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Climate Resilient Road Infrastructure: A Review on Adaptation Strategies and Innovation

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Abstract- *Climate change is one of the challenges that must consider the road infrastructure, with gradual changes and innovations to make the road infrastructure more resilient. The unhealthy weather conditions, heatwaves and other changes in precipitation patterns contribute to structural and functional breakdown of transport networks. There should thus be greater resilient road infrastructure installed to provide serviceability in the long term and to provide some degree of resilience to disturbance which would destabilise connectivity and economic stability.*

The combination of enhanced material, excellent structures, and the adoption of green infrastructure is usually an adaptive intervention to resilient infrastructure. Climatic variability pavement can withstand the weather fluctuation that includes low and high temperatures, poor rainfall, and floods. On the same note, proper structural designs will minimize the vulnerability to erosion and washouts. The nature-based and hybrid ones, including bioswales and permeable pavements, play a central role in the stormwater runoff management and mitigation of flood damages, besides providing environmental co-benefits. Another important climate-resilient infrastructure driver is innovation. Polymer-based pavement foundations have also been developed as a high-performance material, being more stable at the repetitive stress pulse condition to minimize the chances of rutting and cracking. Predictive modeling and geospatial intervention analysis can also use predictive analytics to help the decision-makers with the identification of the at-risk locations and prioritization. As digital technologies such as artificial intelligence (AI) and the Internet of Things (IoT) have been introduced, the infrastructure operations and maintenance can be conducted in real-time more, which, in turn, will allow the systems to anticipate and act in response to environmental stress factors before they lead to failures. Those innovations need cross-sectoral cooperation, governance frameworks, and structures to work and a scale. The issue of sustainable practices should be incorporated in the systems of national and regional planning so that the process of climate adjustment becomes systematic instead of reactive. The administrations overseeing roads in the European context have recognized the importance of having an international partnership to complement the adaptation efforts. Comparing policy studies of the different areas of jurisdiction can give information on the best practices, and cities and communities can get to know how to construct more adaptable and economically viable built-in infrastructures. The identification of the threshold beyond which the adaptation processes will be cost-effective to guarantee resilience investments will bring socio-economic benefits in the long term is made possible by the risk, cost, and benefit estimation of the adaptation strategies.

Keywords- Climate resilience, Road infrastructure, Adaptation strategies, Sustainable materials, Nature-based solutions, Climate change impacts, Infrastructure innovation.

1. INTRODUCTION

The road network is increasingly vulnerable to a number of climatic risks like heavy rain, flooding, rising of sea levels, and overheating that have the ability to transform climatic signals into engineering, operational, and economic problems. The intense precipitation and pluvial flooding are already more than the drainage systems, which are historically developed, physically crippled, such that they require additional maintenance and more frequent service failure [1; 2]. Cities are very susceptible particularly factoring in the fact that more urbanization means a greater severity and rate of run off and consequently, the possibilities of run off flooding of the streets and tunnels are heightened [2].

There is the compounded risk of eroding pavements, bridges, and rail tracks, growing tidal water, and other causes of sub ground erosion and salinization of groundwater effects, which may not become evident until the appearance of surface flooding [2; 3].

These risks are expected to grow, in the case of climate change and the cost of maintenance, repairing of assets, and connecting failure in the low areas and coastal areas are significant consequences [3; 4]. Prescriptive adaptation strategies such as redesign of design criteria, and enhancements in drainage capacity, and incorporation of climatic predictions in the planning process have been found to save on long-term costs and enhance resilience [1; 4].

By so doing, the risk of climate change needs to be considered during the planning and management of road infrastructure to ensure the survival of significant assets and also the capacity of transport infrastructure to endure in a shifting climate [1; 2]. The excessive temperatures also strain the performance of roads and pavement further in that they elevate the temperatures of surfaces and under-surfaces, which enhance wear and tear. Research has found that extreme heat and regular heat waves have a tendency to increase the stress of the concrete pavements that are also prone to more regular cracking, slab curling, and joint distress, particularly those that are pavements, which are thicker in nature [5].

Surface deformation and rutting have a close relation with heat waves on the pavements that are flexible (asphalt).

It is demonstrated that, rutting performance can decrease up to 18.8 percent regarding the kind of subgrade, and that this can be in part recovered by increasing asphalt thickness [6; 7].

Mitigation measures aimed at helping reduce pavement temperature and sustainability using high albedo, thermal emissivity, reflective surface, vegetative cover, water-absorbing material, and new cooling techniques all prevent pavement temperature in high temperature [8; 9]. It has been demonstrated using simulations and lab experiments that alternative materials such as light concrete blocks, grassed surfaces, and porous pavement can significantly reduce surface temperatures and are able to provide thermal comfort even better than traditional asphalt [10; 11].

These results highlight the importance of revising the pavement design and maintenance standards to capture extreme temperatures, like the use of cool pavement technology, to allow the delivery of climate-resilient and sustainable transport infrastructure [12].

Recent studies have revealed that a large proportion of road and rail networks is already being run to or near thermal limits, and temperature-induced stressors have been found to be a serious concern to the functioning and wellbeing of the infrastructure. These alterations in the ambient temperatures could result in severe deviations and deflections in the suspension bridges, particularly in the rail networks, and consequently, increase the safety risk and the maintenance needs [13]. The high temperature conditions that occur over time enhance the likelihood of rutting of pavements and buckling of rail tracks, which led to the rise of the operation and maintenance costs in a warming climate [14]. Extreme heat events and freeze-thaw cycles are spreading at an accelerated rate worldwide and this undermines the security and maintainability of transport infrastructure and highlights the urgency of the climate adaptation interventions [15].

One of the mitigation pathways of such risks, which may be used to reduce the risk of track buckling, explosive rail fractures, and structural damages at high-risk points of contact, is through thermal surveillance and incremental repair [16; 17]. Quality can be enhanced with the help of surveillance technology, including thermal imaging, and the vulnerable areas can be identified, and the maintenance efforts may be concentrated on areas affected by high temperature exposure [17]. Besides monitoring, the transport systems are supposed to be furnished with resilience models and dynamic solutions that consider the long-term trends of warming [18; 19].

