ADAPTING FLEXIBLE PAVEMENT INFRASTRUCTURE TO CLIMATE CHANGE: IMPLICATIONS AND SUSTAINABLE STRATEGIES

ADAPTANDO A INFRAESTRUTURA DE PAVIMENTOS FLEXÍVEIS ÀS MUDANÇAS CLIMÁTICAS: IMPLICAÇÕES E ESTRATÉGIAS SUSTENTÁVEIS

ADAPTACIÓN DE LA INFRAESTRUCTURA DE PAVIMENTOS FLEXIBLES AL CAMBIO CLIMÁTICO: IMPLICACIONES Y ESTRATEGIAS SOSTENIBLES

SUSAN MAYUMI KOCK PALU, MSc. | UFRGS – Universidade Federal do Rio Grande do Sul, Brasil
MÔNICA REGINA GARCEZ, Dra. | UFRGS – Universidade Federal do Rio Grande do Sul, Brasil
LÉLIO ANTÔNIO TEIXEIRA BRITO, PhD. | UFRGS – Universidade Federal do Rio Grande do Sul, Brasil

ABSTRACT
Road networks are vital links for people and freight transportation, influencing the environment and socio-economic development worldwide. Under restricted budgets, the sustainable management of massive roadway inventories to ensure adequate serviceability, safety, and durability has been a big challenge for infrastructure authorities. Climate change cannot be underestimated since it may require innovative practices, management strategies, and budgeting. This paper discusses the implications of climate change and adaptation strategies for flexible pavement infrastructure under non-stationary climatic conditions, addressing the following key issues: i) The effects of weather and climate on structural pavement performance; ii) The most relevant changes in weather and climate affecting the road transport infrastructure; iii) Projections of changes in weather and climate relevant to the road transport infrastructure; iv) Potential impacts of climate changes on pavement infrastructure throughout future years; v) Strategies to adapt flexible pavement infrastructure in response to a changing climate; and vi) The role of life cycle sustainability assessment of flexible pavement infrastructure to identify and manage economic, environmental and social impacts while ensuring its resilient capability to a changing climate. Considering the relevance of Brazil for South America, an emerging and continental country, the discussion establishes a link between the Brazilian road network context and the worldwide perspective.

KEYWORDS
Road infrastructure; climate change; adaptation strategies, resilience, life cycle sustainability assessment

RESUMO
As redes rodoviárias são ligações vitais para o transporte de pessoas e cargas, influenciando o meio ambiente e o desenvolvimento socioeconômico em todo o mundo. Sob orçamentos restritos, a gestão sustentável de extensos inventários rodoviários para garantir adequados níveis de serviço, segurança e durabilidade tem sido um grande desafio para as autoridades de infraestrutura. A mudança climática não pode ser subestimada, pois pode exigir práticas inovadoras, estratégias de gestão e alocação de recursos financeiros. Este artigo discute as implicações das mudanças climáticas e as estratégias de adaptação para a infraestrutura de pavimento flexível sob condições climáticas não estacionárias, abordando as seguintes questões-chave: i) Os efeitos do clima e do tempo na performance estrutural dos pavimentos; ii) As mudanças mais relevantes nas condições meteorológicas e climáticas que afetam a infraestrutura de transporte rodoviário; iii) Projeções de mudanças climáticas e meteorológicas relevantes para a infraestrutura de

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transporte rodoviário; iv) Os potenciais impactos das mudanças climáticas na infraestrutura de pavimentos ao longo dos próximos anos; v) Estratégias para adaptar a infraestrutura de pavimentos flexíveis em resposta a um clima em transformação; e vi) O papel da avaliação da sustentabilidade do ciclo de vida da infraestrutura de pavimentos flexíveis para identificar e gerenciar impactos econômicos, ambientais e sociais, garantindo sua capacidade resiliente diante de um clima em mudança. Considerando a relevância do Brasil para a América do Sul, sendo um país emergente e de dimensões continentais, a discussão estabelece uma conexão entre o contexto da rede rodoviária brasileira e a perspectiva global.

PALAVRAS-CHAVE
Infraestrutura rodoviária; mudança climática; estratégias de adaptação; resiliência; avaliação da sustentabilidade do ciclo de vida

RESUMEN

Las redes viales son enlaces vitales para el transporte de personas y mercancías, influyendo en el medio ambiente y el desarrollo socioeconómico a nivel mundial. Con presupuestos restringidos, la gestión sostenible de extensos inventarios viales para garantizar niveles adecuados de servicio, seguridad y durabilidad ha sido un gran desafío para las autoridades de infraestructura. El cambio climático no puede subestimarse, ya que puede requerir prácticas innovadoras, estrategias de gestión y asignación de recursos financieros. Este artículo analiza las implicaciones del cambio climático y las estrategias de adaptación para la infraestructura de pavimento flexible bajo condiciones climáticas no estacionarias, abordando las siguientes cuestiones clave: i) Los efectos del clima y el tiempo en el desempeño estructural de los pavimentos; ii) Los cambios más relevantes en las condiciones meteorológicas y climáticas que afectan la infraestructura del transporte vial; iii) Proyecciones de cambios climáticos y meteorológicos relevantes para la infraestructura del transporte vial; iv) Los posibles impactos del cambio climático en la infraestructura de pavimentos a lo largo de los próximos años; v) Estrategias para adaptar la infraestructura de pavimentos flexibles en respuesta a un clima cambiante; y vi) El papel de la evaluación de la sostenibilidad del ciclo de vida de la infraestructura de pavimentos flexibles para identificar y gestionar impactos económicos, ambientales y sociales, garantizando su capacidad resiliente ante un clima en transformación. Considerando la relevancia de Brasil para América del Sur, siendo un país emergente y de dimensiones continentales, la discusión establece un vínculo entre el contexto de la red vial brasileña y la perspectiva global.

PALABRAS CLAVE
Infraestructura vial; cambio climático; estrategias de adaptación; resiliencia; evaluación de la sostenibilidad del ciclo de vida

1. INTRODUCTION

The extensive climate change debate among scholars, practitioners, and officials led to a comprehensive list of scientific publications in assorted fields. However, regarding engineering practices, at which extension could climate change impose threats? According to the National Academy of Sciences (NASEM, 2019), curbing climate change and adapting to its impacts is one of the significant challenges for Engineering in the 21st century.

The 64 million km (Pörtner *et al.*, 2022) global road network is a vital link for people and freight transportation, influencing the environment and socio-economic development worldwide. In the US, highways and roads are responsible for nearly 72% of goods transport (USD 17 trillion), which requires a reliable road transport network. Nevertheless, the road transport system received a score of D on the 2021 ASCE Report Card for America's Infrastructure. About 43% of 6.4 million km of public roadways were in poor or mediocre condition (ASCE, 2021). The report highlights that USD 177 billion was invested in 2017 (62% for road system preservation) against a need of USD 786 billion. In addition, the rising temperature trend might cost USD 19 billion annually by 2040 (ASCE, 2021).

In Brazil, an emerging country with continental dimensions, the 1.7 million km roadway infrastructure is the primary mode of transport, responsible for more than 60% of freight and 90% of passenger moving (CNT, 2022). Despite the demand, only 12% of this network is paved, and 9% is planned (CNT, 2018). The demand for roadway transport by car will increase by 2035, with a rate of intercity passengers of 19 to 29% compared to 2017 (MI & EPL, 1021). In 2022, BRL 6.4 billion (USD 1.3 billion) of public investments were allocated to federal roads, from which BRL 4.4 billion (USD 908 million) were exclusively for maintenance services. Nevertheless, 23% of federal paved roads are classified as bad (MT, 2022).

Climatic change cannot be underestimated and neglected since it may require innovative engineering practices, management strategies, and budgeting (Abreu *et al.*, 2022). Schweikert *et al.* (2022) indicate that pro-active adaptions of road infrastructure to climate change in all ten countries studied result in lower costs than the reactive no-adaption approach for the years 2050 and 2100. The research confirms that developed nations will face relatively higher annual fiscal costs. In contrast, developing countries will endure higher opportunity costs – the amount of future road infrastructure development that will not materialize as resources are currently directed to cover climate change costs, whether due to pro-active or reactive actions (Schweikert *et al.*, 2022; Chinowsky *et al.*, 2011)

Therefore, this paper aims to contribute to the state-of-the-art regarding the impacts, resilience, and sustainability of flexible pavement infrastructure under non-stationary climatic conditions. Considering the relevance of Brazil for South America, an emerging and continental country, the discussion establishes a link between the Brazilian road network context and the worldwide perspective. The paper's relevance lies in dealing with a vital asset, considering the protagonism of road transport infrastructure and the vast territorial extension, potentially one of the most threatened by climate change. The subject is in line with the 2030 United Nations Agenda for Sustainable Development (UN, 2015), especially those related to making cities inclusive, safe, resilient, and sustainable (Goal 11), building resilient infrastructure (Goal 9) and taking urgent action to combat climate change and related impacts (Goal 13).

