

• Solar radiation and albedo: Asphalt pavements have a low albedo and absorb much of the solar radiation. This further increases the temperature of the coating and can lead to the formation of ruts, waves, and other deformations.

• Specific cases such as airstrips: the same effects are observed on the asphalt pavements of airstrips for taxiing, where the conditions for load-bearing capacity and safety are even stricter.

Impact of high temperatures on railway infrastructure and surface urban rail tracks [8]:

• Thermal expansion of rails: At high temperatures, rails can expand to impede the movement of rolling stock. This may cause traffic to stop or reduce mileage.

• Overheating of cables: High temperatures can cause catenary cables to overheat, which can interrupt rail traffic or reduce running speeds.

• Temperature amplitude: The thermal gaps of the long-welded rails track are sensitive to the variation of the temperature range, which leads to tension/pressure in the track and is directly related to its normal and safe operation.

Effect of high temperatures on fire risk:

• Correlation with periods of drought: High temperatures often coincide with periods of drought, leading to increased fire risk. They can have a destructive impact on road infrastructure, including asphalt surfaces, curb systems, and road bodies.

• Impact on structural elements: Fires can cause severe damage to some structural elements of the road structure, road accessories, and facilities such as bridges, tunnels, etc. This could lead to temporary or long-term closure of key transport routes.

• Safety and traffic issues: Fires and smoke can reduce visibility and create hazardous driving conditions. This can increase accidents, traffic disruptions, and even human casualties.

• Erosion and geological risks: Periods of drought and high temperatures can activate processes of destruction in the soil massifs, which become more susceptible to wind and precipitation erosion. This can create additional geological risks, such as landslides, rockslides, and road closures.

3.2 Rainfall, storms, and rainfall-type floods.

In a changing climate, precipitation and water conditions pose a significant risk to transport infrastructure, affecting its sustainability, safety, and functionality.

Floods and water quantities:

• Floods with a priority precipitation nature can cause flooding of various sections of the transport infrastructure.

• Flooding and undermining of bridge facilities, which can lead to the direct destruction of the substructure bridge, in which the superstructure is also compromised. Complete destruction of the bridges is also possible.

Waterlogged soil from the terrestrial body:

• The primary source of waterlogging is surface water, which can cause loss compaction, undermining, transport of particles, displacements of layers, and destruction of slopes during excavations and embankments.

• In second place are underground waters, which move along a capillary path and form wetlands and transfer particles, which also leads to deformations in them and damage to pavements, unevenness, and network-like cracks.

Hydraulic capacity and drainage systems:

• Exceeding the hydraulic capacity of drainage and small facilities (type culverts) on roads and railways.

• Overloading drainage systems in urbanized areas is especially important for the traction of pavements and the safety of car traffic.

Surface conditions and safety:

• Retention of a thick film of water on pavements can cause loss of traction and cases of aquaplaning.

• During rain, storms, and hail, visibility is impaired, which disrupts the continuity and safety of traffic.

Erosion and geological risks:

• Intensification of erosion processes, especially rain and wind erosion, in various parts of the transport infrastructure.

• Increasing the degree of geological risk, such as landslides and rockslides, especially at high wind speeds or after prolonged periods of drought.

Additional factors:

• Water retention: Water retention in road pavement cracks, which freezes and expands as temperatures drop.

• Groundwater: Prolonged retention of high groundwater levels can compromise the structural linings of underground facilities such as tunnels and subways.

3.3 Extremely low temperatures, prolonged colds with low temperatures, temperature amplitudes

The tendency is for extremely cold days (so-called "ice days") to decrease in Bulgaria. However, climate change can lead to disturbances in atmospheric conditions, resulting in extremely low temperatures in limited areas. For this reason, adaptation to climate change must necessarily include measures aimed at the consequences of very low temperatures:

Impact on road structures:

• Extremely low temperatures: In addition to the deterioration of bitumen elasticity, low temperatures presuppose the appearance of cracks and freezing of water in already existing cracks.

• Temperature cracks: With sudden temperature drops, frozen areas form in the earth's body, and temperature cracks, holes, and pits can form in the coating.

Impact on road safety:

• Black ice: Formed by a combination of low temperatures and fog and is a road safety risk.

• Icy sections: Reduced traction and increased risk to road safety.

• Freezing rain: Leads to the formation of an icy surface on road surfaces, creating a risk to road safety and infrastructure damage.

Impact on railway infrastructure [8]:

• Catenary icing: Causes problems in electrified railway lines.

• Device freeze: railroad switch (cross, connection, the combination of cross and connect) are sensitive to freeze.

Impact on bridges and other facilities:

• Water freezing in drainage elements: This may cause damage to load-bearing and non-load-bearing parts.