The existence of freeze thaw cycles at elevation and high latitudes only exacerbates the situation as concrete and soil deteriorate rapidly. Constant freezing and thawing lead to micro-cracking, high porosity, mass and mechanical properties loss of concrete. The interfaces between soil and clinker, which form embankments, tunnels, and foundations in permafrost and seasonally frozen locations, also become less stable by such processes [20; 21; 22; 23]. The extent of the damage is determined by the pore structure, ratio of water to cement, the initial moisture levels, and the freeze-thaw process improves both macro and micro scale damages [24; 25]. In one case, the temperature cycling can increase the dynamic modulus and compressive strength losses by 3.7 and 1.8 times, respectively, in comparison to the thermal cycle alone [20]. Such processes will lead to shorter life cycles of assets, excessive costs, and less capacity of repair, unless there are substantial changes in the infrastructural design and maintenance regimes [26; 27; 23]. The freeze-thaw losses are therefore important to minimize using optimization plans, which involve, but are not limited to, proper selection of materials, groundwater control, and multi-scale modeling [21; 23].

Flood risk, which has numerous scales and produces the chain effects on the infrastructure and the economies, is another serious challenge. Examples of these topics can be extreme riverine overflows and tropical cyclones, which can lead to overtopping and scouring at the level of the corridor, making major transport corridors temporarily unavailable over an extended period. Even localized failures will propagate wide extending delays and financial losses with the point of initially occurring disruption [28; 29]. Multi-hazard analysis, global asset estimates of road and rail infrastructure show that a quarter of assets are vulnerable to at least one hazard, and 7.5 percent of that figure to a 1-in-100-year flood event. The world has estimated the damages of USD 3.122 billion per year in cases of surface and river flooding, and in certain countries, the damages have been expensive to the point of about 1 per cent of the GDP per annum- illustrating the magnitude of the threat of floods on transport infrastructure [30].

Rise in sea level also exposes transport corridors, ports, and other economically important nodes on the coast to long-term tidal flooding and erosion as a result of storms. The demands are increasing in the adaptation measures, which extend to protection and elevation, to controlled realignment [30]. Investigative modeling has been shown to be an experimental evidence of the sensitivity of road networks to localized floods, and the resilience of these systems can be imposed by careful response and risk-conscious planning to achieve more resilient systems [28; 31].

Unless it is properly adapted, the harm that climate change inflicts will only increase at a disproportionately faster rate annually, and road and rail networks all around the globe will become increasingly susceptible to disconnection and disruption [30]. Transportation has remained one of the largest sources of greenhouse gases (GHG) emissions, with some estimates of the specific industry contributing 15-26 per cent of all emissions in the world with over three-quarters of the total transport CO_2 emissions being ascribed to road transport. Passenger cars and freight trucks constitute the biggest part of this effect [32; 33]. Unless there is a serious response to dealing with emissions through vehicle electrification, low-carbon fuel, demand management, and improved logistics, road transport will continue to augment climate change. This, in its turn, reinforces the same dangers that disrupt the transport infrastructure, which, in this case, the limited budgets and the insufficiency of planning powers have a harmful impact on the development of resilient transport systems in a vicious cycle [2; 15; 32; 34].

The current policy interventions are not strict enough to see to it that deep mitigation objectives are achieved. Integrated solutions will be required to realize successful industry decarbonisation, together with climate resilience, including the blend of strict regulations, market-based mechanisms, and clean infrastructure investments [2; 15; 33; 35]. To this end, road assets need to be designed and maintained in a climate-resilient manner and transport mitigation processes enhanced [2; 15; 34].

Some evidence exists that the economic effects of investment in robust infrastructure are significant in the long run. The initial costs of resilience are often dwarfed by the disruption of service and the cascading costs resulting from the fluctuating infrastructure. It has been shown that investments made proactively and strategically are more productive, in returns per dollar invested, than reactive investments, particularly in low- and middle-income countries, and are seen to include: increasing roadbed gradients, increasing culvert cross-sections, and using quality materials [36; 37; 38]. The cost-benefit analysis and scenario planning always point to the fact that resilience reduces the losses and enhances the capacity of recovery following the hazards; hence, resilience is an essential component of the risk-based and cost-effective strategies [38].

Long-term socio-economic losses due to the infrastructural crashes resulting from natural hazards are typically much larger in the long-run than the costs of implementing resilience during the design and maintenance stages.

This element of resilience will secure economic development, predictability of service delivery as well as stabilization of livelihoods during climate-related risks [37]. Consequently, to make sure the policymakers and the stakeholders are guided towards sustainable and climate-protected infrastructure investments, rigorous economic analysis is required to protect the communities, as well as the national economies [36].

Figure 1. Integrated Strategies for Climate-Resilient Infrastructure

1.1 Standards and Design

Infrastructure planning to mitigate climate risks needs to go against depending on old climatic data since traditional and past methods are becoming less sufficient in the environments of changing environmental loads and occurrence of more extreme cases [39; 40]. Design requirements of the future should include revised climate forecasts, such as intensity-duration-frequency (IDF) curve, storm surge, sea-level rise allowance, and recalibrated design temperature. This is necessary to make sure that there is resilience and safety during the service life of infrastructure systems [41; 42]. It is also important for material selection. Climate-resilient design in the future must focus on alternatives that are more resistant to changes in thermal and environmental conditions. Contrary to the traditional construction materials (TCMs) that cannot easily be modified to suit new climate conditions, new materials can provide better long-term performance to their changing climatic stress conditions [39].

It is also important to include decision-making frameworks that address deep uncertainty, such as adaptive management and scenario-based planning. Experience from the United States and Europe shows that regulatory frameworks must change alongside advances in climate forecasting. These changes inform how we plan infrastructure, manage assets, and execute projects [42; 43].

