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Climate change impacts on roadways

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Abstract

Roadways provide safe and efficient transport and are essential to the function of societies and economies. However, climate change increasingly pushes pavements beyond their engineering limits, leading to deterioration. In this Review, we explore the impacts of climate change on roadways and approaches to mitigate them. Roadways are vulnerable to changes in temperature, precipitation and sea level rise driven by climate change. High temperatures soften asphalt pavements, causing rutting, which is projected to increase by 2% per 1% increase in mean temperature. Increased moisture in the underlying soil caused by precipitation and sea level rise reduces the load-bearing capacity of roadways for months and in some cases halves their lifetime. Roadway closures due to extreme weather events or resulting reconstruction cause delays and detours; by 2100, high tide flooding in the USA is expected to cause delays of 3.4 billion vehicle-hours per year. Climate change is projected to increase national annual costs of pavement maintenance by over US\$500 million on average by 2050, depending on the country. Adaptation strategies include adjusting the type of asphalt, reinforcing concrete with steel, stabilizing gravel roads and adding nature-based features. Rapid implementation of policies, guidance on evaluating adaptation alternatives and exploration of the combined impacts of multiple climate stressors are needed.

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Summary and future perspectives

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Introduction

Globally, almost 65 million kilometres ([The World Factbook](#)) of roadways provide essential economic and societal functions. These roadways enable safe and efficient transport, support quality of life, provide access to education and health care, connect communities and facilitate social interaction. In addition, they underpin economic growth, transporting the vast majority of goods; the first and last mile of nearly every supply chain involves roadways¹. Accordingly, regions with well-maintained roadways and good connectivity experience enhanced overall property values, greater economic development and increased quality of life^{2–4}.

The primary element of a roadway is the pavement. Pavements are made of engineered layers of various materials, which distribute the load from traffic to prevent excessive deformation of the underlying natural soils, topped with a smooth surfacing layer. Roadway pavements include asphalt pavements with an asphalt concrete surface (also referred to as flexible pavements), concrete pavements with a Portland cement concrete surface (also referred to as rigid pavements) and composite pavements, which typically consist of a Portland cement concrete base with an asphalt concrete surface. Base and subbase layers made of gravel, crushed rock, sand or soil stabilized with asphalt, Portland cement or other binders make up the layers between the surface and the subgrade, which is the natural in-place soil. Unpaved roadways do not have asphalt concrete or Portland cement concrete surfaces and typically carry a lower volume of traffic at slower speeds than paved roadways.

Given their constant exposure to climate elements, roadways of all kinds are vulnerable to damage and deterioration by the climate. Most roadways engineered for high traffic volumes were designed to withstand expected environmental and traffic conditions with a specified level of statistical reliability. However, these guidelines use historical data as a proxy for future conditions and do not explicitly consider extreme weather events. Changes in heat waves⁵, cold snaps⁶, pluvial and fluvial flooding⁷, sea level rise (SLR)⁸, average temperature⁹ and freeze–thaw cycles¹⁰ driven by climate change pose considerable threats to roadways. The reconstruction of one lane of roadway is estimated to cost US\$304,565 per kilometre (ref. 11), and physical damage also has socioeconomic impacts from reduced accessibility. Damage caused by the 2015 debris flows in the Atacama Desert, Chile, was valued at US\$1.5 billion (ref. 12), Cyclone Idai resulted in more than 642 km of roadways needing reconstruction in Zimbabwe

in 2019 (ref. 13), and North Carolina, USA, received US\$100 million in emergency relief funds for almost 5,400 damaged roadway sites¹⁴ from Hurricane Helene^{15,16}, with the total repair and replacement estimated to be several billion dollars¹⁷.

The observed and projected impacts of climate on roadways reinforce the need for engineers, planners and decision-makers to have a toolkit of adaptation approaches that consider engineering, social, environmental and economic goals¹². Yet efforts to incorporate climate change into the design, maintenance and management of roadways have been disconnected. Therefore, delays owing to closed roadways and increased construction from climate-related damage will continue to increase in the future¹⁸.

In this Review, we outline how roadway infrastructure will be affected by anthropogenic climate change. We begin by exploring the mechanisms and impacts of climate stressors on roadways, including temperature, precipitation and moisture, and SLR. Next we outline how these aspects collectively influence operation and maintenance. We then discuss possible adaptation strategies and transportation policies, concluding with recommendations for future research.

Climate stressors and impacts

Temperature, moisture (largely as precipitation but also through humidity), SLR, snow and wildfire affect the structural (ability to carry traffic loads) and functional (ability to provide a smooth and safe roadway surface) capacity of roadways, collectively termed distresses (Table 1). Where possible, this section quantifies the effects of these factors on roadways using available data. However, quantification is sparse, and existing results are obtained using different model ensembles, time periods and/or performance prediction methodologies because no standard set of parameters to use for these assessments has yet been established. Although there is substantial variation in the individual results, general trends emerge.

Temperature

Gradual changes in temperature accelerate distress, reducing the pavement lifespan and increasing maintenance requirements. Air temperature, direct sunlight exposure and near-surface wind speed all affect roadway surface temperatures. Surface temperature changes alter the properties of roadway materials and induce stresses from thermal expansion and contraction^{19–21} (Fig. 1a). Fatigue cracking develops from repeated traffic loading and appears as interconnected cracks in

Table 1 | The impact of climate on roadway performance

Impact	Increased temperatures	More freeze–thaw cycles	Increased precipitation	Sea level rise	Drought
Structural					
Fatigue cracking (asphalt and concrete)	Increase (only asphalt)	Increase	Increase	Increase	Varies
Thermal cracking (asphalt and concrete)	Decrease	Increase	Little impact	Little impact	Little impact
Rutting (asphalt and gravel)	Increase (only asphalt)	Varies	Increase	Increase	Decrease
Functional					
Buckling (concrete)	Increase	No change	Little impact	Little impact	Little impact
Roughness (all road types)	Increase	Increase	Increase	Increase	Varies
Delays (all road types)	Little impact	Little impact	Increase	Increase	Little impact
Detours (all road types)	Little impact	Little impact	Increase	Increase	Little impact
Safety (all road types)	Decrease	Increase	Decrease	Decrease	Varies

Review article

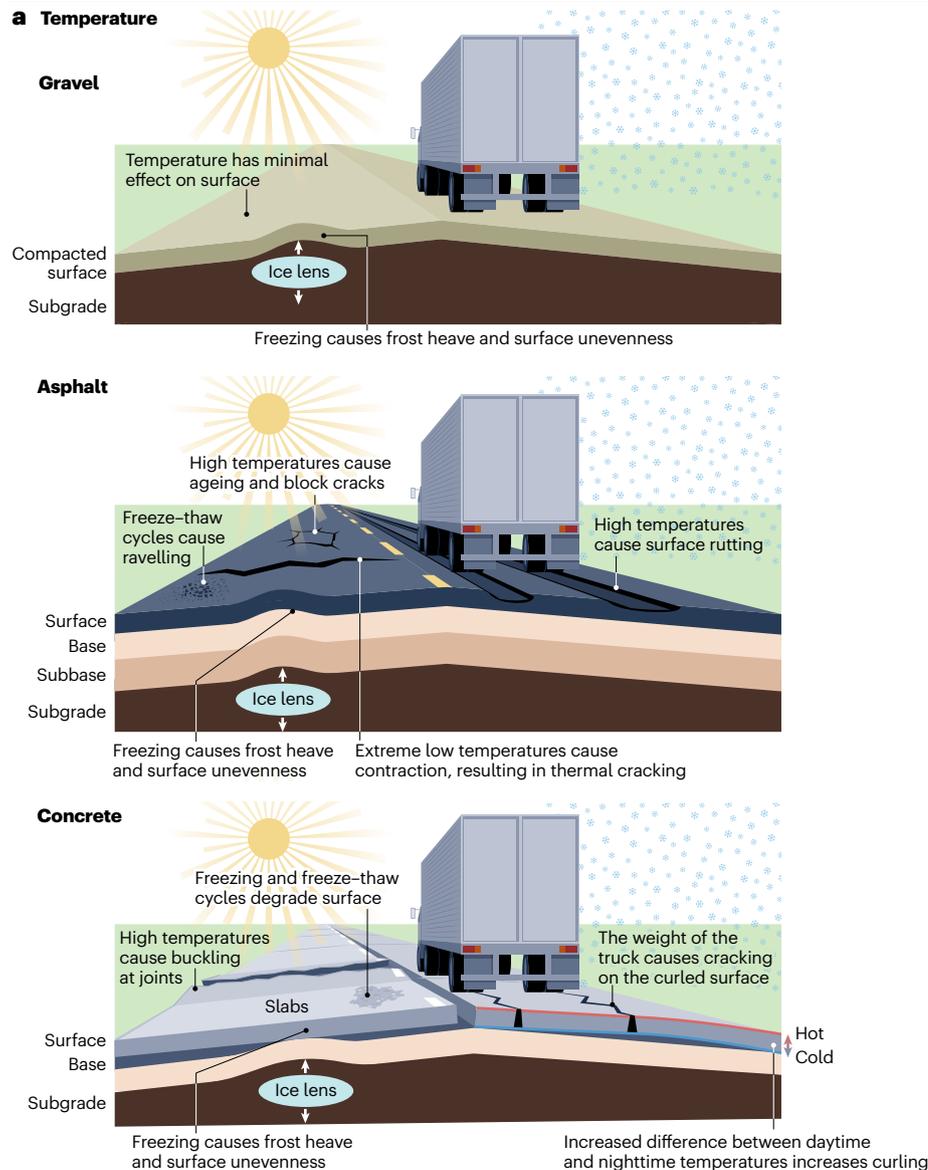
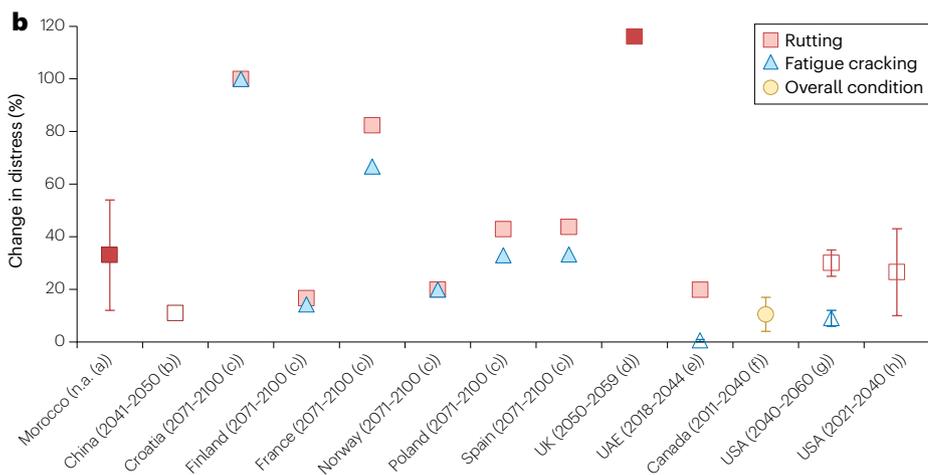