Based on a comprehensive literature review, the paper discusses the effects of non-stationary climatic conditions on flexible pavement infrastructure, addressing the following key issues: i) The effects of weather and climate on structural pavement performance; ii) The most relevant changes in weather and climate affecting the road transport infrastructure; iii) Projections of changes in weather and climate relevant to the road transport infrastructure; iv) Potential impacts of climate changes on pavement infrastructure throughout future years; v) Strategies to adapt flexible pavement infrastructure in response to a changing climate; and vi) The role of life cycle sustainability assessment of flexible pavement infrastructure to identify and manage economic, environmental and social impacts while ensuring its resilient capability to a changing climate.

The paper synthesizes publications resulting from the widespread scientific debate around the effects of climate change on the global road transport network, focusing on the impact of non-stationary climatic conditions on the flexible pavement infrastructure. The scope was established based on the issues presented in the introduction, which resulted in the following keywords: climate change, flexible pavements, impacts, adaption strategies, resilient infrastructure, and life cycle sustainability assessment. The gathering prioritized journal articles issued over the last ten years, encompassing different continents and countries, to give a big picture of the subject. Specific publications reporting the Brazilian context were emphasized, given the scarcity and urgent need for research on the country's road transport infrastructure and its relevance in the South American context.

2. THE EFFECTS OF WEATHER AND CLIMATE ON STRUCTURAL PAVEMENT PERFORMANCE

The discussions on the interference of weather and climate on structural pavement performance comprise physical and chemical mechanisms through which meteorological phenomena may affect flexible pavement infrastructure performance, influencing design, operation, maintenance, and repair approaches (Taylor & Philp., 2015).

The climate is a combination of meteorological phenomena (e.g., cloudiness, humidity, temperature, wind, barometric pressure) that characterize, over a long period, the average state of the atmosphere and its evolution in a particular geographic area (Medina & Motta, 2015). In contrast, the weather is a temporary and often exceptional setting of those atmospheric elements. Thus, the climate might be constant while the weather is supposed to change. Although only long-term climate changes were supposed to occur, scientists have noticed and discussed intense stressors that can drastically speed up the related disturbances (Medina & Mota, 2015). Climate Stressors disturb the energy and moisture balance, impacting the pavement deterioration rate and, consequently, the infrastructure performance, maintenance, and life-cycle costs (Qiao *et al.*, 2015). The effects of temperature and precipitation generally accelerate road pavement damage (Lnott *et al.*, 2019a; Knott *et al.*, 2019b; Nemry & Demirel, 2012), but other factors such as cloud cover, wind speed, and thermal properties of materials also affect the energy balance (Qiao *et al.*, 2015).

Daily and seasonal temperature variations change pavement stiffness (Medina & Motta, 2015), and the temperature gradient can determine the water movement in the vapor form. In desertic places where days are hot and nights are cold, there is a probability of vapor condensation under the wearing course. Temperature raising reduces the stiffness of asphalt materials, reducing the capability to spread loads and resist permanent deformations (Harmaeni *et al.*, 2018); it also accelerates the asphalt mixture aging, resulting in cracking due to brittleness (Qiao *et al.*, 2015). On the other hand, a reasonable period of low temperature may impact the pavement subbase and subgrade by the expansion of frozen water (frost heaving) if the water that fills the pores can break down or weaken the soil mass or pavement layers. Furthermore, the freezing process increases the negative pore pressure by reducing the soil humidity, and more water may then be attracted to the frozen subgrade and pavement (Medina & Motta, 2015).

Precipitation, flooding, and rising sea levels in regions where the groundwater level is shallow may influence unbound materials, soil, and the adhesion between bitumen and aggregates (Mallick *et al.*, 2017; Nivedya *et al.*, 2020). The runoff can reach the subgrade through shoulders by infiltration not intercepted by drains, especially those with no coating layer, through cracking, not sealed joints, and pores. The groundwater level variation changes the subgrade humidity (Medina & Motta, 2015), which may decrease the resilient modulus and the shear strength of unbound materials and soil, reducing the subgrade rutting resistance and causing permanent deformation that can lead to collapse (Elshaer & Daniel, 2019). A pavement structure with an elevated proportion of fine materials can exacerbate the damage due to excessive moisture. In addition, asphalt layers' saturation escalates asphalt raveling (Qiao *et al.*, 2020). Precipitation also affects the pavement top, reducing the skid resistance of tires and increasing the hydroplaning risk when the surface is wet or ice-covered (Khan *et al.*, 2017; Lu, Tighe & Xie, 2020), which can be worsened by climate changes.

The combined effects of solar radiation and precipitation induce the weathering of mineral aggregates and bituminous materials, which usually get worse due to traffic (ICF International, 2010). The disintegration leads new surfaces to the chemical-physical action, resulting in asphalt oxidation and polymerization that stiffens the asphalt mixtures, causing embrittlement, mainly at lower temperatures (Medina & Motta, 2015). Temperature and moisture also cause freeze-thaw cycles in cold regions that affect pavements (ICF International, 2010). The significant reduction in resilient modulus and rutting resistance expected during thawing can be worsened by climate change, resulting in more extended periods of thawing and traffic load restrictions (Qiao *et al.*, 2020).

Therefore, climatic data (temperature, precipitation, wind speed, cloud cover, and relativity humidity) have been used to predict pavement layer temperature and moisture conditions and estimate pavement performance throughout the life cycle (AASHTO, 2008). Considering the limited availability of weather stations, Hasan and Tarefder

(2018) proposed an interpolation method to estimate the annual average temperature and precipitation in New Mexico State, US. Predictions incorporating average temperature and precipitation data increased rutting and fatigue in hotter regions by 45% and 225% compared to cold ones for the same pavement type and traffic conditions, highlighting the importance of accurately considering the climate conditions.

In an era of climate change debate, it is fundamental to anticipate how changes in the intensity and frequency of global temperature and precipitation patterns can impact the existing road transport infrastructure.

3. RELEVANT CHANGES IN WEATHER AND CLIMATE AFFECTING THE ROAD TRANSPORT INFRASTRUCTURE

Changes in weather and climate, such as the intensity/ frequency of average temperature, heat/cold extremes, average/extreme precipitation, drought, flood, landslide, wildfire, wind speed, sea level rise, heavy snow, hurricanes, and tornados, threaten the integrity and serviceability of the road transport infrastructure.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2017) noticed relevant facts: i) The globally averaged combined land and ocean surface temperature increase of 0.85°C from 1880 to 2012, ratifying the successive Earth's surface warming since 1850; ii) The annual precipitation over land raised in some regions while reduced in others in a range up to 100mm from 1951 to 2010; iii) The snow cover extent in the Northern Hemisphere diminished by 1.6% per decade (March and April) and 11.7% per decade (June) from 1967 to 2012; iv) in the Arctic Sea the annual average of ice extent reduced at a rate range of 3.5 to 4.1% per decade from 1979 to 2012, while that of Antarctic Sea increased by 1.2 to 1.8% per decade, and finally; v) the global average sea level rose by 0.19m from 1986 to 2005.

The American Society of Civil Engineers (ASCE) Committee on Adaption to a Changing Climate depicts extreme weather metrics in the US for recent decades through the report Adapting Infrastructure and Civil Engineering Practice to a Changing Climate (Mills *et al.*, 2009). The report alerts for observed changes in temperature and precipitation that may affect engineering: i) Reduction in the quantity of unusually cold days and nights globally; ii) Rise in the amount of unusually warm days and nights globally; iii) Increase in length or quantity of heat waves in many regions; and iv) Substantial statistic increases in the number of events of heavy precipitation (e.g., 95th percentile) in more areas than those with significant statistic decrease.

Mills *et al.* (2009) and Tighe *et al.* (2008) agree that future variations in temperature and rainfall associated with traffic growth are the main factors that will influence pavement performance. An investigation on the sensitivity of flexible pavement performance to temperature, precipitation, wind speed, percent sunshine, and groundwater level, performed by Qiao *et al.* (2013), confirmed the protagonism of the seasonal variation and the average annual temperature increase. In turn, Sultana *et al.* (2016) investigated the impact of unprecedented flooding events from 2010 to 2015 on pavements of Queensland, Australia. The 2010-2011 floods compromised 19,000km of roads, while the January 2013 floods and heavy rainfall resulted in the closure of 5,845km of roads. The researchers observed the rapid deterioration of pavements by monitoring roughness and rutting after inundations.

In Brazil, whose territory accounts for approximately half of South America's land extension, relevant events related to climate change have already been observed. Among the extreme and unprecedented climate events in Brazil, the following stand out: flooding that hit 60 municipalities in the Itajaí valley in 2008, being the biggest catastrophe in the state of Santa Catarina (G1, 2018); flooding and landslides in 7 cities in the state of Rio de Janeiro in 2011, being the biggest landslide in Brazil and the 8th in the world in the last 100 years; the worst drought in almost a century in the Center-South of Brazil in 2021 (Busch & Amorim, 2011); flooding and landslide on the coast of the state of São Paulo in 2023, the record rainfall in 24 hours in the country - 683mm in the municipality of Bertioga (G1, 2024); 66 additional days of extreme heat from May/2023 to May/2024, while the annual average was 26 days (Central Climate, 2024). In 2024, the country's most significant climate catastrophe hit the state of Rio Grande do Sul, where at least 14 municipalities recorded, in 24 hours, a volume of rain higher than the expected monthly average (Governo do Estado do Rio Grande do Sul, 2024). The subsequent flooding affected 90% of the southern state of Rio Grande do Sul, washed away roads, collapsed bridges, and caused landslides across the state. The flooding affected 97 municipalities, causing severe damage to 79 roads and leading to 170 road network disruptions.