• Corrosion from anti-icing ingredients: This is especially risky in the presence of shortened drainage pipes and wind.

• Icing of facilities with steel structural elements.

Impact on harbors and fencing facilities:

• Icing of structures: This can lead to critical infrastructure conditions, especially in bulk breakwaters.

Additional risks:

• Retention of water in cracks in reinforced concrete and asphalt concrete elements: When temperatures drop, water freezes and widens the cracks and increases the degree of damage.

3.4 Precipitation, storms, and rainfall-type floods.

In the conditions of variable climatic factors, rainfall, storms, and rainfall-type floods pose a significant risk to transport infrastructure, affecting safety and traffic continuity.

Accumulation of snow and its consequences

• Accumulation of snow on road surfaces: During winter maintenance, it is a problem because it requires repeated regular snow removal.

• Reduced visibility during heavy snowfall: This leads to problems with transport safety and traffic continuity.

• High-speed snow drifts: This is especially problematic for roads and railways due to the deposition of large amounts of snow and the suspension of snow removal.

Influence of precipitation and wind

• Reduced visibility during heavy precipitation (snowfall): A significant risk factor in transport safety, with a priority impact on the national road network (RPM).

• Snowdrifts in stormy winds and heavy snowfall: This combination leads to significant problems with safety and traffic continuity. Road infrastructure is susceptible to these conditions.

3.5 Water level rise. Wind wave effect.

In the conditions of sea level rise, coastal transport, and port infrastructures are exposed to severe risks:

• Destruction of coastal transport infrastructure and port and coastal defense infrastructure in the presence of high water levels or wave impact. The slopes of the coastal areas are most at risk from the intensification of the erosion processes and the entire port and coastal protection infrastructure from the wave impact.

• Destruction of coastal transport infrastructure as a result of waves or combined with rain erosion of the coastline.

3.6 Other impacts with local relevance to serviceability and traffic – fog, high humidity levels, and others.

Other impacts with local relevance to serviceability and traffic include meteorological factors such as fog and high humidity levels. Fog significantly reduces visibility on the road, which can slow down traffic and increase the risk of road traffic accidents. High humidity levels can deteriorate the adhesion between the road surface and vehicle tires, cause corrosion of the steel elements of the transport infrastructure, cause deformations in the wooden sleepers of the railway superstructure, and others. These factors require special maintenance and monitoring measures to ensure the safety and efficiency of the transport system.

4. Methodological guidelines for design and maintenance

4.1 Adaptive strategies to deal with climate risks

Adaptive strategies to address climate risks in road infrastructure are vital to ensure the safety, resilience, and efficiency of transport systems in a changing climate. Here are some potential strategies that could be implemented in the coming years:

Sustainable design and construction

This includes developing sustainable and adaptive road infrastructure designs that consider climate change and extreme weather conditions. When designing, the use of materials that are resistant to climatic influences such as high temperatures, floods, and freezing should be foreseen.

Technological innovations

These could include the integration of Intelligent Transportation Systems (ITS) [9, 10], which offer real-time traffic monitoring and management, as well as warnings of hazardous conditions. This necessitates the application of weather forecasting and monitoring technologies to help respond quickly to extreme weather conditions [11]. Artificial Neural Networks (ANN) and Artificial Intelligence (AI) [12], often combined with the Internet of Things (IoT), are essential to adaptive strategies against climate risks. They help in the analysis and forecasting of climatic conditions, as well as in the automation of responses to extreme events. IoT sensors monitor parameters in real-time, while AI analyzes the data for quick response and warning.

Improved planning and management

This group includes developing risk management plans and emergency plans to address potential climate threats and ensure a rapid and effective response. This means the need to regularly reassess and update climate risk management plans and strategies based on new data and research.

A typical example of key risks is fires and floods, for which it is necessary to define safety measures and adaptation strategies, which include both technological and organizational measures for their prevention and combating them. This may include optimization of materials and methods, early warning systems, and staff training.

Training and awareness-raising

In this regard, training and awareness-raising campaigns among the public and key stakeholders on the impact of climate change on road infrastructure are envisaged, including cooperation with local, national, and international organizations to share knowledge and resources.

Funding and Investments

Adaptation requires providing adequate funding and investment to improve the sustainability of road infrastructure and to develop new technologies.

Legislative framework

All of the above strategies require the development of legislation and regulations to support the sustainable development and adaptation of road infrastructure to climate change.

These strategies can be implemented through a coordinated effort between various stakeholders, including government bodies, local communities, industry, and the scientific community.

4.2 Integrating climate resilience into infrastructure projects

Integrating climate resilience into infrastructure projects requires a holistic approach that covers every stage of road infrastructure design and construction. This can be done as follows:

Advance planning and analysis

It is necessary to start with detailed climate risk analyses and vulnerability assessments to understand how climate change may affect the project, considering different climate scenarios and predicting possible impacts on infrastructure.