Fig. 1 | The effect of temperature on roadways. **a**, The impacts of temperature extremes and increased freeze–thaw cycling on gravel (unpaved) roads, asphalt (flexible) pavements and concrete (rigid) pavements. **b**, The projected change in pavement distress due to temperature from the present day to the indicated time period (n.a., based on specific temperature change of 1–6 °C) from representative examples in which the effects are quantified in a general manner (covering different climate models, pavement structures and regions within the respective countries) and the same performance metrics are reported (data from a²³⁴, b²³⁵, c²⁹, d²³⁶, e²³⁷, f²³⁸, g²⁸ and h²³⁹). These data were chosen to cover various quantitative assessments, analysis methodologies and locations, and generally cover 2040 ± 30 years. The unfilled symbols represent temperature projections from the Coupled Model Intercomparison Project 5 (CMIP5) using the Representative Concentration Pathway 8.5 or 4.5 ensemble, shaded symbols represent the CMIP3 ensemble and solid symbols indicate alternative methods. The error bars indicate the range of results observed when multiple pavement types or materials were considered. Temperature changes can more than double the distress experienced by a roadway. UAE, United Arab Emirates.



the wheel path. Thermal cracking develops from rapid drops in temperature or temperature cycles and appears as regularly spaced cracks oriented perpendicular to the traffic. Temperature changes affect fatigue and thermal cracking in asphalt pavements because the surface stiffness and its ability to resist damage from repeated traffic and thermal loading are temperature dependent. Rutting in asphalt roads refers to the formation of channels in the wheel path caused by traffic loading, and it tends to occur more rapidly at higher temperatures.

Freezing conditions increase the stiffness of the subgrade, increasing the structural capacity of roads; however, freezing can also accelerate distress in various road types. Freezing water in the subgrade or base layers can form ice lenses that create frost heaves on the roadway surface and very rough driving conditions. Freezing and thawing cycles weaken the bond between the cement or asphalt and the rock and sand, leading to surface erosion (known as ravelling) and cracking. Differences in temperature between the top and bottom surface of concrete pavements lead to differential material expansion and changes in the slab geometry, causing curling. In arctic regions, increased temperatures melt permafrost, softening the subgrade, which accelerates pavement subsidence²² and failure⁶.

Extreme temperature events can cause localized failures that require immediate repair. At high temperatures (46–70 °C, depending on the material), asphalt materials soften, leading to deformation such as rutting under loading. Asphalt also ages faster at higher temperatures, making it harder, more brittle and prone to cracking. Asphalt contracts as temperatures drop, and at extreme low temperatures, stresses can build up to the point of cracking the road. Extreme heat events can lead to excessive expansion of concrete slabs, causing them to buckle. In addition, extreme low temperatures can cause joints in jointed concrete pavements to open beyond their design limits, degrading the seal that prevents moisture and debris intrusion²³ and increasing the probability that buckling will occur during high-temperature events.

Increasing global temperatures are likely to increase the amount of accumulated distress in pavements (Fig. 1b), particularly structural distresses associated with repeated traffic loads. Projected gradual increases in temperatures are estimated to increase asphalt layer rutting by 9–40% (refs. 24–29) by the mid-century for a projected mean global temperature increase of 2 °C, or by approximately 2% for every 1% increase in mean air temperature^{28,30}. In addition, extreme heat waves are estimated to contribute another 1.5–6% rutting³¹ and create localized failures⁵ in asphalt pavements. Fatigue cracking is more uncertain, but it is projected that the area of cracked lanes will increase by approximately 1.4% for each degree of mean annual air temperature increase, leading to an increase of 2–14% (refs. 24–28) by mid-century for a projected mean global temperature increase of 2 °C above preindustrial levels. Although the costs of these impacts are not directly calculated, estimates using US conditions suggest that a 20% reduction in the life of a roadway increases the life cycle maintenance costs by between 58% and 64% (ref. 32). Estimates of temperature effects vary widely owing to differences in projected air temperature changes globally, as well as variations in models, scenarios and methodologies used.

High temperatures also reduce the functional capacity of roadways. Buckling of concrete slabs leads to localized failure of pavements, creating safety issues and road blockages until the road has been restored³³. In Wisconsin, such buckling events increased from fewer than 50 in 2013 to nearly 200 in 2021 (ref. 33). In addition, extreme high temperatures from wildfire events can melt asphalt binder and cause

premature ageing that will lead to cracking and faster deterioration^{34,35} as well as rougher roads that will require maintenance or repair and associated traffic delays.

All roadway types are susceptible to increased frost penetration depth from colder wintertime temperatures and corresponding pavement roughness and damage from frost heaves^{36,37}. In addition, rapid drops in temperature associated with extreme low-temperature events will intensify the formation of low-temperature cracks²⁰. Together with asphalt ravelling caused by an increase in the number and frequency of freeze–thaw cycles, this distress leads to a rougher driving surface³³. These freeze–thaw cycles also increase the severity and density of potholes, creating safety and roughness issues. Temperature gradients along the depth of the concrete slabs increase with higher maximum and/or lower minimum daily temperatures, leading to curling, which increases tensile stresses and causes premature cracking of the slabs under self-weight and vehicle traffic loading²¹. Icing caused by freezing temperatures when water is present increased the number of accidents relative to non-winter storm conditions by up to 942% (ref. 38) in Iowa, USA.

Increases in the minimum pavement temperature can reduce low-temperature cracking^{39,40}. In moderately cold climates, temperature increases are expected to reduce the depth of rutting in asphalt pavements by up to 0.2 mm per year owing to the reduced impact of thawing periods on unbound layers⁴¹. Estimates for China suggest that 17% of pavements will experience fewer thermal cracks by 2050 (ref. 42). However, all types of roadway can carry higher loads when frozen; thus, in colder climate regions, shorter periods of freezing weather can reduce the structural performance of roads^{39,43}.

Precipitation and moisture

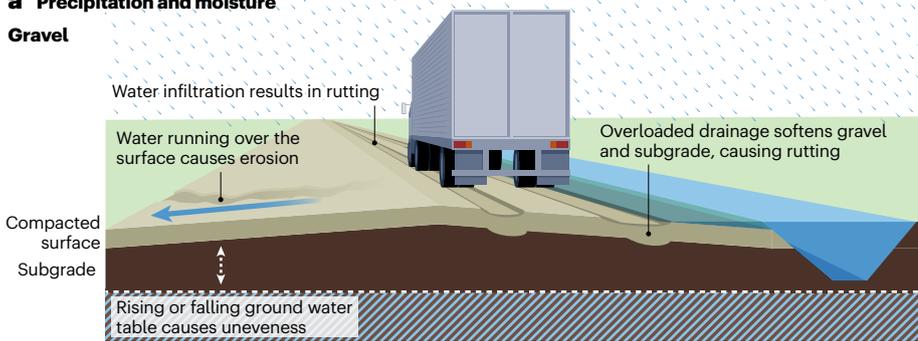
Precipitation influences roadways primarily through its effects on the unbound layers but can also affect the durability of asphalt and concrete materials (Fig. 2a). A lower groundwater table causes land subsidence, leading to road unevenness in all road types. In addition, if the groundwater table rises, water infiltrates the unbound layers or drainage is overloaded, the moisture content of the unbound layers increases. This increased moisture content reduces the structural capacity of the unbound layers and causes rutting in asphalt and unpaved roads and cracking in asphalt and concrete surfaces. The presence of moving water can cause erosion of gravel roads and unpaved shoulders. The presence of water can also damage bonding between pavement layers, degrade the adhesion between asphalt binders and aggregates and cause cohesive failures within asphalt binders^{44–46}.