Figure 1 illustrates hazards to the Brazilian road infrastructure mapped by Pörtner *et al.* (2022) in the IPCC

Sixth Assessment Report. The main hazards projected and observed correspond to the increase of high mean temperature, extreme heat (heat waves), and floods/ landsides in all regions. It is interesting to note the rise in extreme precipitation observed in the South (SES) despite the reported projection and the sea level rise confirmed in the NSA, NES, and SES regions.

4. PROJECTIONS OF CHANGES IN WEATHER AND CLIMATE RELEVANT TO THE ROAD TRANSPORT INFRASTRUCTURE

The climate models, or General Circulation Models (GCM), are formulated using mathematical equations to characterize the energy and matter interaction over the ocean, atmosphere, and land (NOAA, 2022). Such models have been improved over the last 60 years, incorporating physical, chemical, biological, and biogeochemical parameters for the numerical simulations of the Earth system, aiming to determine human-related emissions released to the climate system.

Climate scenarios are established as inputs for global climate simulations through GCM based on greenhouse gas concentration pathways (time-dependent values in the future). Such Representative Concentration Pathways (RCP) are identified by numeric values (2.6, 4.5, 6.0, and 8.5 for the worst case, in Watts /m2), corresponding to the change in radiative forcing at the tropopause by 2100 relative to preindustrial levels (Wuebbles *et al.*, 2017). The outputs of climate model simulations are spatial-temporal projections of several climate parameters such as temperature (e.g., average, minimum, maximum daily temperature, number of heat wave days), precipitation

a) Observed Hazards

Observed Hazards	NSA	NES	SAM	SES
Mean temperature	H	H	H	H
Extreme heat	H	H	M	H
Cold spell and Frost	H	H	H	H
Mean precipitation	H	H		H
Extreme precipitation				H
Drought, Dryness, Aridity	L	H	M	L
Flood and Landslides			H	H
Wildfire			L	
Wind speed				
Sea level	H	H		H

b) Projected Hazards

Projected Hazards	NSA	NES	SAM	SES
Mean temperature	H	H	M	H
Extreme heat	H	H	M	H
Cold spell and Frost	H	H	H	H
Mean precipitation	M	H		H
Extreme precipitation	M	M	M	M
Drought, Dryness, Aridity	M	M	M	
Flood and Landslides	M	M	M	M
Wildfire	H	H	H	
Wind speed	M	M	M	
Sea level	H	H		H

Direction of hazard: Increase; Decrease and Increase; Decrease

Confidence in attribution: H=High; M=Medium; L=Low

Figure 1: Hazards to the Brazilian road infrastructure.
Source: authors.

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(e.g., average daily precipitation, number of days with extreme rainfall, periods of severe drought), moisture (e.g., soil moisture index), and wind (e.g., annual maximum wind speed), as illustrated in Figure 2, with a certain level of uncertainties (Galiana *et al.*, 2015). Such uncertainties are inherent to climate models because establishing physical interactions between atmosphere, land, ocean, and sea ice is challenging, especially considering the Earth's size and complexity. The uncertainties in the projected climate change throughout time may be a result of (Wuebbles *et al.*, 2017; Hawkins & Sutton, 2009): i) Limitations in modeling and understanding Earth's climate system, that is, different models respond differently to the same radiative forcing (scientific uncertainty); ii) Human activity and future emission levels of greenhouse gases emissions (scenario uncertainty); and iii) Variations in climate resulted from natural fluctuations, not related to radiative forcing (internal variability).

In this sense, confidence and probability of occurrence are metrics used in climate models to verify the prediction's certainty. The confidence level is a qualitative measure based on the level of the evidence and the degree of agreement. At the same time, the probability of occurrence is quantified based on a statistical analysis of observations, model results, or expert judgment (Mastrandrea *et al.* 2017), as shown in Figure 3.

Thus, adopting existing climate models requires a previous approach to compare the projections delivered by the models with observed regional data. In addition, it is also relevant to take into account that as climate scenarios range from the most optimistic to the most pessimistic regarding greenhouse gas emissions, the projections cannot be dissociated from related regional socio-economic conjectures.

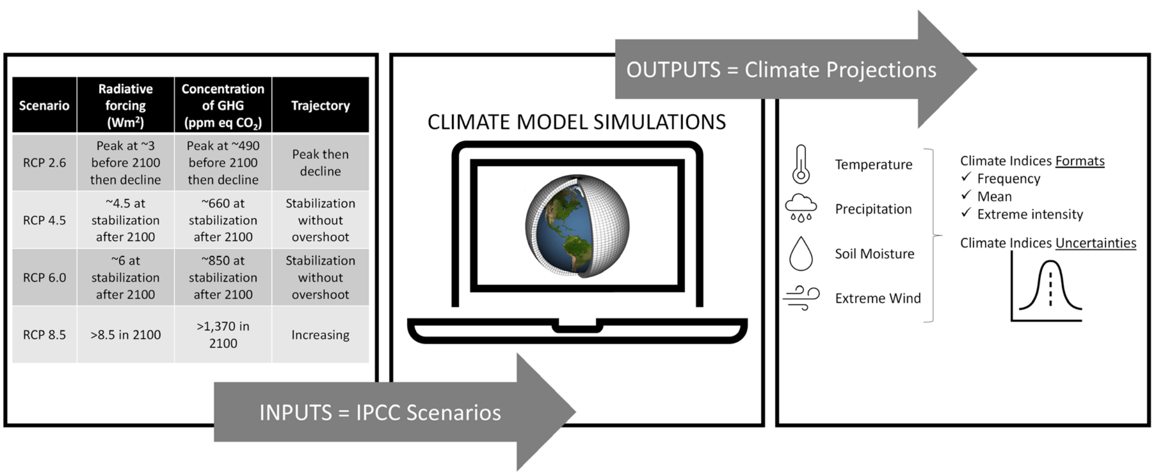

Figure 2: Global climate model simulation pathway.
Source: authors.

Term	Probability of occurrence
Virtually Certain (VC)	99-100%
Very Likely (VL)	90-100%
Likely (L)	66-100%
About as Likely as Not (ALN)	33-66%
Unlikely (U)	0-33%
Very Unlikely (VU)	0-10%
Exceptionally Unlikely (EU)	0-1%

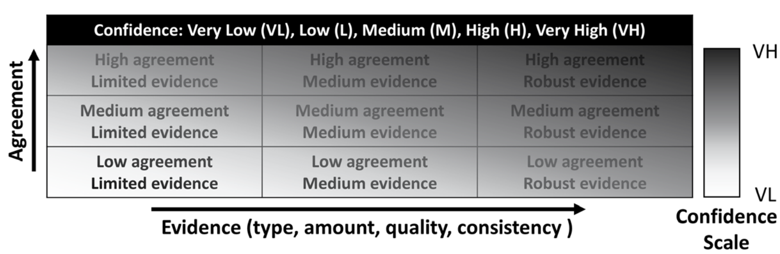

Figure 3: Levels of uncertainty.
Source: authors.

Table 1 summarizes projected changes for weather and climate variables at a global scale and the related probability of occurrence, as issued by IPCC and discussed in Field *et al.* (2012). Tables 2 and 3 summarize changes and impacts on the physical environment based on IPCC projections and the most crucial potential climate changes to US transportation systems, as highlighted in the TRB Special Report 290 (TRB, 2008).

Variable	Projected changes related to weather and climate variables
Temperature	• Decrease in frequency and magnitude of unusually cold days and nights (≥99%) • Increase in frequency and magnitude of unusually warmdays and nights (≥99%) • Increase in length, frequency, and/or intensity of heat waves (≥90%)
Precipitation	• Increase in frequency of heavy precipitation events or increase in the proportion of total rainfall from heavy falls over many areas of the globe, particularly in high altitudes and tropical regions, and in winter in the northern mid-latitudes (≥66%)
Tropical Cyclones	• Increase in mean maximum wind speed, but possibly in not all basins (≥6z6%) • Increase in heavy rainfall associated with tropical cyclones (≥66%) • Decrease or no change in frequency (≥66%)
Extratropical Cyclones	• Impacts on regional cyclone activity (≥66%). However, low confidence in detailed regional projections due to only a partial representation of relevant processes in current models • Reduction in the number of mid-latitude storms (medium confidence) • A poleward shift of mid-altitude storm tracks (medium confidence)
Monsoons	• Projected change in monsoons presented low confidence because of insufficient agreement between climate models
El Niño	• Projected change in El Niño presented low confidence because of insufficient agreement of model projection

Table 1: Projected changes at a global scale.