These approaches collectively underscore the central argument: infrastructure design must prioritize climate resilience, adaptation, and risk-informed decision-making. Integrating these principles into planning enhances safety, extends functionality, and supports long-term performance as climate risks intensify [39; 44; 40].

1.2 Drainage and Hydrology

The historical rainfall patterns and design flows on which the classical tradition of drainage planning was founded are no longer sufficient in the conditions of climate change. Current drainage systems, initially developed under these obsolete principles, should thus be reformulated and modified to reflect the project increases in the maximum flows and changes in the rainfall variability [15; 45; 46]. Based on recent research, this approach is critical so that drivers of a compound climate impact, including floods due to integrated fluvial, coastal, and pluvial actions, can be considered. The change is needed to facilitate a powerful and visionary infrastructure planning [45; 47]. In turn, uncertainties in climatic and hydrological models have become prominent in optimization techniques.

Most notably, scenario-based and staged solutions have come to be considered as effective but cost-efficient, flexible, and reliable strategies to enhance urban and road drainage networks in changing climatic conditions [48; 49].

1.3 Coastal Protection and Alignment

The hierarchical process of defense, adaptation, re-adaptation, or re-adaptation of the coastal infrastructure has been much thought about with the increasing risks and threats of rising sea-levels and permanent inundation. Sea walls and storm surge barriers are hard infrastructure measures that continue to be core protection measures. Meanwhile, nature-based interventions, such as dune reassertion and mangrove revival, are also becoming more accepted as facets of resilience. Alternatives to conventional defenses are also being considered in those places where they might not be feasible or expensive, like raising roadbeds and junction points [50; 51; 52].

Hybrid and adaptive solutions are on the way as viable alternatives that can strike a balance between the technical viability and environmental and social concerns. The decision between or a combination of hard and nature-based strategies can be based on the local geomorphological situation and importance of the infrastructure at risk [53; 54; 51]. In the case of coastal cities, road and trade infrastructure have to change to accommodate the increased chronic flooding risks that come with climate change [50; 55].

Academic opinions also support the significance of the integration of green and grey infrastructure with participatory and scenario-driven governance and planning with the aim of achieving resilience [53; 51].

Finally, successful adaptation must be seen as a dynamic and changing process, influenced by the timing of threats and the needs and priorities of the stakeholders [53; 52; 51].

1.4 Operations and Maintenance

Climate-resilient infrastructure operational planning, especially during its implementation after natural disasters like floods or heat waves, must include climate-sensitive inspection periods aimed at finding and removing weak points in a prioritized manner [56; 57]. Post-event testing ought not to only focus on bridge scour reviews but should also incorporate a set of additional tests with the ability to reduce risks and maintain services continuity when climatic conditions shift [56; 57; 58].

Another important step in controlling climate risks outside the scope of immediate safety issues or structural damage is operational changes like the temporary imposition of speed or weight limits in adverse weather [56; 57]. Also, real-time traveller information systems are resilient since they can deliver a dynamic response to extreme weather conditions in order to reduce the cost of disruption and enhance the safety of the population [56].

On a larger scale, resilient and flexible infrastructure should also be in a position to respond to information on climate-related data, handle uncertainties, and coordinate well with various stakeholders. This type of flexibility is critical to ensuring stable performance in a wide range of climatic risks [56; 57; 59]. Taken together, these steps lead to the shift towards more climate-adaptive and resilient infrastructure operations.

1.5 Governance and Finance

To achieve long-term sustainability and minimized risk, the resilience-oriented infrastructure planning will need to be incorporated into the governance and funding policies. By instilling resilience into the structures of governance, a system of infrastructure ensures that the systems achieve not only the objective of sustainability, but also acquire adaptive, collaborative, and redundant attributes that increase the institutional capacity to absorb shocks [37; 60]. Under some circumstances, investments in resilience at the upfront level can be rationalized when the program-level evaluations of the costs avoided by users, the reliability of the supply chain, and the cost-effectiveness of resilience entry into the new and existing infrastructure are the lifecycle cost analyses [37; 61]. International measures and standards also underline the fact that resilience investments give significant socio-economic returns in the long run, especially when realized at the early phases of project development [61].

Material financing policies also entail that there must be a balance of governmental and non-governmental funds to make sure that it is in tandem with other climate and development agendas. This is possible by applying new financing mechanisms like the public-private partnership, coupled with pledges of transparency and explicit sharing of risks and rewards in the financial markets [61; 62; 63; 64]. However, there are still barriers like political recalcitrance, insufficient funding, and a small-mindedness in the way planning is done.

These impediments are, however, mitigable by applying good governance practices, open procurement systems, and involving policy holders in consultations to enhance institutional and financial stability [37; 65].

2. CLIMATE CHANGE IMPACTS ON ROAD INFRASTRUCTURE

A strategy to adapt to climate change in the road transport sector involves the organizational, engineering, and nature-based measures geared towards reducing the negative effects of extreme weather events. Strategic interventions, such as conducting vulnerability assessment, integrating resilience of infrastructures into strategic pre-disaster planning, hardening material, improving drainage system, and providing timely maintenance, among others, should be considered as part of short-term measures [2; 66; 67; 68].
In addition to these short-term steps, an emerging research base also emphasizes the importance of a hybrid adaptive approach involving integrating technological interventions with nature-based interventions. These strategies are based on green infrastructure and are now also being considered as economical ways to provide resilience to the road network [2; 69]. Nevertheless, such solutions can only be successfully implemented with the assistance of favorable policy frameworks, collaboration among stakeholders, and long-term investment to help them become a part of the planning and decision-making process [70; 71].
These advances notwithstanding, there are large gaps in knowledge. Current practices should be further analyzed, and the emerging technologies should be researched as a way of enhancing the evidence base of effective adaptation. Besides, as the urban centers continue to grow, there is a high level of urgency to harmonize road infrastructure adaptation plans with the entire city development and sustainability strategies [2; 71].