Precipitation and associated flooding increase the moisture content of the unbound layers, affecting their structural capacity. This moisture can reduce the structural capacity for up to 6 months after an event⁴⁷ (Fig. 2b), depending on the amount of precipitation, natural and engineered drainage features, the type of roadway and the materials that constitute the structure⁴⁸. The reduced structural capacity from increased moisture makes a roadway more prone to accelerated damage from traffic loading^{9,49,50}. Therefore, the deterioration of the structural capacity is likely to increase if the roadway is open to traffic immediately after an event^{51,52}. Flooding also reduces the lifetime of a pavement by 3–16 months, depending on the roadway type and flooding severity⁷, with asphalt roadways being affected more than concrete roadways. Precipitation and flooding are estimated to increase rutting by 5–50% (refs. 31, 53–55) and cracking by up to 60% (refs. 53, 56–58) in asphalt roadways, depending on the severity and recurrence of floods. These estimates vary substantially depending on the specific pavement

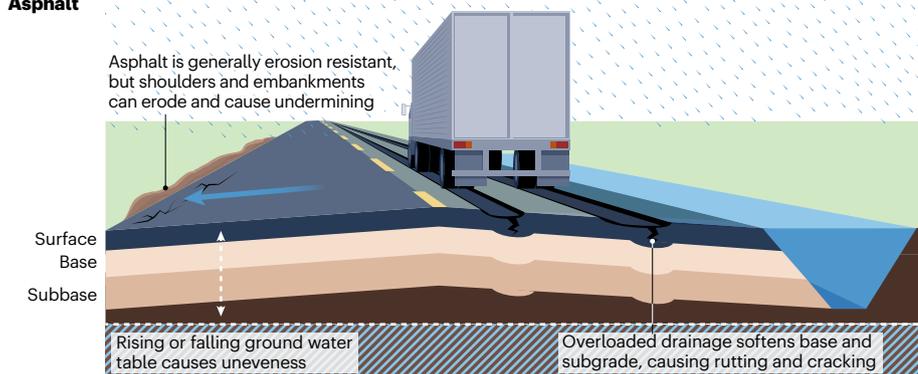
Review article

a Precipitation and moisture

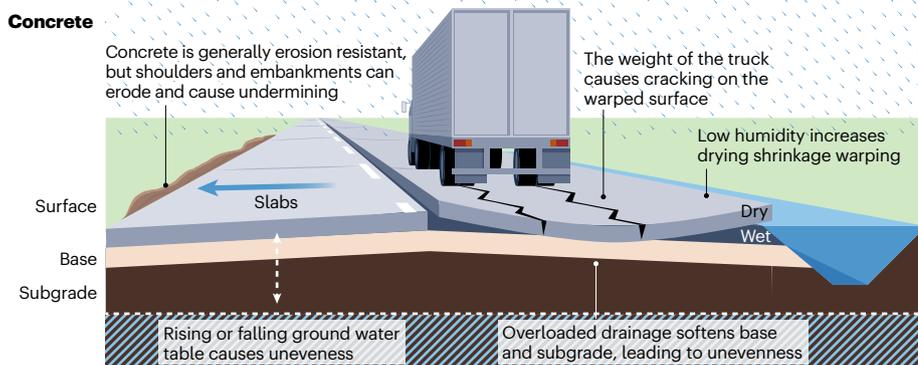
Gravel



Asphalt



Concrete



b

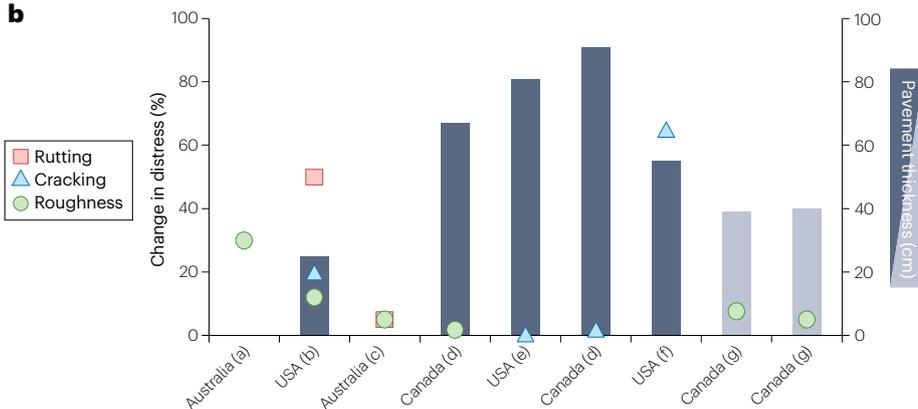


Fig. 2 | The effect of precipitation and moisture on roadways. a, The impacts of precipitation and flooding on gravel (unpaved) roads, asphalt (flexible) pavements and concrete (rigid) pavements. **b**, The projected change in pavement distress due to precipitation and flooding from representative examples (data from a⁵⁵, b⁵³, c⁵⁴, d⁵⁶, e⁵⁸, f⁵⁷ and g⁷), which use various research methodologies, pavement types, pavement layer thickness, magnitudes of flooding (characterized by depth, duration and return period) and locations. These examples were chosen because they quantify the impact of flooding on rutting, cracking or pavement roughness, or include sufficient information to estimate these impacts. The bars represent the thickness of the asphalt (dark grey) and concrete (light grey) pavements; the absence of a bar indicates that pavement thickness was not specified. The flooding and precipitation scenarios are not linked to a specific time period. Increased moisture generally causes more distress in thinner asphalt pavements than concrete pavements.

structure and precipitation or flooding scenario evaluated as well as the analysis methodology used.

In addition to structural effects, precipitation and moisture influence the functional capacity of pavements. Increased exposure to moisture can cause rutting and ravelling of asphalt surfaces and increase faulting (difference in elevation between slabs that creates a bump in the road) in concrete pavements. Moisture is estimated to increase the roughness of asphalt and concrete roadways by up to 45% (refs. 53–56) and 10% (ref. 7), respectively (Fig. 2b). Thicker pavement structures generally show lower distress than thinner pavement structures.

Changes in precipitation patterns and partitioning (such as, rain, snow and ice) can affect the moisture content of the unbound layers. Extreme precipitation from storms causes short-term increases in moisture content and triggers debris flows that run adjacent to or parallel with river channels, leading to slope erosion and structural damage to roadway embankments and pavements¹². In addition, low shoulders can channelize run off and cause erosion. Erosion from extreme precipitation events from storms such as Cyclone Idai in Zimbabwe¹³ and Hurricane Helene^{15,16} in North Carolina, USA, completely wash out and destroy sections of roads, requiring complete reconstruction to restore access. Unsealed cracks and joints in the pavement allow water to infiltrate faster, while the pressure from passing heavy vehicles generates upwards hydraulic stresses that form potholes and pump moisture-susceptible subgrade materials (silts and clays) upwards, creating voids beneath the pavement that can lead to cracking. Reduced humidity following drier conditions increases the drying shrinkage at the top of concrete roads, causing warping and increased cracking from self-weight and heavy vehicle loading^{59,60} on the warped slabs. Conversely, increased humidity following wetter conditions lengthens the curing time for asphalt emulsions, which are used as maintenance-related or preservation-related surfacing treatments and to bond or seal various layers⁶¹, negatively affecting performance if proper curing is not achieved.

Climate change is expected to increase the frequency and severity of droughts, with various impacts on the structural and functional capacity of pavements. Droughts have been linked with roadway damage in Europe⁶² and the USA^{63,64}. The lowering of groundwater tables during droughts can positively impact pavement structural response by reducing moisture contents in unbound layers⁶⁵. Drier conditions will generally improve pavement performance⁶⁶ owing to increased structural capacity and decreased deterioration of the surface. However, some soils undergo substantial decreases in volume under drier conditions, leading to land subsidence that can cause pavement cracking^{63,67–70}. Water pumping and reduced recharge in drought-prone areas can also lead to pavement subsidence^{71,72}.

Co-located and interconnected engineered and natural systems, which are affected by precipitation, can indirectly affect roadways. For example, storm water systems can be overwhelmed during extreme flooding events, leading to pavement inundation and associated damage⁷³. High-velocity water causes scour and erosion on the roadway shoulders and embankments and, in extreme cases, the paved surface^{74,75}. Damage to pipes and culverts from high volumes of water causes settlement in isolated areas, which makes the road rougher and, in extreme cases, sinkholes are formed, which compromise the pavement structure⁷⁶. These effects can take months or years to appear^{77–79}. Intensive precipitation causes cut slope failure, shallow landslides and debris flows over roadways, causing traffic disruptions and pavement damage⁸⁰. This phenomenon is especially frequent in regions affected by wildfires where eroded slopes are vulnerable^{81–83}. In addition, the

impact of extreme climate events on wildlife can indirectly influence pavement performance. For example, upstream beaver dam failures during Hurricane Florence led to flooding, which caused several pavement failures in North Carolina (USA)⁷³.

SLR

In coastal regions, increased surface water and subsurface moisture from SLR will impact the performance of roadways (Fig. 3). These impacts are typically gradual rather than acute. SLR will increase the frequency and duration of surface flooding from higher tides^{18,84} and storm surge. SLR also raises the groundwater table, increasing subsurface moisture content in the subgrade and granular layers⁸⁵ up to several kilometres inland depending on the geological conditions^{8,86,87}. Exposure to salt water also negatively impacts the strength and durability of asphalt concrete^{88,89} and Portland cement concrete and can cause accelerated corrosion of the reinforcing steel used in concrete pavements⁹⁰. The extent of the impact of SLR on roadways depends on the relative elevation of the roadway, local geological conditions and soil properties.