Source: authors.

Variable	Projected impacts
Droughts	• Increase in duration and intensity, including Southern, Mediterranean, and Central Europe, Central and North America, Northeast Brazil, and Southern Africa (medium confidence)
Floods	• Projected increases in heavy precipitation would contribute to rain-generated local flooding in some regions (medium confidence based on physical reasoning) • Earlier spring peak flows in snowmelt and glacier-fed rivers (≥90%) • Low confidence in global magnitude and frequency because of insufficient evidence
Extreme Sea Level and Coastal Impacts	• Mean sea level rise will contribute to upward trends in extreme coastal high-water levels (≥90%) • Locations with current coastal erosion and inundation will continue to be exposed to it due to increasing sea levels in the lack of changes in other contributing factors (high confidence)
Landslides	• Changes in heavy precipitation will affect landslides in some regions (high confidence)

Table 2: Projected impacts on the physical environment at a global scale.

Source: authors.

Variable	Projected critical changes related to weather and climate variables
Temperature	• Increases in very hot days and heat waves • Decreases in very cold days • Increases in Arctic temperatures • Later onset of seasonal freeze and earlier onset of seasonal thaw
Precipitation	• Sea level rise • Increases in intense precipitation events • Increases in drought conditions for some regions • Changes in seasonal precipitation and flooding patterns
Storms	• Increases in hurricane intensity • Increases in intensity of cold-season storms, wind, waves and storm surges

Table 3: Critical changes to transportation systems in the US.

Source: authors.

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Figure 4 illustrates long-term climate projections (2081-2100) relevant to pavement planning, design, construction, and maintenance in Brazil at the end of the 21st century. Data were generated using the IPCC Interactive Atlas tool (IPCC, 2023), setting the Coupled Model Intercomparison Project Phase 6 (CMIP6) models and the baseline period of 1850-1900 for temperature and precipitation and 1995-2014 for sea level rise. Data for Representative Concentration Pathways (RCP) 2.6, 4.5, and 8.5 (change in radiative forcing at the tropopause by 2100 relative to preindustrial levels in Watts /m2) scenarios show: i) An annual average temperature rising to 3, 4, and 7°C; ii) An annual number of days with maximum temperature above 40°C increasing to 34, 60, and 120 days; iii) An annual total precipitation increase of 12,17, and 28% in the south and decrease of 10,14, and 28% in the north; iv) An annual sea level raising more intense in the south coast, up to approximately 0.5, 0.6, and 0.8m.

These data ratify the projected hazards for the vast Brazilian territory illustrated in Figure 1. It is interesting to highlight that although climate modeling and impact analysis are suitable for strengthening discussions on the resilience and sustainability of flexible pavement infrastructure, case studies and empirical data are essential to validate the model predictions. As the models' outputs are valid for the set initial climatic conditions and geographical location, the projections for other countries may lead to different consensus. Regional-specific assessments performed by researchers and skilled professionals will undoubtedly support decision-makers committed to implementing infrastructure resilience and sustainability policies worldwide.

5. POTENTIAL IMPACTS OF CLIMATE CHANGE ON PAVEMENT INFRASTRUCTURE THROUGHOUT FUTURE YEARS

The potential impacts of climate change on pavement infrastructures have been debated among scholars, practitioners, and officials since it may affect the current performance, design, operation, maintenance, and rehabilitation of pavements. The Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance report, issued in 2015 by the US Department of Transportation Federal Highway Administration (FHWA), highlights the following impacts on flexible pavements due to climate stressors [40]: i) Pavement rutting/shoving and concrete joint heaving due to extreme heat; ii) Road closures (frequency, duration) and washouts related to flooding (rain-driven or coastal); iii) Road closures as a result of wind; iv) Pavement cracks due to extreme droughts; v) Potholes as a result of freeze/thaw cycles; and vi) Timing of permafrost thaw.

The Transportation Research Board highlights that the impacts of weather and climate extremes of importance for transportation in the US can be either negative or positive, as summarized in Table 4 (TRB, 2008).

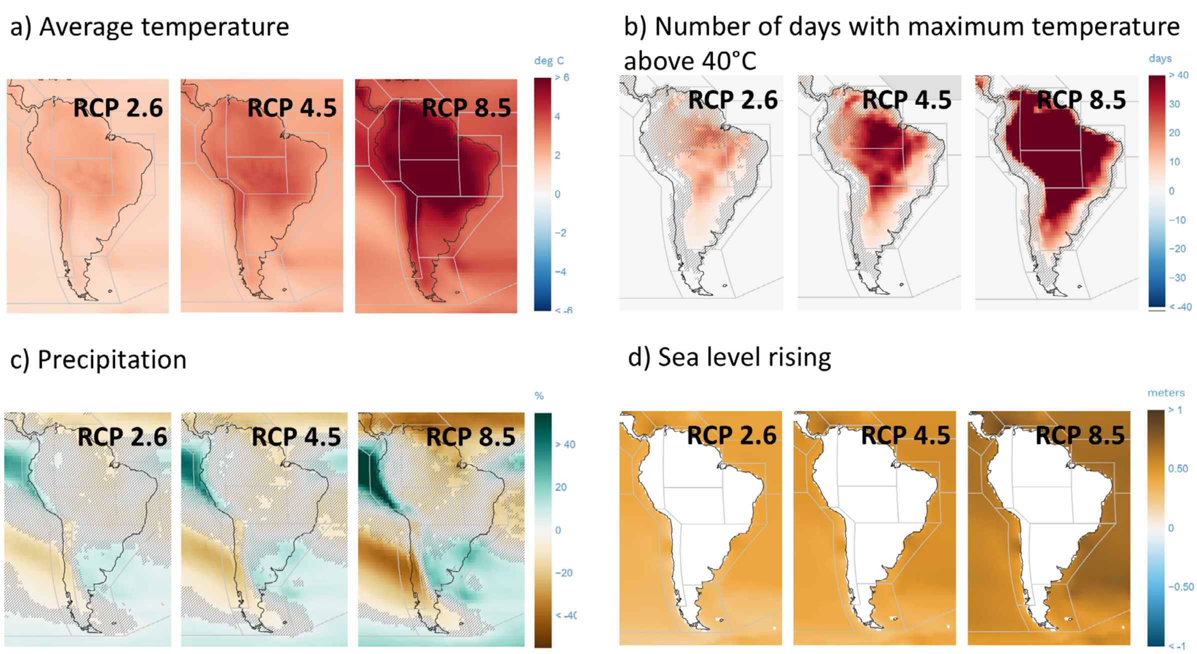

Figure 4: Long-term projections (2081-2100) for South America.
Source: authors.

	Potential Climate Change	Road Operations Impacts	Road Infrastructure Impacts
Temperature	• Increases in very hot days and heat waves	• Periods of construction activity restrictions; vehicle overheating; tire deterioration	• Need to change construction practices of pavement and concrete; thermal expansion of paved surfaces; traffic-related rutting; liquid asphalt migration
	• Decreases in very cold days	• Snow/ice removal costs; use of deicing salts/chemicals; cold-related restrictions for maintenance activity	-
	• Increases in Arctic temperatures	-	• Subsidence due to the thawing of permafrost
	Later onset of seasonal freeze and earlier onset of seasonal thaw	• Changes in seasonal weight restriction; improvement in mobility and safety; longer construction season	• Reduction of pavement deterioration
	• Sea level rise	• Interruptions on coastal traveling	• Erosion of road base; land subsidence
Precipitation	• Increases in intense precipitation events	• Delays; traffic disruptions; flooding routes of evacuation; disruptions in construction and maintenance activities	• Overloading of drainage systems; landslides and mudslides; change in levels of soil moisture affecting the structural integrity of roads; standing water on road base
	• Increases in drought conditions for some regions	• Reduction of visibility and road closures due to wildfires	• Mudslides in the deforested areas by wildfire
	• Changes in seasonal precipitation and flooding patterns (snow to rain)	• Benefits for safety; less interruptions	• More risk of floods, landslides, slope failures, and damage to roads
Storms	• More frequent strong hurricanes	• More debris on roads; emergency evacuations	• Reduction of expected highways (exposed to storm surge) lifetime

Table 4: Potential climate change impacts on road operations and infrastructure.
Source: authors.

In 2012, the European Commission released the report Impacts of Climate Change on Transport: A Focus on Road and Rail Transport Infrastructures (Nemry & Demirel, 2012), concluding that changes in design and maintenance are expected due to warming trends in Europe. The report shows the annual cost for asphalt binder upgrading due to temperature increase levels in 27 countries of Europe by 2040-2070 and 2070-2100 periods under distinct climate scenarios: E1 (more favorable), A1B (intermediate) and RCP8.5 (worst case). The incremental cost for the A1B scenario results in 38.5 to 135 million €/year by 2040-2070, which represents 0.1% to 0.5% of current maintenance road costs (~26 €/year); while for the long term, by 2070-2100, it results in 65 to 210 million €/year, corresponding to 0.2% to 0.8% of current maintenance road costs. In contrast, milder winter projections, considering frost depth and freeze-thaw cycles, might reduce materials and maintenance costs in Europe. Thus, costs regarding asphalt binder upgrading are expected to be moderate, and costs due to hotter summers are expected to be outweighed by milder winters.