Conceptual and detailed design

Climate resilience measures should be integrated in the initial stages of design, considering future climate projections. This also includes the choice of materials and construction solutions resistant to extreme weather conditions.

Construction

In the construction phase, sustainable construction practices and materials should be used that reduce the impact on the environment and increase the project's resilience to climate risks. At the same time, risk management strategies must be implemented during construction to prevent or minimize damage from extreme weather events.

Monitoring and evaluation

It is important to verify the conformity of the predicted behavior and state of the infrastructure and its actual state during operation. This requires the development and implementation of plans to monitor and assess the climate resilience of the project after its construction, followed by the collection and analysis of data on the actual behavior of the infrastructure in response to climate conditions and the use of this information to improve future projects.

Support and management

During operation, it is essential to implement a maintenance and management plan that includes measures to maintain climate resilience long-term. This plan should be continuously updated based on new information on climate change and best practices.

By integrating these and other measures at every stage of design and construction, it can be ensured that road infrastructure can withstand the challenges of climate change and continue to serve society efficiently and safely.

4.3 Opportunities to optimize support

Optimizing road infrastructure maintenance is critical to improving resilience, reducing costs, and increasing road safety. One of the key opportunities for optimization is the introduction of Intelligent Transport Systems (ITS), which provide automated solutions for traffic management, road surface condition monitoring, and real-time incident response. Innovations in materials also offer opportunities to improve the durability and resilience of road surfaces by using durable and high-performance materials that reduce the need for frequent repairs. Also, precise data from satellite and drone technologies can support the effective planning and execution of maintenance operations by providing accurate information on the condition of the infrastructure in real-time.

Another aspect of optimization is the development of effective maintenance strategies and procedures based on best practices and data analysis. An example is the application of preventive condition monitoring to identify and fix problems before they lead to severe damage or costly repairs. Integrating information and communication technologies [12] can improve coordination and communication between different units in the maintenance process and facilitate rapid response to incidents.

5. Complex and multidisciplinary approach

5.1 The importance of research and monitoring

A comprehensive and multidisciplinary approach is key to understanding and addressing the impact of climate change on road infrastructure. Scientific research plays a significant role in providing the necessary knowledge about how climate factors affect infrastructure systems, including the materials and structures most resistant to these conditions. The multidisciplinary nature of the research allows analysis of various aspects of road infrastructure, from geotechnical and material issues to traffic planning and management.

Systematic monitoring is another critical element in this comprehensive approach. Continuous monitoring and collecting real-time climate data allows engineers and governing bodies to monitor climate change and its impacts on infrastructure. This monitoring includes monitoring of atmospheric conditions, road surface conditions, and traffic. Collected data is analyzed to identify trends, predict future problems, and develop adaptation strategies, which provides a science-based basis for decision-making and rapid response to changing conditions.

5.2 The role of strategic planning and management

Strategic planning and management play a central role in adapting road infrastructure to climate change.

Strategic planning is crucial to the adaptation of road infrastructure to climate change. It helps to define long-term goals and priorities, as well as to develop a concrete framework for action. In this context, an analysis of potential risks and opportunities, as well as the necessary resources for successful adaptation, is carried out.

Strategic management allows effective coordination of the adaptation process. It includes coordination between different stakeholders, management of resources, and monitoring of progress. Ensures that decisions are scientifically sound and conform to established policies and regulations.

Strategic planning and management support a cycle of continuous learning and improvement. Through periodic reviews and evaluations, successful practices and improvement areas are identified. This allows the adaptation of strategies in response to new information or changing conditions.

6. Conclusions

In the conditions of the climate trends, the road infrastructure in Bulgaria faces several challenges, and in the future, this process will deepen. Climate change leads to adverse climatic consequences that make traffic difficult and increase the risk of accidents. Adapting these changes using research and monitoring is essential to improve knowledge of these risks and develop effective strategies to address them.

Adaptability and innovation are critical to improving the sustainability of road infrastructure. Preventive maintenance, intelligent transport systems, and new materials and technologies can help reduce the impact of climate change. Flexibility in strategic planning and management is also essential, as it allows organizations to respond quickly to changing conditions and improve their practices based on new scientific discoveries and technological innovations.

Success in climate change adaptation requires collaboration between the scientific community, industry, and the public sector, which can accelerate the development and deployment of innovative solutions and improve coordination and resource planning in response to climate challenges. Sharing knowledge and experience between different sectors can help create a resilient infrastructure that can cope with future climate change. These findings highlight the importance of an integrated approach to climate change adaptation and innovation in infrastructure projects in Bulgaria to ensure the long-term sustainability and safety of the road network.

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