As with precipitation, the increased moisture content from SLR will reduce the structural capacity^{91,92} and lifespan of roadways⁸. The reduction in life due to SLR is projected to be up to 94% for rutting and 68% for cracking distress^{8,93,94}, depending upon the soil type, pavement structure and extent of groundwater rise. The lifetime of roadways is expected to reduce more with faster SLR⁹⁵, when the groundwater moves into the base layer of the pavement^{8,96} and for thinner pavement structures⁹³. In the sea coast region of New Hampshire, USA, sea levels are projected to rise by 2 m by 2100, putting approximately 23% (235 km) of roadways at risk of premature failure⁹⁶. In Miami-Dade County, Florida, USA, a high SLR scenario⁹⁷ is projected to cause damage to up to 12% of interstate, 46% of arterial and 76% of collector and local roadways⁹³ owing to rising groundwater tables by 2070.

SLR also makes roadways more susceptible to impacts from storms. SLR increases the potential for erosion of embankments, and roadways can be completely washed out from wave action and storm surge⁹⁸. Roadways on barrier islands are affected by the combined effects of water from the ocean and back-barrier lagoon and morphological changes that affect the exposure of the road to the water⁹⁹.

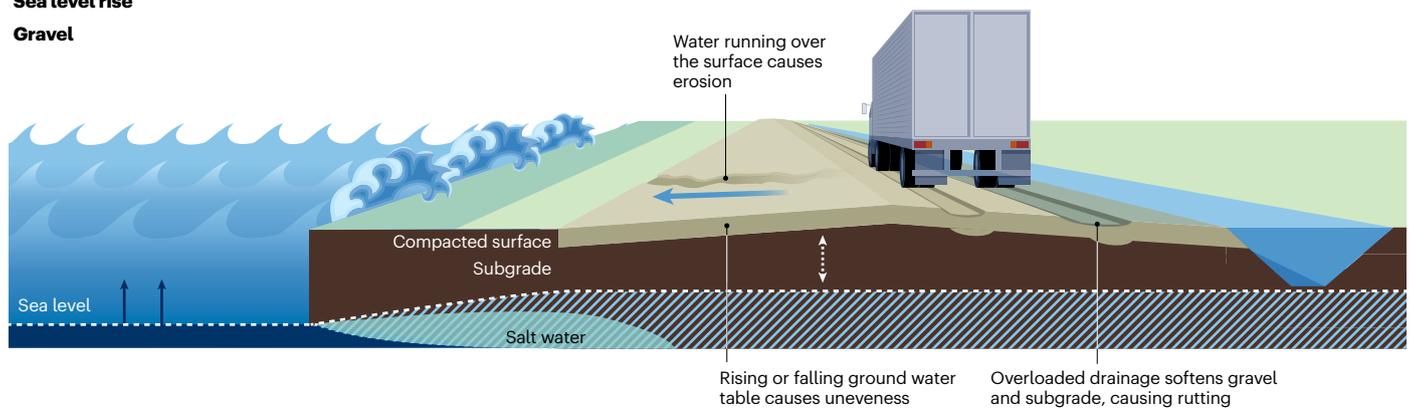
Combined effects

The structural and functional performance of roadways is often affected by the combined impacts of multiple climate stressors (Fig. 4). Increases in average temperature have a higher impact on asphalt pavements than increases in average precipitation¹⁰⁰, but the combination of stressors creates interactions that can accelerate deterioration. For example, high temperatures increase pavement fatigue cracking^{24–28}, which increases the likelihood of water (from precipitation or flooding) infiltrating the pavement foundation, further reducing the structural capacity¹⁰¹. Crack sealants and pavement seals can mitigate these effects, but there can be unintended negative safety consequences (for example, reduced skid resistance) from using such treatments to an extreme¹⁰². In addition, asphalt rutting caused by high temperatures increases the risk of hydroplaning when water accumulates in the ruts¹⁰³, increasing the likelihood of crashes¹⁰⁴. In concrete pavements, surface and subsurface moisture can interact with increased temperatures to increase the likelihood of buckling³³. The combined effects of moisture and exposure to repeated freeze–thaw cycles also cause crack formation through the expansion of absorbed

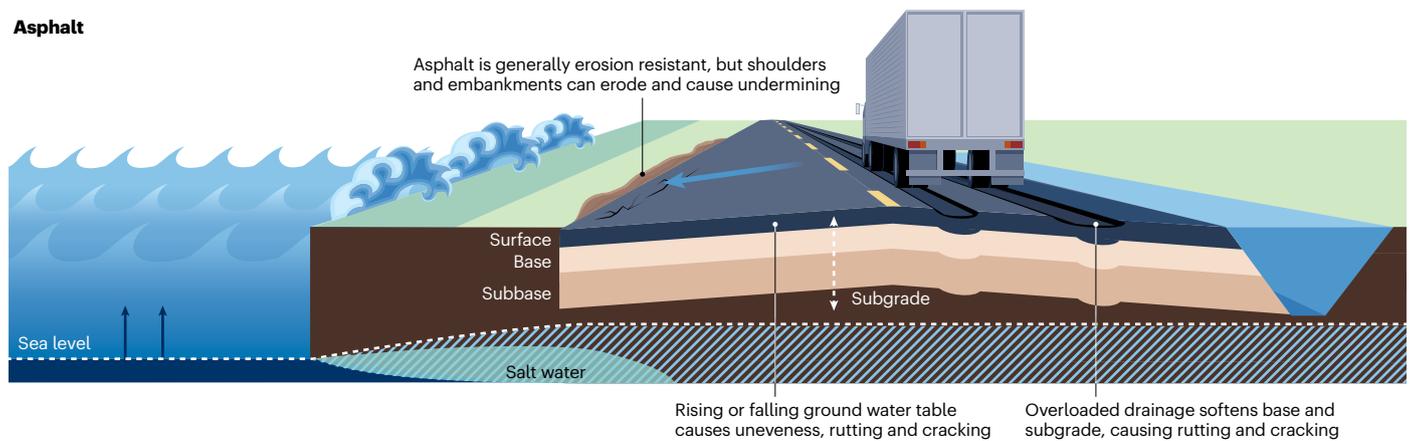
Review article

Sea level rise

Gravel



Asphalt



Concrete

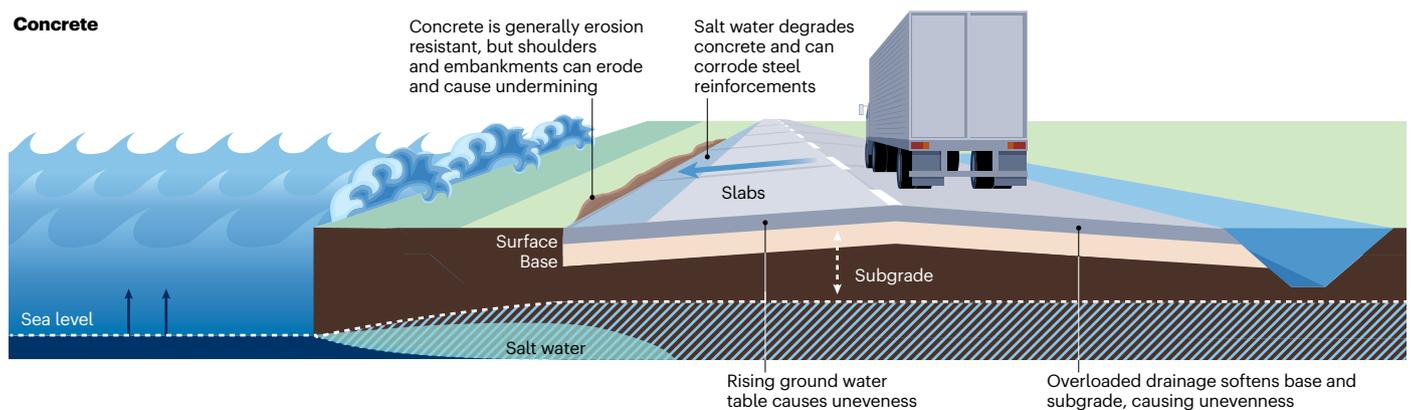


Fig. 3 | The effect of sea level rise on roadways. The impacts of rising groundwater table and higher storm surge caused by sea level rise on gravel (unpaved) roads, asphalt (flexible) pavements and concrete (rigid) pavements. Gravel roads are generally more vulnerable to the effects of sea level rise than paved roads.

moisture within asphalt and concrete^{10,105}. Unbound layers can also be weakened by the build-up of excess moisture from spring thawing of frost in cold climates¹⁰⁶.

Roadside vegetation stabilizes embankments against water erosion. Coupled changes in precipitation and temperature, especially through droughts and SLR-induced salinity changes, can modify the

viable range of existing vegetation and the growth habits of viable vegetation. If roadside vegetation is decreased, water volumes and velocities on the road can increase, causing accelerated damage in extreme events¹⁰⁷⁻¹⁰⁹. For example, the loss of salt-intolerant plants designed to buffer impacts of storm surge and wave action can accelerate the erosion of roadways and embankments¹¹⁰.