Swarna *et al.* (2022) assessed 16 flexible pavement sections throughout Canada under climate change scenarios tracking the deterioration evolution along the future years intervals 2010-2040, 2040-2070, and 2070-2100 caused by two non-stationary environment factors: increase in air temperature and change in precipitation pattern. Figure 5 summarizes the mechanisms leading to declining pavement performance, as reported by Swarna *et al.* (2022). The increased air temperature raises pavement temperature, reducing the elastic modulus of the asphalt concrete layer, which becomes softer and augments the asphalt concrete rutting

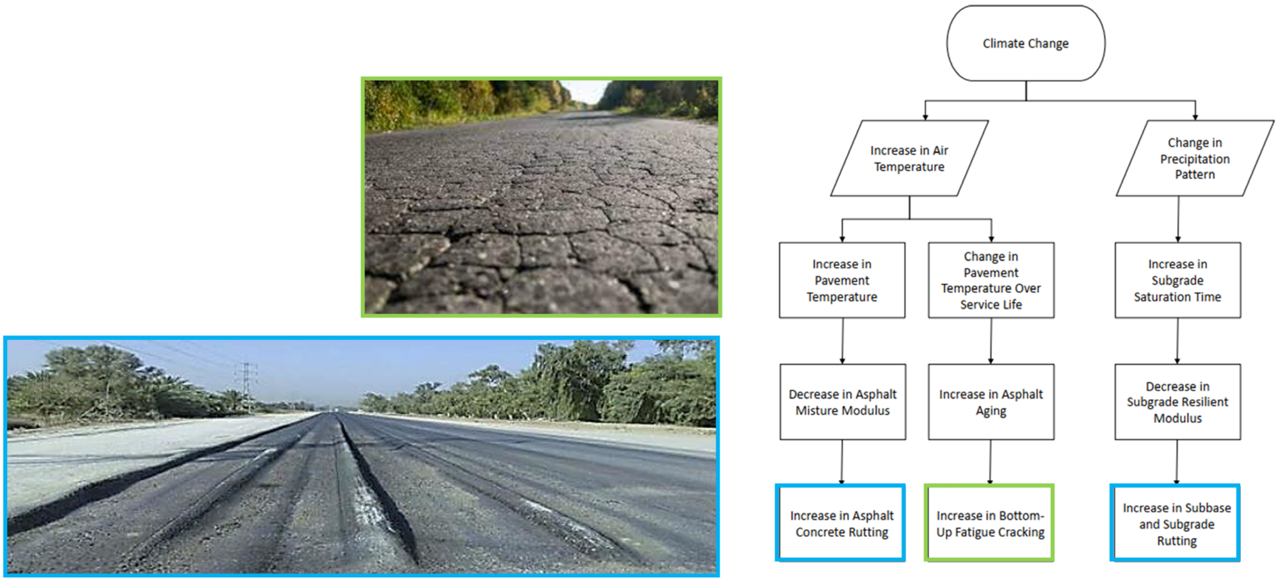

Figure 5: Mechanisms through which climate change affects flexible pavement.
Source: authors.

The increase in air temperature also contributes to the asphalt binder aging, which becomes stiffer (principally for thin pavements), increasing bottom-up fatigue cracking. Furthermore, precipitation increases contribute to water infiltration into the subgrade, boosting subbase and subgrade saturation, reducing the subgrade resilient modulus, and resulting in subbase and subgrade rutting (Khan *et al.*, 2017; Matini, Gulzar & Castorena, 2022).

Underwood *et al.* (2017) report that 35% of 799 asphalt pavement locations across the US suffer from inappropriate material selection due to the assumption of stationary temperatures in the design stage. Once the Superpave Performance Grading (PG) system is utilized in the US, which attributes a grade to the asphalt related to the maximum and minimum temperatures between which it must perform adequately, with climate changes, the first concern is the need for grade modifications for high temperatures – it corresponds to 26% of incorrect material selection, resulting in faster degradation, which will demand more maintenance services and earlier reconstruction. The authors report that in comparison to an adequate pavement expected to last 20 years, a pavement in which the asphalt grade was incorrectly assigned by 6°C increment will need premature rehabilitation starting at 16-17 years, while wrong by 12°C increments will need rehabilitation even earlier at 14-16 years, incurring extra costs. Keeping the current practice for material selection in the mid and long term may add approximately US$26.3 and US$35.8 billion to pavement costs by 2040 and 2070, respectively, under the worst-case scenario (RCP8.5). These impacts are equivalent to roughly 3-9% of construction and maintenance costs for the entire country's infrastructure over 30 years.

Climate change consequences are not limited to pavement deterioration, but the impacts may also extend to maintenance methods, budget, and the environment. Taking no action regarding infrastructure adaption strategies can impact users' safety, time, and additional costs with fuel consumption. Furthermore, the indirect impacts of climate change as traffic volume increases or decreases due to demographic changes may affect pavement performance, design, operation, maintenance, and rehabilitation (Qiao *et al.*, 2020).

A study conducted by Espinet *et al.* (Espinet *et al.*, 2016) projected an extra cost for road maintenance and repair in Mexico that ranges from USD$1.3 to 4.8 billion by 2050 due to climate change impacts, with temperature the main driver for climate change impacts compared to precipitation in the country.

In contrast to the abovementioned studies, Blaauw *et al.* (2022) discussed how potential climate change might benefit flexible pavements in South Africa, highlighting a trend of South African climate becoming increasingly arid, reducing pavement deterioration and road user emissions. A simulation using the Highway Development and Management 4 (HDM-4) software for a 30-year analysis with pavement deterioration trends quantified through the International Roughness Index (IRI) revealed that pavements in arid zones perform better than in humid zones under the same traffic and maintenance conditions. The IRI only exceeded the 6m/km threshold for the humid scenario. Maintenance costs significantly increase for low-volume roads as the climate zone becomes wetter, while maintenance costs remain constant for high-volume roads.

Although reports considering the Brazilian scenarios are rare, Shuster *et al.* (2022) assessed the impact of climate change in the selection of binders in Brazil since considering the Performance Grade (PG), which consists of the maximum and minimum asphalt temperature along the pavement lifespan, established in the SUPARPAVE method. The PG for 1961-1990 compared to 1991-2020, obtained from 115 meteorologic stations throughout the country, showed an increment in the maximum temperature of the PG in almost 15% of the stations. The effects can be even worse in the medium and long term.

6. STRATEGIES TO ADAPT FLEXIBLE PAVEMENT INFRASTRUCTURE IN RESPONSE TO A CHANGING CLIMATE

"Curb Climate Change and Adapt to Its Impacts" is one of the "Grand Challenges for Engineering in the 21st Century" of the National Academy of Sciences agenda (NASEM, 2019). Engineering usually assumes weather and climate as stationary; however, planning, designing, constructing, operating, and maintaining infrastructures must accommodate changes affecting the flexible pavement infrastructure. Assuming that weather and climate are stationary implies that statistical properties (mean and variance of a stressor distribution) remain constant. This assumption is ineffective since stressors may significantly vary with time (NHI, 2023), as illustrated by the hypothetical normal distribution curves for temperature shown in Figure 6.

In Figure 6 (c) against (a), focusing exclusively on the mean, whose value does not change from present to future, would lead one to neglect the increment in temperature amplitude (e.g., this knowledge is fundamental for concrete pavement expansion joints design) and the intensification of maximum and minimum temperatures (e.g., awareness of the magnitude of extreme temperatures is crucial to specify the asphalt binder in flexible pavements). In this sense, long-term recorded data availability allows for developing a statistical distribution of indispensable weather or climate parameters to obtain the probability of occurrence of a value above or below an established threshold of interest in engineering design (Field *et al.*, 2012).

The American Society of Civil Engineers (ASCE), in the published report Adapting Infrastructure and Civil Engineering Practice to a Changing Climate (ASCE, 2015), pinpointed two distinct models for vulnerability assessment: top-down and bottom-up (Figure 7). In the top-down approach, the projections generated by global climate models are downscaled to a local or regional scale to estimate the consequences on the system. The opposite path, bottom-up, consists of establishing thresholds where the system fails and assessing the possibility of exceeding that threshold.