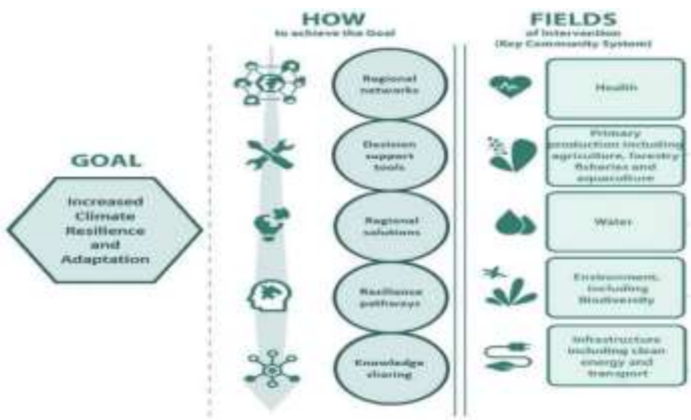

Figure 2. Conceptual framework of climate-resilient road infrastructure

Climate change is a set of numerous interacting physical processes whose action sites, both in time and space, are diverse. This is essential to understanding the pathways and hence engineering/policy interventions, which respond to the root causes of infrastructure, collapse, but not the symptoms.

2.1 Thermal Stress Mechanisms

The effects of rising temperature on road infrastructure are numerous and interdependent, with many having the potential to undermine structural integrity. Extended periods of high temperatures cause asphalt binders in bare pavements to become soft and thus more prone to rutting, creep, and irreversible damage in times of extreme heat conditions [14; 72]. High temperatures also enhance oxidative ageing in asphalt binders, which results in embrittlement and an increased vulnerability to cracking throughout the lifetime of pavement [73].
Moreover, the changes in temperature cause internal stresses in pavement structures, which also cause fatigue failures, especially in areas with large temperature ranges and severe thermal variations [73; 74].
Diffusivity, emissivity, and conductivity of pavement materials are important factors that determine the heat transfer and storage between the pavement surface and the surrounding environment and hence affect the performance of pavement and the local climate [75]. The temperature variations and effects of urban heat islands further increase the rate of pavement deterioration, particularly in concrete roads, by enhancing the strength of internal stress and cracking caused by shear [73; 75].
These results support the importance of improving the thermal performance of road infrastructure in warmer climate by utilizing new materials, climate-sensitive engineering designs, as well as design-based techniques that reduce heat-related degradation [72; 74].

2.2 Moisture-Related Deterioration

Differences experienced in the amount and distribution of rainfall during the year pose severe threats to the road infrastructure, mainly by washing away the soils that destabilize the structures. These effects are commonly magnified by large scale drainage, which creates an overflow, water stagnation, cross-layered seepage, and pavement material cracking. These processes may hasten surface failure, rutting, and eventually, deterioration of road systems [76; 77]. Besides this, landslides and debris flow in neighboring localities may cause a few centimetres of irreversible damage to road networks. Such damage in the majority of cases cannot be dealt with as part of the routine maintenance and involves a long-term recovery or a total reconstruction of the damaged areas [78;79].
Vulnerability mechanisms warranting consideration and explanation are the degradation of bearing strength and aggregate bonds, as well as repeated water intrusion of pavement subgrades during extreme weather events [76; 80]. Very long-term stability of the soils and ground conditions is a key factor in the infrastructure performance due to the hydraulic processes that most of the materials that are used underground experience several decades after they are initially dehydrated [80]. In order to reduce these risks, studies show that it is essential to enhance the design of drainage, create finishes with high levels of waterproofing, and create a proactive maintenance system. These could be helpful in making road networks much more efficient and resilient to variable and extreme weather conditions [77; 81].

2.3 Freeze-Thaw and Permafrost Dynamics

Permafrost thaw and freeze-thaw cycles are one of the problems common in the road infrastructure of cold sub-regions, and climate change exacerbates the problem as well. The consequences of thermokarst, mass wasting, and increasing instabilities of sites on the ground by increasing temperature affect infrastructure on the large-scale level, as 30 50 percent of critical circumpolar infrastructure might be affected by 2050, and effects of up to 30 percent of surface damage to roads in some regions of the Arctic are already being experienced as a direct consequence of increasing degradation of permafrost [82]. Even the existence of infrastructure could lead to higher thawing of permafrost as a result of higher heat flow, snow cover, and ponding processes, although the processes of gradual thawing is lost and bare ground destabilizes quickly within the road service life [82].
Frost heave and thaw settlement also occur due to freeze-thaw cycles and form uneven road surfaces with increased maintenance needs based on the local soil, moisture, and temperature [83; 84; 85]. They are among the most prevalent causes of road damage in seasonally frozen soil areas and are conditioned by the local weather and environmental conditions [83; 86]. This inherent vacuity of the traditional pavement design practices to over-optimize past assumptions on the forecasts of the future climate and mitigation techniques like convection embankments, thermosyphons, geosynthetic, and improved materials is why it is so essential to have new analytical frameworks which incorporate both future weather forecasts and mitigation techniques [82; 85].

2.4 Compound and Cascading Effects

The net impact of these events might be milder than the possible impact of personal stressors on on-road infrastructure, flooding, storms, and traffic congestion. It is noted that minor floods, as well as traffic congestion, can lead to disastrous disconnection of the road net, since the network connectivity is very vulnerable to the emergence of compound failures that can propagate rapidly in the interconnected system [23; 87]. Cascades of such failures can lead to floods of paths to unused working state far enough to cause serious congestion, and local mobility events thousands of times larger than the damage of the underlying activity itself [23; 88].
Other related subsystems responding to the emergency and supply chains are also a negative contributor to the consequences of the failure in the road infrastructure and increase the effects that the primary failures have on society [89; 90]. The priority of the first is that analytic techniques should take into account co-occurring and mutually dependent events to determine and rank the major weaknesses in the transport infrastructure and the infrastructure on which the latter relies on as point failures may turn into a wholesale transport infrastructure crisis and a crisis of the infrastructure on which the latter relies [88; 91].
This brings up the value of compound risk assessment, compounding redundancy, and adaptive plans on emergency response to road infrastructure to enhance the road infrastructure resilience to both compound and cascading climate change impacts [92; 93].