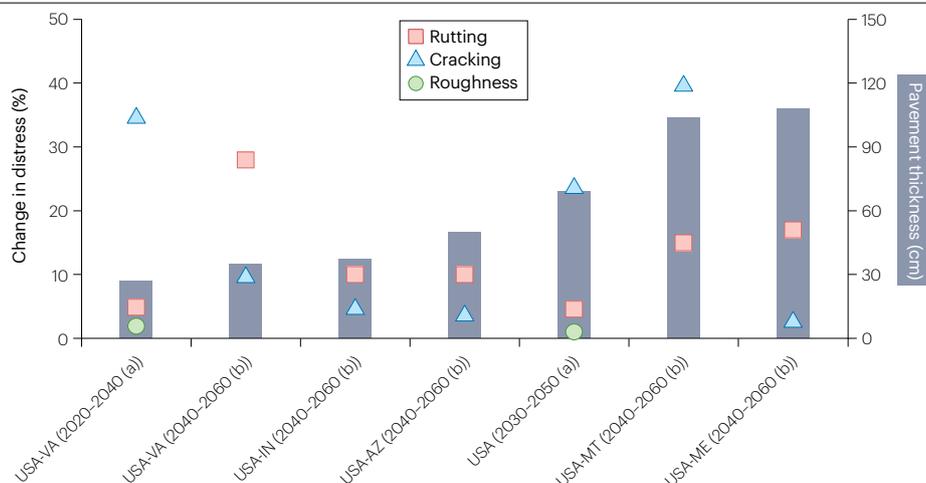


Fig. 4 | Combined impacts of multiple climate stressors on asphalt pavements. The projected change in the distress of asphalt pavements with various thickness (grey bars) caused by the combined effects of increased temperature and precipitation from representative examples between the present day and the indicated time periods (data from a¹⁷⁷, b²⁸ and c²⁴⁰) in various

states in the USA (VA, Virginia; IN, Indiana; AZ, Arizona; MT, Montana; ME, Maine). These data were obtained using different methodologies, pavement types, layer thicknesses, assessment periods and climate scenarios. The combined impacts of multiple stressors vary depending upon the stressors and pavement structures evaluated, with some being more critical for cracking and others for rutting.

Operational effects

Roadways must often be closed during and after extreme weather events, resulting in delays and detours. In addition, distress caused by climate change is increasing the need for maintenance, rehabilitation and, eventually, replacement of roadways¹¹¹. Rehabilitation is a construction activity that is more extensive than maintenance and helps to restore the condition of the roadway and improve its service life. The impact of climate change on roadway operations is outlined here in terms of delays, detours and changes in service life and required maintenance.

Delays and detours

Climatic events often necessitate full or partial roadway closures, leading to delays and detours for roadway users. It is estimated that, by 2100, high-tide flooding in the USA will cause 3.4 billion vehicle-hours of delays each year¹⁸. Average commute distances in Thailand more than doubled for days with riverine flooding in 2019 owing to detours¹¹². In Switzerland, 35% of roadway closures linked to climatic events during 2012–2016 caused detours of over 10 km (ref. 113). Road closures have the largest impact when alternative routes are limited – for example, when roadways on barrier islands⁹⁹ or bridges¹¹⁴ are closed. In January 2024, heavy rainfall destroyed four rural bridges in Coffee Bay, South Africa, cutting off local villages and preventing residents from accessing schools, health care and livelihoods¹¹⁵. Climatic events such as rain^{116,117} and snow¹¹⁷ can cause delays even if there are not roadway closures. Storms also cause operational disruptions due to road closures and detours and can result in pavement washouts where road embankment and structure is eroded from the flow of water over and around roadway⁷³. Pavement washouts can result in large potholes, completely washed out road structures and the formation of sinkholes.

The delays and detours from climatic events can result in substantial costs. A 4-day closure of Interstate 5 in Washington State, USA, in 2012 due to flooding led to a loss of economic output of US\$47 million by users¹¹⁸, and the closure of Interstate 29 and Interstate

680 in 2019 was estimated to have a total user cost of US\$200,000 per day (ref. 119). Flooding-related disruptions to the Pan Americana Highway in Peru are projected to cost users over \$100 million per year (ref. 120) throughout 2060–2099. It is estimated that, by 2100, delays due to high tide flooding in the USA will cost users a total of \$270 billion per year (ref. 18).

Detour pavements are not always designed to handle the additional loading¹¹⁹ and degrade more quickly. This impact is particularly evident in low- or middle-income countries such as Mozambique where 80% of the total roadway network consists of non-paved secondary and tertiary roadways¹²¹. After an extreme climate event, substantial debris needs to be disposed of^{35,122} and new materials must be transported for rebuilding, which can overload detour roadways, leading to degradation. Many local roadways were initially built by residents before the development of modern engineering and construction quality standards and were then resurfaced or upgraded by local authorities. Therefore, the standards to which local roadways were engineered and constructed vary, and they are often more vulnerable than highways.

Climate impacts can sometimes reduce traffic volume and delays. For example, the number of vehicles per kilometre travelled decreased by 12% within flood-impacted areas in Norfolk, Virginia, between August 2017 and August 2018 (ref. 123). In addition, probability for traffic delays reduced by up to 300% in New York on hot (20–30 °C) and cold (below 0 °C) days owing to reduced traffic volumes¹¹⁶. Similar reductions in delays, detours and maintenance costs are likely as more winter precipitation events occur as rain rather than snow.

Maintenance and service life

Climatic events can also impact the integrity of roadways; therefore, more frequent repairs and reconstructions^{28,124} are needed to ensure that roads are safe to use¹²⁵. Roadway maintenance and repair requires access to the roadway to be partially or fully reduced. The resulting interruption must be operationally managed by considering network

interdependencies and redundancies to ensure that the overall impact to mobility is minimized¹²⁶. Repair needs become more acute when extreme events occur, because during and immediately after the extreme events agencies need to prioritize decisions for emergency evacuation, human safety and recovery operations over road repairs¹²⁷. Vulnerability assessments of road networks help to identify areas where the chance of exposure to a climatic event or condition that could cause damage (hazard) is high, the importance of keeping the road open and accessible is greatest, and the overall road condition makes it particularly sensitive to hazard exposure¹²⁸. Once the vulnerability is understood, operational decisions can be made to reduce the cost and disruption of rerouting and to maintain connection with emergency facilities¹²⁹ – for example, by staging personnel and resources (such as stockpiling materials, having dedicated repair equipment and stationing personnel near vulnerable roads) and/or by developing long-term plans to make repairs and harden roadway assets¹³⁰.

The direct costs from increased maintenance due to climate change will be substantial^{30,32,131,132}. The global estimate of the cost of roadway maintenance for 1 km of a single-lane roadway is US\$27,219 (ref. 11). Although estimates vary, climate change is expected to increase national annual roadway maintenance costs by US\$88–727 million by 2050 (refs. 30,32,131,133,134), with the largest impacts occurring in regions with a high percentage of unpaved roadways^{135,136} (Fig. 5). Available funding for transportation infrastructure is already insufficient to improve the overall US road infrastructure¹³⁷; therefore, it is unlikely that agencies will be able to adequately keep up with the increased demand for repairs. Thus, the overall condition of roadways is expected to get worse under climate change. The increased costs of

faster pavement damage and the commensurate increase in costs for maintenance and repair will particularly affect countries, regions and communities unable to increase funding for infrastructure resilience to climate change.

Besides the direct costs, there will also be an economic burden to users from worsening roadway conditions. For example, rougher roadways will increase fuel and vehicle maintenance costs^{138–140}. In addition, increased delays due to decreased free-flow speed¹⁴¹ and increased construction for road repairs will result in higher road user costs.

Construction and maintenance activities are also likely to be impacted by climate change because pavement construction and, to a lesser extent, maintenance are highly dependent on weather. An increased number of hot weather events can affect road construction and maintenance worker safety and limit the number of days available to construct and repair pavements. An adaptation strategy is to work at night, but night work has been attributed to poorer long-term performance¹⁴² and increased safety risks for workers¹⁴³.

In some regions (for example, China, India and Africa), there have been substantial investments since 2010 to build new roadway networks, with more upcoming^{144,145}. In these cases, there is potential for careful upfront planning for climate-change-related impacts. Elsewhere (for example, the USA, Europe and Japan), new roadways are generally not being built and there are limited resources for large improvements. In these cases, roadway building authorities need to consider how to work within the confines of the existing system and develop climate change resilience as part of regular maintenance and repair cycles¹⁴⁶. It will be important to consider a long-term view of the pavement asset when making these maintenance and repair decisions to include the effects of future climate conditions.