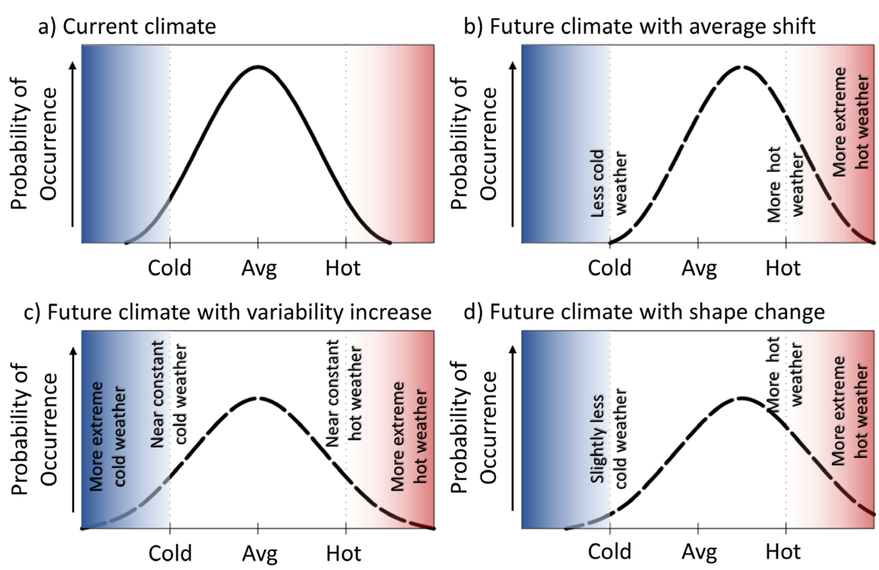

Figure 6: Normal distribution curves for temperature.
Source: authors.

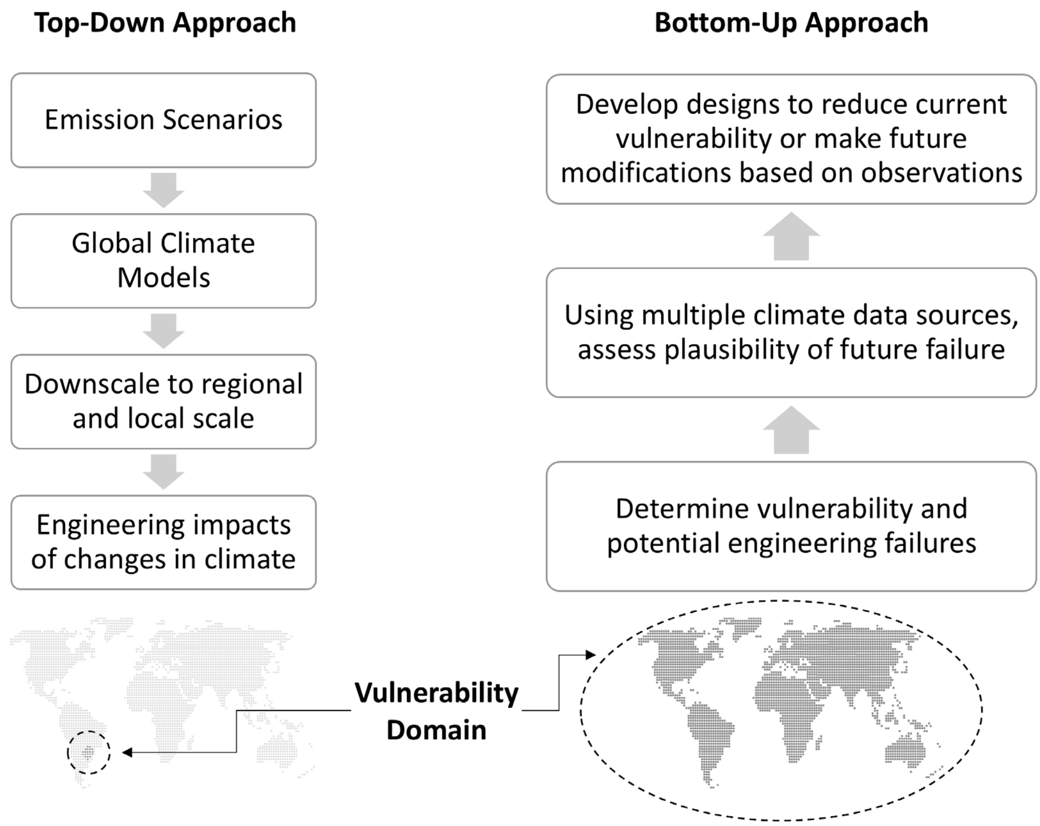

Figure 7: The Top-Down and Bottom-Up approaches as recommended by ASCE to assess the vulnerability level of infrastructures to climate change.
Source: authors.

Table 5 shows examples of governmental documents regarding the Climate Change Adaption Policy on different continents, showing worldwide efforts in addressing resilient infrastructures. These documents show a growing concern on the subject, based on the data recorded since the 20th century that clearly show a temporally and spatially-dependent non-stationary temperature tendency varying from one location to another. Therefore, planning, designing, constructing, operating, and maintaining infrastructures should accommodate these changes (TRB, 2008).

In the US, the Federal Highway Administration issued the Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance to subside departments of transportation (DOT) regarding infrastructure vulnerability and responses to adapt them. The report highlights that pavement designed must resist specific temperature thresholds – high temperatures may cause rutting, while cold conditions may lead to potholes. Different maintenance approaches in the future might consider: i) boost inspection and following of road conditions (short-term); ii) evaluation of projected temperatures to define if modifications in pavement mix are necessary (medium-term); and iii) application of modified asphalt mixture where necessary when repaving takes place (long-term). Those actions may result in allocation and budgeting distinct from today regarding operation, maintenance, and emergency management (Asam *et al.*, 2015).

Qiao *et al.* (2020) affirm that pavement adaption requires pavement design and modification of usual life cycle management practices. Similarly, Blaauw *et al.* (2022) state that selecting appropriate design and adopting rigorous maintenance are critical factors in addressing pavement infrastructure resilience.

In addition, road authorities may benefit from considering future projections instead of historical data. Underwood *et al.* (2017) point out four key factors to adapt asphalt pavement infrastructure: i) Increase air temperature and year-to-year variation; ii) Geo-spatial location – especially latitude; iii) Current engineering practices; and iv) Roadway type. Swarna *et al.* (Swarma *et al.*, 2022) utilized the following adaption strategies in their research: i) Change in asphalt binder grade, asphalt mixture gradation, and thickness of asphalt layer for asphalt concrete rutting; ii) Increase in asphalt layer thickness for bottom-up fatigue cracking; iii) Change in thickness of base and subbase layers, and use stabilized bases for subbase and subgrade rutting.

In a comprehensive literature review, Abreu *et al.* (2022) identified potential measures to adapt the road infrastructure to climate threats, especially related to the temperature-increasing trend. Such measures range from implementing pavement irrigation and vegetation around highways to mitigate the effects of heat waves to adapting pavement materials to minimize the impact of sensible heat flow. To adapt the binder selection in response to changes in temperature patterns for Brazil, Shuster *et al.* (2022) signalize the utilization of polymer-modified asphalt, whose impact on road infrastructure costs should be expected. Asphalt binders that are more flexible to support a broad range of temperatures and moisture conditions can lead to more durable asphalt mixtures, while lighter-colored pavement materials that reflect sunlight and absorb less heat might reduce the deleterious effects of urban heat islands..

Strategies to conserve and recover existing biodiversity, accompanied by strengthening the monitoring of precursor variables of natural disasters through reliable meteorological and climate forecasts, are essential actions to be implemented in road infrastructure adaptation plans (Garcez, 2024).

Location	Documentation	Governmental Agency/Organization
Australia	• Climate Change Risk and Adaption Assessment Framework for Infrastructure Projects (DTMR, 2020a)	• Department of Transport and Main Roads
	• Engineering Policy 170 – Climate Change Risk Assessment Methodology (DTMR, 2020b)	• Department of Transport and Main Roads
Brazil	• Plano Nacional de Adaptação à Mudança do Clima – Relatório Final de Monitoramento e Avaliação Ciclo 2016-2020 (Silva et al., 2021)	• Ministério do Meio Ambiente
	• Relatório Final de Monitoramento e Avaliação do Plano Nacional de Adaptação à Mudança do Clima Ciclo 2016-2020 – Síntese e Análise dos Resultados do Levantamento Realizado Junto ao Setor Empresarial (Silva et al., 2021)	• Ministério do Meio Ambiente
	• Plano Nacional de Adaptação à Mudança do Clima – Estratégia Geral – Volume I (Silva et al., 2016a)	• Ministério do Meio Ambiente
	• Plano Nacional de Adaptação à Mudança do Clima – Estratégias Setoriais e Temáticas – Volume II (Silva et al., 2016b)	• Ministério do Meio Ambiente
	• Estratégia de Adaptação às Mudanças Climáticas da Cidade do Rio de Janeiro (La Rovere & Sousa, 2016)	• City Hall of Rio de Janeiro, COPPE/ UFRJ, Centro Clima
Europe	• European Climate Adaptation Platform Climate-ADAPT (EC & EEA, 2022)	European Commission and European Environment Agency
	• Impacts of Climate Change on Transport: A focus on road and rail transport infrastructures (Nemry & Demirel, 2012)	• European Commission – Joint Research Centre
Japan	Practical Guidelines on Strategic Climate Change Adaption Planning – Flood Disasters (RB, 2010)	• River Bureau – Ministry of Land, Infrastructure, Transport and Tourism, Japan
South Africa	• National Climate Change Adaptation Strategy Republic of South Africa (DEFF, 2019)	• Department: Environment, Forestry and Fisheries – Republic of South Africa
United States	• Climate Change Adaption Guide for Transportation Systems Management, Operations, and Maintenance (Asam et al., 2015)	• US Department of Transportation – Federal Highway Administration

Table 5: Normal distribution curves for temperature.
Source: authors.