3. SPECIFIC CLIMATE HAZARDS AND THEIR EFFECTS

3.1 Temperature Extremes and Heat Stress

High temperature impacts the road infrastructure of both the chronic and acute routes. Performance envelope of asphalt and concrete materials changes with an increase in temperature over time, and the current binder grading systems and mix design systems fail to satisfy the current demand in terms of temperature. Other instances exist where existing binder grading systems and mix design practices are inappropriate; the system has not yet been optimized to suit the present need, and this shift of the shape boundary may lead to rapid infrastructure failure and a zillion times larger increase in the number of their maintenance needs, and the projections are that the cost of maintaining the pavement infrastructure will be zillions of dollars higher in the next few decades unless the Indicatively, in the United States, a continuation of existing material selection under the conditions of global warming would cost a cumulative 35.8-billion dollar.
Heat waves can also result in high road surface temperature beyond safe operating range, which poses immediate operational hazards (tire damage, unsafe driving conditions, and severe rutting beyond societal sustainment and operational capabilities [14; 71; 94]. The effects discussed show that the efficiency and safety of the road infrastructure in the long-term will demand immediate advancements

in the quality of designs and material longevity in the face of climate change, as well as proactive adjustments to the same (3;14;72 95].

3.2 Precipitation Changes and Flooding

The way the alteration in the distributions of precipitation will impact the available road infrastructure may be represented differently and at various levels. Additional excessive precipitation can exceed the ability of the present drainage infrastructure to handle historic storms and cause surface flooding, which would have one of the following effects, directly impacting the transportation system, increasing underlying pavement erosion and scour, or physically damaging the structure by erosion and scour (76;77;96]. The time-accumulating and time-persistent impacts on road regimes within a territory of an individual, reiterated occurrence of flooding can be monumental, and a local happening can result in a devastating collapse [78].

Freeze-thaw damages and thermal expansion cracks, respectively, occur due to the regime of moisture of pavement constructions and material properties of water, low precipitation and, thus, low moisture in summer, and high precipitation and, thus, high moisture in winter, respectively, based on the seasonal variations of precipitation [76]. The infrastructure of regions surrounding the sea is also weakened by the rise of the sea level, and thus, this leads to the constantly recurring levels of submerging and flooding of inland salt water, erosion of the concrete they are building on, and hence, ultimate destruction of lower-order region functionality [77].

The conditions improve the fresh analysis and optimization of the risk of the drainage and change of approach alternative to survive the occurrence of the change in the precipitation and road floods on the road stream [77; 96].

3.3 Extreme Weather Events

Storms, hurricanes, and heavy rainfall pose emergency threats to road infrastructure due to their extreme weather conditions, which often lead to multiple and simultaneous failures across the whole transport industry, posing a greater stress on emergency operations. These events can cause overlapping hazards, including floods, landslides, and mass movements that generate extensive long-term upheavals that spill out far beyond the localized point where they have occurred. The robust evidence provided on the basis of combined hazard modeling and real-life experiences confirms that such localized effects can impair the operation of the entire regional networks [78; 97]. Cascading delays due to the vulnerability of transport, destruction of critical infrastructures such as roads and bridges, will lead to a critical bottleneck, a setback to the emergency department, and an affected increase in response period [97; 98].

The increasing momentum and intensity of extreme weather fail to accommodate the traditionally developed paradigms of coping with risks, which are largely based on historic conditions. Existing infrastructure that was designed to address the weather conditions of the previous decades may not be capable of dealing with the extremes of the future [99; 100]. This fact brings about the need to conduct systematic vulnerability tests, revise the design requirement, and undertake active adaptation measures to improve the resiliency of road infrastructure. Some of the suggested interventions that should be given priority include targeted repair work, structural reinforcement, and improved drainage systems. In addition, the infrastructure planning and management must include climate planning and management to anticipate risks to be better prepared [97; 100].

4. MATERIAL SCIENCE AND ENGINEERING PERSPECTIVES

4.1 Asphalt Binder Performance and Selection

Climate change is a structural problem to the existing dependence on asphalt binders, especially in the Performance Grade (PG) system, which has traditionally been elaborated on the grounds of the previous climatic conditions. Such a model might not be sufficient for future climate projections. In a recent comparative study of China, Canada, Morocco, Estonia, and Chile, it is shown that pavement performance and life expectancy will be increasingly sensitive to the choice of binder depending upon future temperature changes. Increases in temperature will necessitate upgrades of large portions of road networks in these countries, as the pavement grade of the roads will need to shift to higher grades, although at the same time, they will be accommodating both the higher and lower extreme temperatures by providing both high-temperature and low-temperature grades [101; 102; 103].

There is potential in improving the flexibility to future climatic conditions through advanced binder technologies, such as polymer modification and the use of chemical additives. Nevertheless, the technologies require additional confirmation and validation to guarantee their usefulness in the long term [104; 105]. Also, binders and aggregates' performance are highly affected by temperature and moisture, which explains the necessity to have integrated material system solutions instead of optimizing components on a case-by-case basis [104].

To get to milestones of resilient and sustainable road infrastructure in the context of a warming climatic, systematic changes in the binder selection processes are necessary. This involves integrating climate projections in the design levels and developing the use of new materials which are capable of surviving the changing environmental conditions.