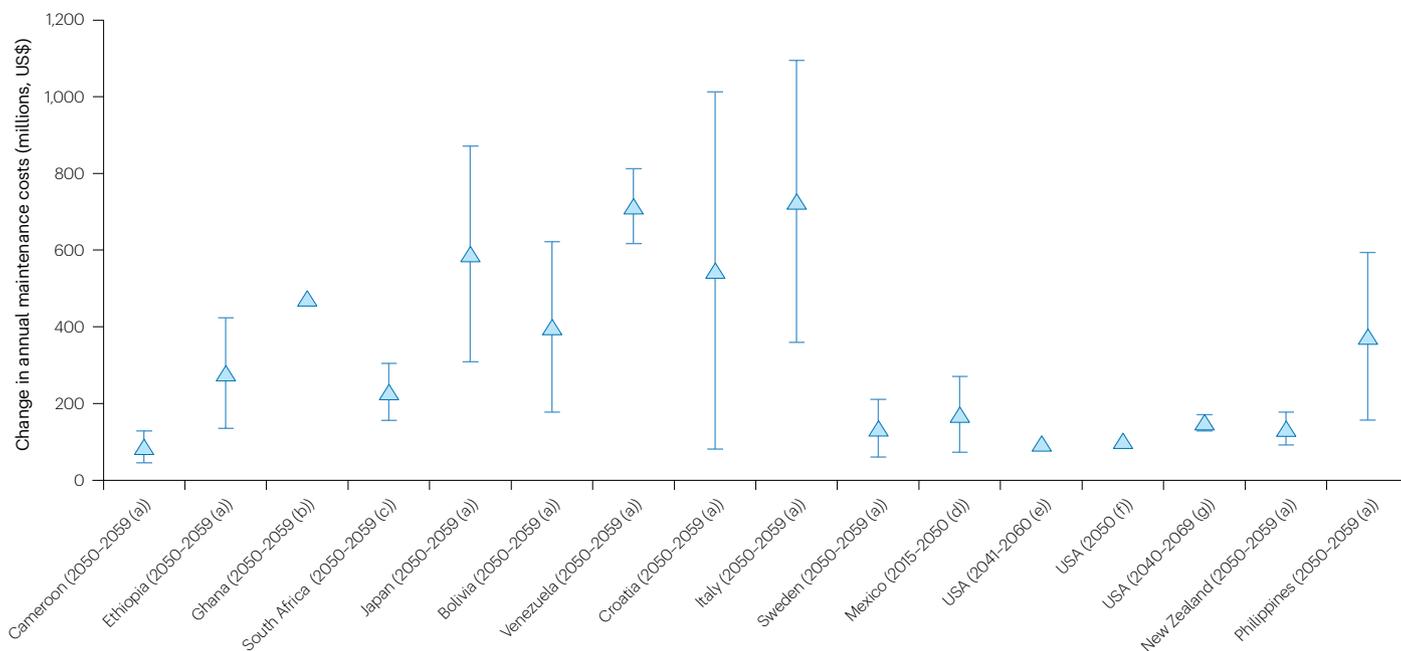
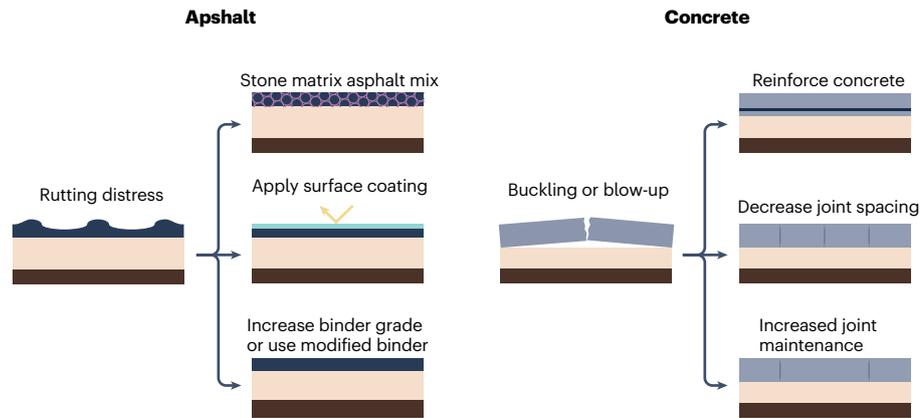


Fig. 5 | The impact of climate change on pavement maintenance costs. The average projected change in annual maintenance costs between the present day and the indicated time periods from representative examples (data from a¹³³, b²⁴¹, c¹³⁵, d²⁴², e³⁰, f¹³¹ and g³²). The error bars represent the range of cost calculated in each example; the absence of error bars indicates that only a single value was

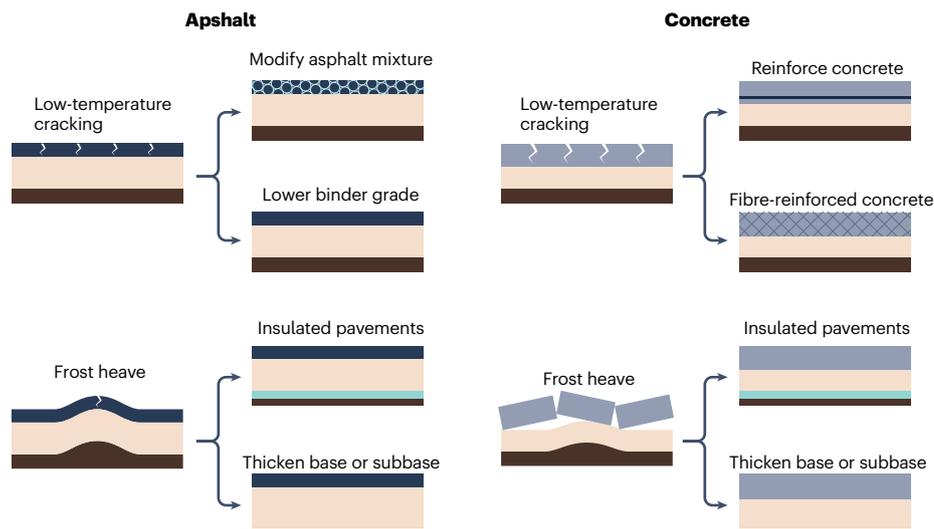
reported. These examples are for different locations (and therefore different projected levels of climate change), stressors, models and scenarios, and use different analysis methodologies. The effects of climate change are projected to increase national annual maintenance costs of pavement by over US\$500 million by mid-century, depending on the location.

Review article

a High temperatures



b Low temperatures



c Flood inundation

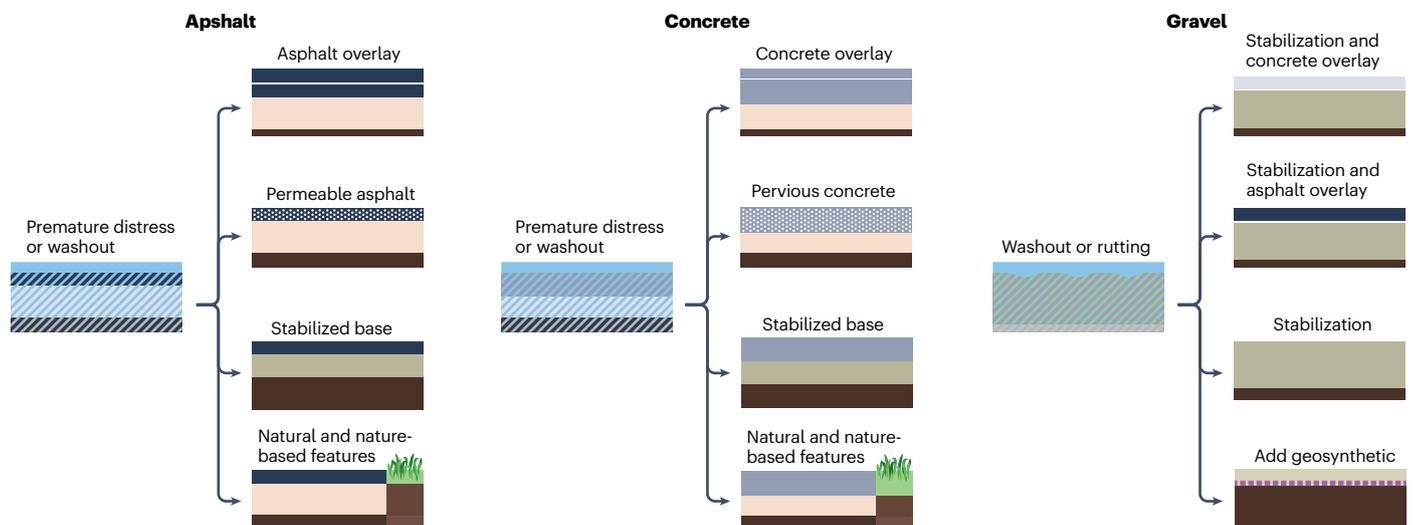


Fig. 6 | Pavement adaptation strategies. **a**, Adaptation alternatives to address the challenges of rutting in asphalt and buckling in concrete caused by high temperatures. **b**, Adaptation alternatives to prevent cracking and frost heave in asphalt and concrete at low temperatures. **c**, Strategies to minimize the effects

of flood inundation from precipitation or sea level rise in asphalt and concrete pavements (distress or washout) and gravel roads (washout or rutting). Each adaptation alternative will have varying economic, environmental and resilience impacts, which should be considered throughout the life cycle of the pavement.

Adaptation opportunities

The loads that a roadway can withstand are strongly influenced by climate change, necessitating adaptation strategies to modify pavement designs or maintenance procedures to increase resilience¹⁴⁷. Adaptation is different from mitigation, as adaptation measures are a response to expected changes whereas mitigation measures are intended to reduce the magnitude of the stressor (for example, reduced emissions). There are relatively few examples of pavement engineering incorporating climate change and, hence, limited reliable guidance on how to increase resilience¹⁴⁸. Nevertheless, various adaptation strategies and approaches have emerged, as now discussed.

Adaptation decision frameworks

Established decision frameworks are used to evaluate adaptation strategies. A typical framework includes goal setting, risk assessment in terms of probabilities of problems and their expected outcomes (usually in terms of safety, financial cost, failure or damage extent), identification of responses, and execution of the policy and plans⁸³. There are numerous tools to evaluate threat probabilities, including Coupled Model Intercomparison Project [climate data processing tool](#), [Hazus, flood maps](#), Hazard Exposure Reporting and Analytics (HERA) and International Panel on Climate Change Working Group I [Interactive Atlas](#) (see Supplementary Note 1 for further examples). However, these tools use various models and combinations, as well as future scenarios, and might require additional processing to achieve the temporal and spatial data resolution needed for project-level analysis.

Frameworks generally fall within top-down, bottom-up and hybrid categories. Top-down approaches use future conditions in existing pavement analysis methods to design and evaluate alternatives⁹ and are used at the network-level by authorities using a forward-looking, data-driven pavement management system that predicts the need for future maintenance and rehabilitation projects based on performance models. This approach can identify vulnerable segments of the network to determine what resilience measures are required in the forward-looking plan for future maintenance and rehabilitation. However, this guidance can vary based on the chosen climate-change scenarios^{149,150}. Bottom-up approaches evaluate pavement performance under the possible range of future climates^{151–153}. Bottom-up approaches are useful for road authorities that do not have the resources to operate a forwards-looking pavement management system because maintenance and rehabilitation projects are triggered when a level of distress can be seen on the pavement surface. Both framework types should include a resilience assessment, checking the level of resilience priority due to factors such as emergency route status, drainage capacity, pavement structure and traffic volume in relation to future climate stressors. Hybrid adaptation approaches combine the benefits of these two approaches¹²⁴ by first determining the response to incremental environmental change and then identifying the timing of critical degradation²⁵.