Zanetti, Souza Jr & Freitas (2016) assessed significant risks of climate change to infrastructure and communities other than temperature (i.e., extreme rainfall and sea level rise). The authors proposed seven related indexes using the municipality of Santos, in Brazil (the largest port in Latin America and an insular area of Pre-Salt Oil and Gas projects) as a case study: i) Landslide; ii) Flooding; iii) Wave exposure; iv) Coastal erosion; v) Population density; vi) Socio-economic level; and vii) Land use to quantify the socio-environmental vulnerability of coastal cities in a scale from 1 to 5. This classification allows for supporting adaption strategies for critical infrastructure. Approximately 70% of the studied area, including major roads and streets, received level 4 (high vulnerability) for the IPCC scenario RCP 4.5. Although vulnerability assessments based on climate change projections have been performed, i.e., Rio de Janeiro (Barata *et al.*, 2020), Minas Gerais (Quintão *et al.*, 2017), Amazon (Menezes *et al.*, 2018), and Maranhão (Vommaro, Menezes & Barata, 2020), there is still a lack of sector-specific research towards adaptions strategies for flexible pavement infrastructure in Brazil.

Future research to support public policies that address adaptation measures in the Brazilian road infrastructure network context is critical, as Abreu *et al.* (2022) reported in a recent bibliometric study. Adaption technologies and methods that meet the country's particularities comprehend innovation in drainage systems, adding non-stationary climate modeling in design specification, robust monitoring and data processing systems for climate changes, and space-time-dependent road infrastructure maintenance plans.

7. THE ROLE OF LIFE CYCLE SUSTAINABILITY ASSESSMENT (LCSA) IN IDENTIFYING AND MANAGING FLEXIBLE PAVEMENT INFRASTRUCTURE IMPACTS

Sustainable pavements are those that: i) Achieve the engineering goals for which it was constructed; ii) Preserve and (ideally) restore surrounding ecosystems; iii) Use financial, human, and environmental resources economically; and iv) Meet basic human needs such as health, safety, equity, employment, comfort, and happiness (Van Dam *et al.*, 2015). Several stakeholders have pursued sustainable pavement projects; nevertheless, assessing the economic, environmental, and social aspects throughout the life cycle is still in the initial stage in many countries. The challenge is even more far-reaching in examining the three pillars of sustainability from a climate change condition perspective. According to the international guidelines issued by the United Nations Environment Programme (UNEP/SETAC, 2011), LCSA evaluates all environmental, social, and economic impacts and benefits in decision-making processes throughout the life cycle.

Thus, sustainable road infrastructure projects might consider the different life cycle stages (Van Dam *et al.*, 2015). Potential strategies to implement sustainability aspects in the road pavement infrastructure through the life cycle stages, illustrated in Figure 8, encompass a life cycle thinking commitment. Especially in the use stage, integrating socio-economic impacts linked to pavement deterioration and maintenance services under changing climatic conditions will provide a more holistic view of sustainability. Due to the extent and complexity of the subject, this approach is only feasible in practical applications if linked to education and cross-collaboration.

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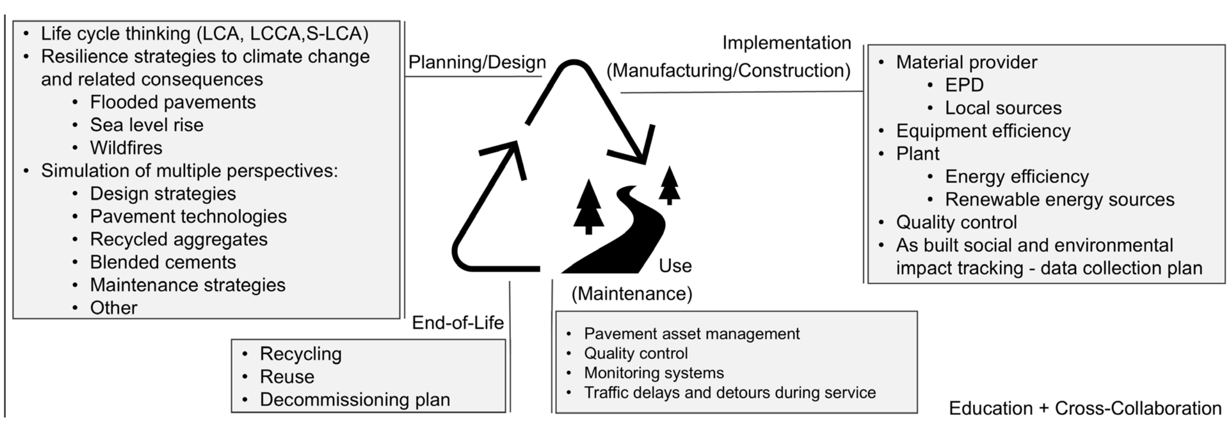

Figure 8: Pavement life cycle.
Source: authors.

The frameworks to carry out environmental Life Cycle Assessment (LCA) and Social Life Cycle Assessment (S-LCA) are similar, comprising four phases: i) Goal and scope definition; ii) Inventory; iii) Impact assessment; and iv) Interpretation [65]. The Life Cycle Costing (LCC) comprises aggregating costs by cost categories to the third phase. Since all cost inventory refers to a single unit of measure, a currency, this phase yields a direct measure of the financial impact (Swarr *et al.*, 2011).

Regarding LCA, ISO 14040 ISO, 2006) states the principles and framework for products or services, while ISO 15686-6 (ISO, 2004) is devoted to buildings and constructed assets. According to the respective ISO standards, an LCA encompasses the following steps: goal and scope definition, inventory analysis, impact assessment, and interpretation of results. The scope defines the life cycle stages (i.e., product, construction, use, and end of life – Figure 9) considered to build the inventory, which consists of background (gathered from reference databases - e.g., Ecoinvent) and foreground (collected directly from the product system). Specifically for the pavement sector, the FHWA issued extensive guidelines through the Pavement Life Cycle Assessment Framework (Harvey *et al.*, 2016), whose principles comprehend the translation of materials and energy inputs and the respective waste and emissions outputs into environmental and social impacts. Different LCA tools can be used to generate environmental and social impacts, whose results depend on the selected impact assessment method (e.g., CML, ReCiPe, EN 15804 + A2, TRACI). The FHWA report (Harvey *et al.*, 2016) recommends the inclusion of a broad set of impact categories such as fuel (renewable and non-renewable), resources (renewable and non-renewable), climate change, ozone layer depletion, acidification, tropospheric ozone, eutrophication, human toxicity (respiratory, carcinogenic, non-carcinogenic), ecotoxicity (freshwater, marine water, soil), freshwater use, waste (hazardous and non-hazardous).

Most LCA studies use environmental LCA to focus on the environmental pavement footprint. While some data sources are well consolidated, others are generated by inaccurate research that may compromise results and conclusions (Santero, Masanetb & Horvath, 2011). Potentially environ-mentally friendly strategies, such as warm-mix asphalt (WMA) and reclaimed asphalt pavement (RAP), have been pursued in the pavement sector, which is not enough to achieve sustainability (Zheng *et al.*, 2019) as a whole in its social, economic, and environmental pillars.

The main challenges to implementing LCA in the road infrastructure field rely on the various stages and unit processes involved, the scarcity of databases and specialized tools, the considerable heterogeneity of functional units, system boundaries, and study periods (Picardo *et al.*, 2023). Furthermore, transparency, heterogeneity, and the lack of information on road design parameters and materials used in the case studies make the results not reproducible (Hoxha, 2020).

Another issue related to the LCA results reported in the literature is that different impact methods may lead to different scenario results, which is not the case for the global warming potential (GWP) indicator, whose results are generally consistent regardless of the impact

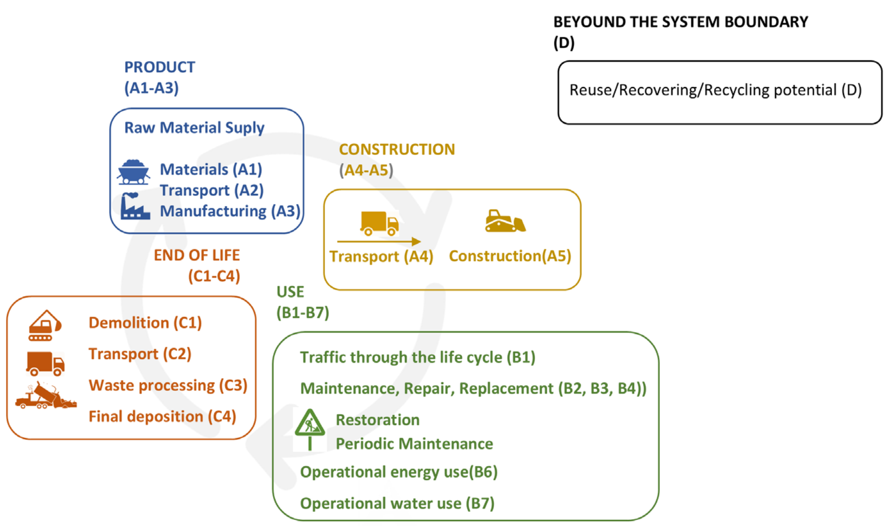

Figure 9: Life cycle stages and processes.
Source: authors.

method (Koch, Friedl & Mihalyi, 2023). The GWP indicator contains subcategories (e.g., biogenic carbon and land use change) to process relevant CO2-eq flows. The GWP reference unit (CO2-eq) does not change for the different impact methods, which is an advantage considering that different reference units may be used to quantify the same impact category (e.g., PO4-eq, NO3-eq, N-eq, P-eq, for eutrophication potential).