4.2 Aggregate and Mix Design Considerations

Aggregate selection and gradation are important variables during stress on pavement under climatic conditions since thermal susceptibility of aggregates is a factor influencing both contraction and expansion, and the aggregate-binder bonding features are very important to withstand damage caused by moisture [106; 107]. Research has suggested that climate adaptation might require regional aggregate specifications whereby local climate prediction and hazard profiles are considered so that the materials are designed with the future rather than the past in mind [107].

Normal practices are not sufficient to ensure climate-resilient mix design balancing rutting resistance, cracking resistance, and vulnerability to moisture damage, and may require adapting to climatic variations [106; 108].

Recent literature mentions that new optimization models are currently being implemented to determine mixes that can simultaneously satisfy mechanical, environmental, and economic objectives, such as low concentrations of carbon emissions and resource usage that have no impact on performance [109; 110].

The designs enable the adoption of recycled aggregates and additional materials; they increase the sustainability and resilience of the pavement structure further [109; 110]. Generally, the prerequisite to climate-resilient pavements is the increasing acceptance of the use of modern analytical and optimization tools as an auxiliary tool in a performance-based framework of aggregate gradation and selection [107; 106].

4.3 Structural Design and Mechanistic Approaches

The need to integrate climate change impacts in infrastructure design depends on the availability of mechanistic-empirical pavement and structural design approaches because these approaches directly relate the climate inputs to the structure response and distress prediction that allows the assessment of adaptation strategies. However, most of these models need recalibration and validation under different climate conditions that are not part of their initial range, as climate change brings non-stationary and more severe climatic events that can greatly impact the new and the old infrastructures [39;111; 112]. The use of climate projections in designs involves advanced uncertainty analysis because neither the climate model nor the performance model is immune to limitations. Both probabilistic and semi-probabilistic design strategies that explicitly consider climate and modeling uncertainties are currently being proposed as the choice to enable robust adaptation planning and to ensure structural reliability throughout the service life of infrastructure [111; 113; 114]. The techniques permit the measurement of long-term reliability and sustainability to facilitate the creation of climate-resilient infrastructure regimes [115; 116].

5. ECONOMIC COSTS AND LIFECYCLE IMPACTS

5.1 Direct Cost Escalation

Climate change has a direct negative impact on the cost of road infrastructure due to the accelerated pavement deterioration, and thus reducing service life and forcing more frequent rehabilitation and reconstruction.

Maintenance costs can usually be relatively high when performed as emergency repairs after severe weather, and costs that accompany economic disturbances caused by such disasters can create indirect costs that are greater than the tangible damages themselves [34; 117]. Studies carried out not just in the United States, but also in other areas have shown that climate change adds hundreds of millions of dollars in added annual spending by road agencies [4; 72]. In order to overcome these issues, the existing lifecycle cost analysis frameworks are undergoing a revision process to include the effect of climate change. Nonetheless, there is a lot of ambiguity on the level and time of future spending. This makes it more difficult to plan investments in it because road authorities are likely to invest either too little or too much in climate adaptation measures [4; 117]. Proactive adaptation policies have been well-known as a cost-reduction over the long-term; however, decision-makers have to find a balance between the short-term cost of adaptation and the savings on the long-term and the reduction in risk it may bring [118; 119].

5.2 Maintenance and Operations Cost Changes

Climate change is transforming the rate and nature of road infrastructure maintenance since the struggle to maintain structural functionality has to respond to the new climatic pressures. An increase in temperature not only enhances wear and tear of pavements, but the growing number of extreme weather events also requires more regular checks and creative maintenance techniques to overcome new types of breakdown [34; 72]. Additionally, changing climatic conditions are also changing conventional maintenance schedules, which further complicate existing operational models [14; 117].

These challenges are further compounded by the increasing intensity of extreme events, with emergency response and recovery spending taking up a larger and larger portion of infrastructure budgets. This trend brings a lot of uncertainty in the process of forecasting and budgeting [4; 119]. Climate-related effects can create hundreds of millions of dollars of added maintenance and operation costs on an annual basis, which local agencies are in most cases left with bearing even though they are already stretched financially [72; 117].

Scholars and practitioners have offered solutions to these growing burdens by suggesting that preemptive mitigation measures be implemented and new engineering standards adopted. This kind of action is necessary to mitigate infrastructural resilience, curb the increasing maintenance expenses, and minimize the possibility of a devastating loss in the event of future climate occurrences [1; 14].

5.3 Network-Level Economic Impacts

Climate change effects on road infrastructure are also in some ways indirect costs that are usually expressed through delays in the flow of goods and travel, and limited access to work and other essential services. The effects are not limited to the destruction of physical assets since they impact the efficiency of the whole transport system.

In most instances, these network failures cause economic losses that are greater than what is incurred in repairing damaged infrastructure. This highlights the need to include network resiliency in adaptation planning approaches [4; 97; 120].

The importance of these effects on the economy depends largely on the position of certain connectors in the transport network and the existence of alternative routes. Areas that have low network redundancy, especially the rural ones, are skewedly susceptible to a disruption brought about by climate related occurrences [4; 97].

It is also noted that extreme weather scenarios would cause bottlenecks and access challenges that go way past the immediate location of the damage, in some cases, up to several miles distant. It has both consequences for the emergency responsiveness and for the overall resilience of the transport network [97].

To overcome these challenges, it is now suggested that important network links should be optimized and strategically reinforced. This sort of preemptive action would be used to reduce the direct and indirect economic and social costs that would occur as a result of climate-induced disturbances in the future [4; 34].

6. GEOGRAPHIC AND REGIONAL VULNERABILITY VARIATIONS

6.1 Regional Climate Pattern Differences

There is extensive diversity of vulnerability to climate change because of the differences by region in climate patterns, infrastructure age, design standards and adaptive capacity. Coastal development is also at risk of considerable losses caused by storms and sea-level surge due to the possible impact of active melting of ice sheets [3; 121].