Adaptation decision frameworks must consider engineering, economic, environmental and socioeconomic factors. Life cycle assessments (LCAs) quantitatively assess the economic and environmental

costs of the construction process, materials and maintenance cycles of pavement adaptation approaches. Economic costs can also be measured using benefit–cost analysis. Pavement-specific LCA tools are increasingly available for project-level^{154–156} and network-level analyses¹⁵⁷. The desired lifetime of the roadway should also be considered, particularly in locations where SLR is expected to frequently affect the pavement within the lifetime of the pavement. At the policy level, both economic and environmental LCA should be considered together when considering alternatives. Social LCA can quantitatively assess social vulnerability and impacts. Social vulnerability indices are best calculated at the neighbourhood level where demographics are often narrowly distributed. Social vulnerability calculation methods have been developed that consider income, age, current health conditions and race using tools such as [CalEnviroScreen](#)^{158–162}. The social impacts of various adaptation alternatives can be calculated in terms of safety, loss of property, and accessibility to jobs, health care, food, education and increased pollution.

Uncertainty and constrained funding are two key challenges in adaptation investment decisions^{163,164}. Categorizing the roadway network into potential risk management categories according to the expected asset loss for different event frequencies can provide clarity¹⁶⁵. Risk can be quantified on the basis of the level of vulnerability, the mobility consequences of failures in specific assets and the sensitivity of an asset to failure¹⁶⁶. Many high-income countries are developing guidelines on climate-resilient pavement or roadway design. Some guidelines are already available for vulnerable low and middle-income countries that have had donor involvement in developing design guidelines for their specific conditions^{167–170}.

Adaptation strategies

Adaptation strategies generally fall under four categories: control, transfer, avoid and accept^{165,168,171}. Control involves hardening and protecting the roadway. Various approaches are used to design the pavement structure to withstand projected future climate and/or elevated groundwater tables^{7,26,83,172,173}. Control can also occur gradually, identifying ways to adapt the roadway to decrease its risk of failure, for example, by increasing maintenance activities^{174–176}. Adaptation alternatives can be a blend of techniques that indirectly harden or protect the roadway, or accommodate and maintain the system.

Adaptation strategies to respond to the reduction in structural or functional capacity under high temperatures differ for asphalt and concrete pavements (Fig. 6a). High temperatures can be addressed in asphalt pavements through adjustments to the asphalt binder grade, which is associated with the temperature in which the pavement is expected to perform^{9,32}; the use of modifiers or additives such as polymers or fibres that increase stiffness, flexibility and/or tensile strength^{9,119,177}; or different mixture types such as stone matrix asphalt, which is designed with a strong aggregate skeleton^{178–182}. Thickening asphalt layers can also decrease the amount of rutting in an asphalt roadway¹²⁴. Solar reflective coatings can decrease albedo and reduce the heat absorbed by asphalt pavements^{20,183,184}. Portland cement concrete roadways can be constructed with steel reinforcement or joints

spaced closer together to reduce the stresses that cause buckling at high temperatures^{185,186}. In addition, increased maintenance of concrete joints also helps to prevent buckling failures.

Similar approaches can be used to prevent damage from low temperatures (Fig. 6b). Cracking associated with low-temperature extremes is addressed by using modifiers, using additives or adjusting the binder grade in asphalt roadways^{187,188} and using steel or fibre reinforcement in concrete roadways^{189,190}. Insulation layers (such as foam blocks or polymeric materials) or thickening of the aggregate base protect asphalt and concrete roadways from frost heaves and can also be used to prevent permafrost from melting under increasing temperatures by limiting heat transfer^{6,22}.

The impact of precipitation, moisture and SLR on roadways is addressed by responding to water inundating unbound layers or eroding shoulders or embankments and undermining pavements (Fig. 6c). Thickening asphalt and concrete pavements^{119,191,192} through maintenance overlays or thicker base or subbase layers during rehabilitation improves the structural capacity of the pavement to withstand flooding and rising groundwater table⁹⁶. The use of full-depth reclamation, which recycles and stabilizes existing asphalt, aggregate and soil layers as a means of stabilizing the base¹⁹², or subgrade stabilization to stiffen the roadway base or subgrade^{193,194} also decrease the susceptibility to changes in moisture content. Separation layers such as geosynthetics mitigate the effects of flooding^{195,196}, particularly for gravel roadways, by helping to absorb the tensile strain at the bottom of the pavement layer when the roadway base is weakened while saturated. The resistance of asphalt to moisture damage can be increased using fillers and other additives^{197,198}, including hydrophobic coatings at the surface¹⁷⁴.

Upgrading subsurface drainage¹⁷⁴ can reduce damage by removing water, which weakens the pavement base, from the pavement system for all roadway types. Green infrastructure and techniques such as infiltration trenches¹⁹⁹, replacing impervious surfaces with porous asphalt or permeable concrete pavements^{200–202}, the use of transport channels and rainwater storage²⁰³ quickly remove water and mitigate the impact of run off on roadways²⁰⁴. For expansive clays in the subgrade, which swell in the presence of water and shrink when water is removed, recommendations include removing and replacing with non-expansive subgrade soils or aggregates, multistage construction to allow for clay expansion and stabilization, the use of additives in the subgrade^{205,206} or the addition of geosynthetics¹⁹⁵.

Natural and nature-based features (NNBFs) such as maritime forests, marshes, mangroves, dunes, reefs and beach nourishment can reduce impacts of flooding, storm surge and waves while also contributing socially and economically¹¹⁰. NNBFs offered benefits on property protection and enhancement, recreation, ecosystem sustainability and climate regulation risk reduction for multiple sites during Hurricane Sandy (USA). In addition, restored marshes distributed wave energy, preventing the Cross Bay Bridge in Jamaica Bay (New York, USA) from being damaged²⁰⁷. There is ongoing work to explore how NNBFs have contributed to roadway resilience²⁰⁸; however, existing documentation is limited.

Transfer adaptation strategies shift the financial consequences of a risk from one party to another²⁰⁹. Financial instruments such as insurance or emergency funds are used at the national level to transfer the financial risk of roadway network losses caused by a climatic event²⁰³. In a long-term maintenance contract or public–private partnership contract, the risk of hazard event loss can also be transferred to the contractor or concessionaire. Although this approach does not adapt

the pavement materials or structure, it reduces the risk for the owner agency and establishes an understanding and responsibility for the contractor or concessionaire to maintain the infrastructure in the event of a disruption.

Avoid strategies, also known as managed retreat, is when the roadway is relocated or abandoned. For example, the Honoapiilani Highway (HI, USA) was realigned further inland in response to SLR and coastal erosion²¹⁰. Relocation can be very expensive and controversial owing to the burden it places on citizens directly impacted. The state law in California (USA) strictly limits the situations in which public roadways can be abandoned, and neither frequent flooding nor the expense of maintaining a highway that experiences repeated damage are permissible reasons for closing and abandoning a roadway²¹¹. These obligations directly impact the ability of local governments and asset managers to develop and implement SLR adaptation measures and will need to be addressed in the future.

Accept is the business-as-normal approach, which often results in doing nothing, at least in the immediate future. Adaptation considerations might include rapid reconstruction of asphalt pavements, the use of technologies such as warm mix asphalt to increase haul distances after a disaster^{212,213}, recycling materials from affected pavements due to disruption-induced supply chain challenges, and developing rapid contracting mechanisms to accelerate recovery efforts¹¹⁹. In addition, roadway closures will need to be maintained after flooding until the subbase has drained sufficiently to provide support^{51,96,214}.

Resilience does not mean that roadways are completely free from disruptions, and it is not financially viable to reduce the risk from all possible climate stressors to zero for all roadways. The most cost-effective option is to combine some robustness, such as changing materials to cope with increased moisture, with an operational response, such as restricting access to the roadway for some days of the year. For example, many Australian rural roadways have river crossings consisting of a concrete pavement at riverbed level that allows vehicles to cross for most of the year^{215,216}. However, during rainy seasons these crossings are closed and vehicles must take longer routes via bridges.

Policy impacts and needs

Roadways are expensive to build, maintain, rehabilitate and reconstruct. Globally, in 2024 approximately US\$3.4 trillion was invested in the building of new roadways, with about half in the Asia-Pacific region, followed by Europe and North America. Approximately another US\$700 billion is spent annually on maintaining, rehabilitating and improving existing global roadway networks¹⁴⁵. The reported spending on global roadways for new construction and work on existing roads combined has an interquartile range of US\$200,000 per kilometre to US\$400,000 per kilometre, with higher levels of spending in regions with higher gross domestic product per capita²¹⁷. Most global investment in roadways uses public funds, either from roadway taxes and fees or international investment (largely Chinese investments in other countries). Mexico is an outlier because it has a relatively high percentage of private investment (almost 25% of total)²¹⁷. In the USA, state and local governments spent approximately US\$154 billion and the federal government spent US\$52 billion in 2021 on roadways, and this spending is expected to increase with the passage of the 2021 infrastructure bill²¹⁸.