The S-LCA approach is more recent and has not been standardized yet (Blaauw *et al.*, 2022). The S-LCA allows for the evaluation of potential social impacts on several stakeholders over the life cycle (Zheng *et al.*, 2019). The Guidelines for Social Life Cycle Assessment of Products and Organizations establishes an S-LCA framework built upon six stakeholder categories – workers, local community, consumer, society, children, and value chain actors; and six impact categories – human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions; to identify and manage potential social impacts (UNEP/SETAC., 2009). In addition to cost and environmental impacts, Zheng *et al.* (Zheng *et al.*, 2019) investigated social implications through the behavior of company management toward the stakeholders (Figure 10) during materials production, construction, use, and maintenance activities. The authors highlight the concern for workers' physical and psychological well-being due to the arduous work environment and the local communities and consumers' protagonism due to the long service life of pavements.

Managing vast roadway networks under a limited budget, reducing environmental pollution, and guaranteeing social well-being has been a widespread challenge. Historically, the introduction of the life cycle cost-benefit concept for pavements was published in 1960 by the American Association of State Highway Officials (AASHO). At that time, two pioneer projects – Flexible Pavement System (developed by the Centre for Highway Transportation Research and the Texas Transportation Institute) and the Rigid Pavement System (created by the Texas Department of Transportation), initiated the use of LCC principles for the selection of pavement type/design. Under the Intermodal Surface Transportation Efficiency Act in 1991, LCC became mandatory in the US to design and construct tunnels, bridges, or pavements (Babashamsi *et al.*, 2016). The Federal Highway Administration continues to foster the application of LCC for transportation assets through technical guidance, tools, training, case studies, and other resources to the public (FWHA, 2023). The European Union determines the regulation for LCC conduction on public procurement (EC & ICLEI, 2022) in Article 68 of Directive 2014/24/EU [80] and Article 83 of Directive 2014/25/EU (EU, 2014). In Canada, except Prince Edward Island, New Brunswick, and Newfoundland, all provinces apply LCC for roadway management plans (Swarma *et al.*, 2022). The two components for pavements are agency cost – initial pavement structure and future maintenance and rehabilitations; and user cost – vehicle operation, user delay, and crash (Walls & Smith, 1998).

Figure 10: Stakeholder categories in the S-LCA framework proposed by Zheng et al. [71].
Source: authors.

Despite growing concern about implementing sustainability principles in road management, modeling LCSA towards pavement alternatives is in the beginning stage; by far, LCC+LCA studies outnumber LCSA for pavement, probably because LCSA modeling demands management concepts instead of just physical or monetary quantification. In this context, Zheng *et al.* (2019) proposed an all-inclusive LCSA methodology comprised of life cycle cost analysis (C-LCA), environmental life cycle assessment (E-LCA), and social life cycle assessment (S-LCA) through a case study applied in Southeast China by combining an Analytical Hierarchy Process (AHP) and VIKOR model to unify the economic, environmental, and social results.

In one of the few reports considering climate change effects on the LCA and LCCA of asphalt pavement, Swarna, Hossain & Bernier (2022) discussed three engaging scenarios for several locations in Canada: i) No climate change; ii) With climate change; and iii) Adaption to climate change including asphalt binder upgrading, increasing hot mix asphalt thickness, different mix gradation, and base stabilization (with lime, cement, or polymer). Despite the initial cost and emission increase to implement the adaption strategies, the authors identified an offset along the life cycle of the pavements in most locations. The most costly and highest emitting adaption alternatives were increasing hot mix asphalt thickness and using base stabilizations; however, these solutions are required for extreme coastal climate change regions such as Newfoundland (east coast) and British Columbia (west coast), which also must be taking into account. Although concluding that climate change adaptation strategies are beneficial from the economic and environmental point of view, the social aspect was not investigated.

Despite addressing material optimization, design, construction technologies, or maintenance strategies, none of the previous research addresses flexible pavement infra-structure adaption measures to face non-stationary climatic conditions throughout the life cycle from an LCSA perspective. This lack of knowledge demands further investigation to ensure that the infrastructure conceived today remains resilient through a potential climate change, considering time-space-dependent climate change stressors.

8. LIMITATIONS AND PERSPECTIVE FOR FUTURE RESEARCH

The discussions presented in the paper highlight the need for future research to face the challenges imposed by extreme climate events that will demand robust strategies to adapt the existing road infrastructure. Some suggestions can be drawn as follows:

- Overcoming the gap in developing or identifying existing climate models appropriate for the Brazilian specificities demands highly skilled research efforts to minimize internal variability and scientific uncertainty.
- There is a lack of knowledge on LCSA applied to the road infrastructure, addressing simultaneously time-space-dependent climate change stressors conditions and resilient solutions to endure climate change.
- Adapting flexible pavement infrastructure to climate change requires innovation, focusing on sustainability from a triple-bottom-line perspective that balances economic aspects, people's needs, and planet regeneration.
- From a technical point of view, addressing particularities of Brazilian Infrastructure in the future might require consideration of climate change-related factors and performance parameters as part of the pavement design process, where local specificities are conditioning factors.

9. CONCLUSIONS

The discussions presented in this paper ratify the importance of not underestimating the effects of climate change on the existing and planned road transport infrastructure, leading to the following conclusions:

- Changes in the intensity and frequency of global temperature and precipitation patterns affect pavements' performance, design, operation, maintenance, and rehabilitation regarding engineering, costs, and social development, demanding a deep upgrading of engineering practices and design standards to assume time-space-dependent stressors.
- Research and development fostering LCSA may reveal management strategies for vast roadway networks under a limited budget, reducing environmental pollution while promoting social well-being.

- Efforts and investments in resilient infrastructures depend on climate projections, whose accuracy is influenced by the uncertainty of climate models. Risk analysis may offer support in the decision processes as numerical simulations evolve.
- Investments in climate science are necessary to reduce prediction uncertainties.
- The main practical implication in pavement design and maintenance strategies resulting from the discussions proposed in the paper is the need to incorporate life cycle thinking in decision-making to allow the pavement infrastructure to adapt to future climate conditions, which might include:
- Allocating budget for adaptation to climate actions in road infrastructure business models to incorporate mitigation strategies throughout all life cycle stages.
- Combining LCA, LCCA, and S-LCA results in pavement infrastructure's design, implementation, use, and decommissioning stages.
- Setting appropriate asphalt grading considering non-stationary climate conditions, especially regarding high temperatures and potential traffic volume increases due to demographic effects related to climate change.
- Developing less polluting pavement materials accompanied by durability assessment considering climate and weathering-related extreme events.
- Boosting inspection and following of existing road infrastructure.

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AUTHORS

ORCID: 0009-0006-1197-5753
SUSAN MAYUMI KOCK PALU, MSc. - Federal University of Rio Grande do Sul, Civil Engineering Post-Graduation Program: Construction and Infrastructure, Porto Alegre, RS - Brazil. Correspondência para: 99 Osvaldo Aranha Av. – 7th floor, room 706, ZIP Code 90035-190, Porto Alegre – RS, Brazil. e-maill: susan.palu@ufrgs.br

ORCID 0000-0003-1641-5705
MÔNICA REGINA GARCEZ, Dra. - Federal University of Rio Grande do Sul, Civil Engineering Post-Graduation Program: Construction and Infrastructure, Porto Alegre, RS - Brazil. - Correspondência para: 99 Osvaldo Aranha Av. – 7th floor, room 706, ZIP Code 90035-190, Porto Alegre – RS, Brazil. - e-maill: monica.garcez@ufrgs.br

ORCID 0000-0002-7774-2948
LÉLIO ANTÔNIO TEIXEIRA BRITO, PhD. - Federal University of Rio Grande do Sul, Civil Engineering Post-Graduation Program: Construction and Infrastructure, Porto Alegre, RS - Brazil. - Correspondência para: 99 Osvaldo Aranha Av. – 7th floor, room 706, ZIP Code 90035-190, Porto Alegre – RS, Brazil. - e-maill: lelio.brito@ufrgs.br

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