Various difficulties existing in inland territory are a shift in the temperature and rate of the precipitation pattern that might influence the severity and the regularity of the extreme weather and have an impact on the stability of the roads [1; 122]. Freeze-thaw transitions and thawing of permafrost are particularly detrimental to arctic and sub-Arctic areas and can, by themselves, cause instability in the ground and performance of infrastructure, often having very little redundancy and despite being highly costly to replace [3]. It demonstrates in the literature of the region that both the susceptibility to a specific road link and the availability of a route alternative are key factors that define the vulnerability scale in general, and rural and remote areas face higher vulnerability than those networks that enjoy less redundancy and adaptability resources [122; 123]. The correct adaptive planning encompasses area-wide risks related to vulnerabilities and centralized resiliency responses to all these diverse hazards under climate change [121].

6.2 Infrastructure Age and Design Standards

Older infrastructure systems are also more susceptible to climate change than the others because older systems were built to accommodate weather conditions experienced in the past, and most of them are not equipped with current resilience improvements. Regional differences are also present among the age composition of infrastructure, leading to different vulnerability patterns, and must therefore be considered in adaptation planning, as most existing infrastructure is old and might not react to the present and future climatic conditions [124; 125].

The regional differences between the standards of designing buildings and the method used in their construction also considerably affect climate vulnerability. Areas that require more requirements and are designed more recently are better capable of withstanding the stresses of the climate compared to areas that require fewer requirements or are older in design [39; 113; 126].

To make matters worse, the uncertainty of future climatic forecasts also heightens the need to implement risk-based decision-making and continuously revise the design codes so that the emerging risks in climate conditions might be reflected in them [113; 125; 126].

6.3 Socioeconomic and Institutional Factors

The ability and or inability to respond to the effects of climatic changes through adjusting road networks would by far depend on the socioeconomic and institutional conditions within the society, including the financial capabilities, technical skills, performance within the governing sectors of the society, etc. Territories with more natural resources and institutions with functional performance would be much better equipped to respond to the requirements to adopt holistic methods, even though those with a thin resource base may struggle to afford to fund or even upgrade infrastructure to suit new climatic conditions [127; 128].

Inadequate financial concurrence, unequal standards of risk evaluation, and non-unification of management may also be facilitators to successful adaptation, alongside situations in which more than two actors must be aligned [129]. Particularly, this problem is not easily managed in rural and remote areas due to the lack of financial and technical capabilities, reduced population density, and the fact that infrastructure investment cannot be justified by costs, but rather depends on relationships with the infrastructure to create a connection [113]. This mix of good institutional capacity, financial resource access, and action incentives will result in successful local-level adaptation in China and in the Sponge City Program case studies [127]. To manage these imbalances and better maintain and govern institutions and place-specific response plans, vulnerable regions cannot be disaggregated in climate buffering [128; 129).

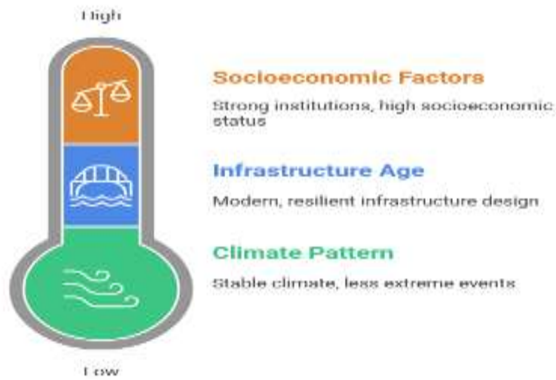

Figure 3. Vulnerability based on local and regional factors

7. ADAPTATION STRATEGIES AND RESILIENT DESIGN APPROACHES

7.1 Engineering and Design Solutions

Measures to ensure road infrastructure adaptation to climate should include integrated response to multiple risks such as floods and average temperatures through multiple mechanisms, including increased drainage, quality of the selection of used materials, and structural change [2; 34; 67]. In line with the quest to make pavement more immune to climate effects, the creation of higher-order pavement technologies is underway, including anti-rutting mixes, cool surfaces, self-healing and self-deicing asphalts, and fast-draining surfaces [130; 131]. A climate-oriented design approach focuses on implementing the projected climate settings in requirements, which means that new standards, new materials, and modified construction procedures will be needed to ensure the performance under changing weather conditions [34; 130; 131]. Infrastructure planning is given a priority based on a holistic model and interdisciplinary cooperation [2; 67].

It must also be based on the adaptations of operations and maintenance, in which adaptive management is employed to adjust inspection exercises, maintenance cycles, and monitoring systems due to the impact of climate, thereby assessing damage early and improving resilience [2; 67; 131]. More severe and frequent climate-related incidents can be managed with better emergency preparedness with accessible repair materials, rapid response, and interagency coordination [34; 67].

Effective integration of the transport planning, land use, and emergency management, as well as intense coordination across and within agencies and between different levels of government and long-term planning considering climate forecasts and uncertainty analysis to ensure that infrastructure remains viable under future conditions, also constitutes part of climate adaptation [2; 67; 119;132].

8. POLICY AND PLANNING IMPLICATIONS

8.1 Regulatory and Standards Updates

The emerging rules and requirements of the infrastructure architecture might not reflect the future climate that will require the systematic adjustment of the pavement design and its construction and drainage needs, and the foreseeable capacity of the climate and its resiliency needs. The fact of the matter is that the standard design and maintenance will not make a preferable requirement in the current situation, and both the quality and healthy processes will be needed to balance the risk intensification of structural failures and harmful environmental loads in the fluctuating weather conditions [39; 44]. Additional incentives to promote the use of climate-resilience design and construction can also be facilitated with the presentation of procurement options, climate-sensitive specifications (including performance-related specifications), firm lifetime cost accounts, and firm requirements in relation to climate-sensitive design capability [44; 133].

The financial endowment to re-architect the roads so that they can meet the requirements of climate change is detestable and even more distasteful than more traditional capital sources. It is suggested to mobilize the adaptation capital with the instrument of new financing: climate bonds, resilience funds, and public-private partnerships and change the system of cost-benefit to internalize the risks and benefits of climate risks and adaptation. The adjustment needs related to the climate are also linked with the enhancement of the institutional capacities of the considered transportation agencies, the specialized climate knowledge, updated analytics and contact with other agencies. The human and institutional capacity to take coordinated and effective actions against the adaptations is influenced by both professional development and training, and the intergovernmental coordination [134].

9. FUTURE PROJECTIONS AND RESEARCH NEEDS

9.1 Climate Modeling and Downscaling

The conditions that make quality adaptation possible are enhanced spatial and time climatic conditions that can be accessed and used ahead of time and during the planning of infrastructure, the planners will get better information on how often and harsh extreme events occur and when and how often compound risks that could not be taken into account so far manifest themselves, and the models that have been used up to now do not agree effectively with these conditions [135; 136]. Projections of global climate should be inverted to give fine scales to infrastructure planning; downscaling modes are poorly developed, and validation of variables, including precipitation and extreme weather events, is highly spatially discontinuous [137; 138].
The past uncertainty with the downscaled climate projections may be of critical relevance to infrastructure resilience decision-making, and by proxy, numerous datasets may find themselves in different estimates of future extremes, which means that prudent planning that accounts for uncertainties is warranted [137; 126]. The incorporation of climatic projections into the strategies of infrastructure planning, but also the infrastructure engineering process, is gradually becoming a necessity, whereas converting climate- and weather-related extremes into useful infrastructure design and management information is somewhat of a challenge [135; 138].

9.2 Infrastructure Performance Modeling

Existing pavement performance models must also be validated and recalibrated to respond to climatic variables that they were not initially developed to respond to, as factors affecting weather, such as temperature, humidity and wind speed, influence wear and tear on pavement, as well as material behavior in extreme conditions, to a large extent [139; 140; 141]. Advanced modeling strategies, including machine learning and Bayesian neural networks, have demonstrated superiority in forecasting the behavior of pavements by including regional weather variability and quantifying uncertainty with respect to forecasting such aspects as rut depth and roughness index [139; 140].

Modeling frameworks at the network level that integrate infrastructure performance with traffic flow and economic impact analysis are becoming central to the analysis of system-wide climate-damaging, as well as to strategic decision-making and investment decisions [142]. These holistic models enable more responsive planning due to the combined effects of climatic and traffic environments, as well as the properties of materials on the pavement performance.

9.3 Adaptation Effectiveness and Cost-Benefit Analysis

Adaptation measures should be evaluated systematically to facilitate investment-based decisions made to improve adaptation measures. It is not limited to the engineering performance evaluation, but an economic cost-benefit evaluation has demonstrated that cost-benefit models are integrated with adaptation pathways to deliver an uncertainty-induced evaluation of economic efficiency in adaptation investments [143; 144; 145].
Others have also been shown to help identify strong and effective adaptation solutions in uncertain climatic conditions, such as expectation-quantile-investment analysis and portfolio analysis [145; 146].
To enable adaptive management, long-term monitoring and evaluation programs should validate adaptation investments, but current adaptation planning does not offer sufficient mechanisms to measure both infrastructure outcomes and system-wide outcomes [147]. To enable monitoring and evaluation frameworks to be more efficient in addressing the problem of ensuring the effectiveness of adaptation measures over time and decision-making on future investment and policy [148].

9.4 Social Equity and Environmental Justice

Perhaps, it is because, due to the climate adaptation activities, the local populations will be unfairly impacted, and equity and environmental justice in climate adaptation will have to be put at the center of the stage to guarantee that the more vulnerable population groups will not be disproportionately targeted by climate change [149]. It has also been found that the adaptation planning must engage more individuals in the process of adaptation planning pay greater attention to the growing marginalized urban centres, multiple multi-level approaches and introduce justice to the infrastructure and urban planning to enable it to deliver a fairer outcome [149]. Developing smarter and fair strategic choices, such as the realization of preferences and community participation processes, and distributional impacts of adaptation investments, requires some studies of the social dynamics of infrastructure climate adaptation [150]. This social-cultural importance and personal interaction are incredibly urgent in individual awareness of opinions and limitations, to take action to address the needs and values of divergent groups of people [150].

10. CONCLUSION

Climate change is a broad-based challenge to road structure systems across the world, which operates at various overlapping directions that accelerate degeneration, augment upkeep expenses, and jeopardize the functionality of the network. The physical process of climate effects, such as thermal stress, moisture damage, extreme weather events and other hazards of compounds, needs a thorough understanding to come up with proper modes of adaptation techniques. The material science and engineering perspectives underscore the importance of climate-aware design methods that no longer rely on historically informed climate assumptions but reflect future conditions as projected.

It involves new material selection standards, new mix design procedures, and new structural design procedures that explicitly consider climate stresses.

The economic analysis shows that climate change will impose significant costs on the infrastructure lifecycle by reducing service life and maintenance frequency, as well as emergency repairs. Such costs can, however, be minimized through proactive adaptation investments that enhance system resiliency and reliability.

Geographic and regional differences in the susceptibility to climate demand spatially differentiated strategies of adaptation that consider the local climate pattern, infrastructure, and institutional capability. The rural and resource-limited regions can have specific problems that need specific assistance and new financing instruments.

Testing multidisciplinary solutions that integrate engineering solutions, modifications in operations and policy changes are all that is needed to allow adaptation to happen. This encompasses new design requirements, better emergency readiness and improved coordination among levels and agencies of government.

Improved climate-infrastructure modeling, systematic assessment of adaptation performance and more insight into the implications of social equity are among the critical research requirements. Climate adaptation planning will expose us to uncertainties that will require long-term monitoring and adaptive management strategies.

The problem of climate change effects on road infrastructure is not only technical in nature, but it needs a comprehensive transformation in the way transportation systems are planned, designed, built and maintained.

Success will rest on committed adherence to adaptation, sufficient funds, and good coordination among several stakeholders and levels of governance.

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