Roadway construction and maintenance cost inflation are often higher than general inflation, and the ability of fuel taxes to cover roadway maintenance is decreasing. In 2024, general construction

cost inflation was lowest in Europe at 2.8% and highest in Africa at 6.6% (ref. 219). The [US National Highway Construction Cost Index](#) increased by approximately 50% between 2021 and 2023, which is almost double the rate of increase of producer prices and consumer prices in the same period. Many fuel taxes are not inflation indexed and lose their buying power as construction prices increase over time (the [USA federal fuel tax](#) was last raised in 1993).

Although the transition to battery electric and fuel cell vehicles has many environmental benefits, it is expected to increase damage caused by trucks on roadways and reduce funds available for roadway repair and maintenance. Estimates for pathways to alternative fuel trucks vary depending on incentives, regulations, charging infrastructure deployment and power train technology developments²²⁰. For example, it is estimated that 25–70% of long-haul and 40–95% of short-haul and medium-duty trucks in California will have battery electric or fuel cell power by 2050 (ref. 221). Revenue from fuel taxes will decline as vehicle fleets transition to battery electric and later fuel cell propulsion systems. In the USA, further work is needed to implement vehicle mile travelled taxes or other alternative funding approaches²²². Adopting battery electric and fuel cells can increase the weight of trucks by 20–30%, increasing pavement stresses^{221,223,224}. However, future battery and fuel cell developments will reduce power train weights and soften the impacts on pavements. Despite these challenges, the climate change mitigation benefits of alternative propulsion deployment are much larger than the increased emissions caused by the increased pavement damage and resultant need for more frequent maintenance and rehabilitation. It is likely that improvements in pavement construction quality, design, management and materials over the next 10–30 years will compensate for the additional costs²²¹.

The need for roadway construction and maintenance and associated costs will continue to increase. Distances travelled by vehicles are likely to increase nationally and globally, with global tonne-kilometres of freight movement expected to approximately double between 2020 and 2050 (according to [Statista](#)). Ageing infrastructure requires additional investment and is susceptible to damage from climate change stressors. Climate-related migration will indirectly impact roadways by increasing traffic loads in some areas and causing land-use change that results in abandonment of infrastructure in other areas^{225,226}. Many roadways are paid for through fuel taxes; therefore, migrations are likely to change the funding models and budgets available for roadway repair and maintenance. There are also uncertainties regarding the impacts of climate change on decisions regarding mode of transportation, which will affect demand for roadway infrastructure capacity²²⁷ and how the increased frequency of extreme weather events will increase demands on evacuation routes and damage to pavements from recovery efforts²²⁸.

Practices in transportation infrastructure planning, engineering and asset management aim to minimize risk; however, these practices often use outdated assumptions and limited information. Many countries, states and local governments use historical climate records that are 30 years old or more²²⁹ for decision support and design. Vulnerability assessments used to support management decisions²³⁰ usually include only environmental parameters and not an assessment of roadway vulnerability. Although the US Federal Highway Administration issued guidelines in 2017 for assessing highway vulnerability under various climate change scenarios²³¹, there are very few assessments of roadway vulnerability to coastal hazards, and these might not be updated as climate change projections are updated. Transport

authorities rarely systematically collect data for long-term assessments of roadway vulnerabilities²³².

Summary and future perspectives

Roadways are vulnerable to the impacts of climate change because of their constant exposure to the environment. The type and severity of impact depends on the type and location of the roadway (Fig. 7), with local roads more vulnerable than highways owing to their lower design reliability. Temperature extremes caused by climate change are degrading asphalt and concrete roadways through rutting, fatigue cracking, ageing-related cracking and buckling. In addition, flooding, increased rainfall and SLR weaken roadways for months and reduce their lifetime or completely wash them away. Increased funding is therefore needed to maintain and repair roadways and for adaptations to increase roadway resilience. Adaptation strategies include hardening or protecting the roadway, gradually adapting to reduce the risk of failure, retreating, or accepting the risk and planning for repairs.

There is a lack of understanding of how climate stressors interact because the impacts are not necessarily additive. The variation in reported distress illustrates that a range of factors interact to impact road performance. Advanced pavement modelling that accounts for multiple stressors and their interactions, full-scale test facilities capable of controlling multiple climate factors and field performance data linked with climate history are required to explore the interactions between stressors. For example, understanding the impact of tidally induced changes in groundwater and salinity will require a combination of pavement modelling that accounts for vertical water movement in the subgrade and base layers and physical testing of materials under various salinity conditions over time. Roadway washout and cascading effects from interconnected systems due to flooding and storm events are common but are not well understood, and there are few datasets that document washout failures. Dedicated funding is needed to conduct experiments, gather field data on failure sites and event conditions, and develop models that can quantify the impacts of failure of interconnected systems and moving water over and adjacent to roadways. In addition, a standardized approach is needed to translate climate model outputs into the climate variables and temporal scales required for pavement analysis.

Data science techniques can be used to better understand the vulnerability and associated risk of assets and the extent of potential damage. Many agencies collect datasets of roadway conditions through pavement management systems. By linking these datasets with structural performance history, traffic mapping, geographical systems and historical weather station monitoring systems, it will be possible to develop statistical probabilities of maintenance frequencies and failures based on historical, ground-truth data. Although this step will require substantial computational power, it will enable the vulnerability of assets and the system to be evaluated using future climate projections to understand the vulnerability and associated risk of the system to a disruption, helping with adaptation planning. In addition, these models might be applicable, with some calibration, to under-resourced countries and communities that do not have a rich pavement performance dataset but that are still subject to climate-related disasters. Pavements with embedded monitoring systems (smart pavements) could help to assess weather-related impacts. However, it is unclear how these next-generation pavements and their infrastructure will be affected by climate change.

There is little work connecting roadway pavement damage to operational impacts and the socioeconomic repercussions. More research

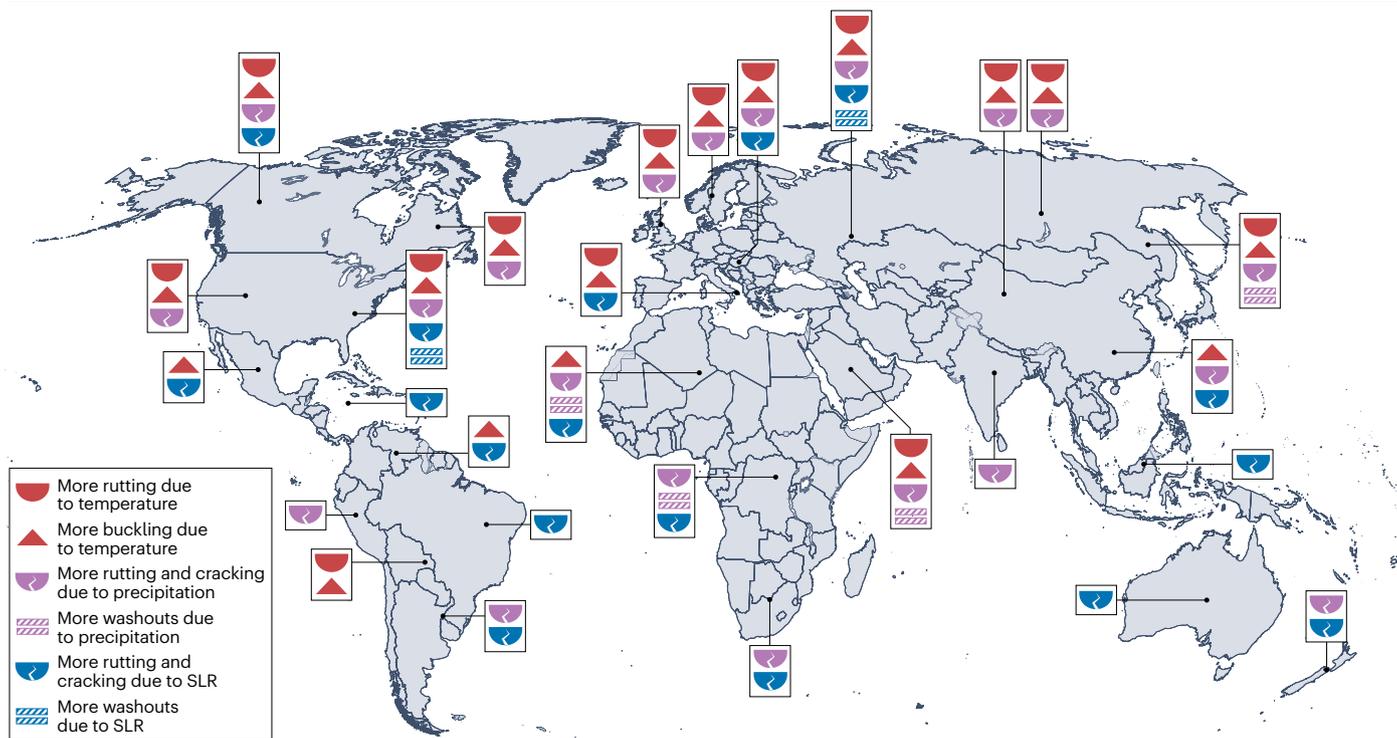


Fig. 7 | The global impacts of climate change on roadways. Locations where an increase in rutting due to temperature (asphalt pavement temperatures projected to increase by over 2 °C), rutting and cracking due to precipitation (over 8% increase in precipitation) or sea level rise (SLR; of 0.3 m), buckling due to temperature (over threefold increase in buckling events³³ due to an increase in mean temperature of at least 2.2 °C), or washout due to precipitation (over 15% increase in precipitation) or SLR (0.4 m) is expected for projected climate change by 2041–2060. The projected climate changes are based on median

values obtained from International Panel on Climate Change 6 [Interactive Atlas](#) using Coupled Model Intercomparison Project 6 and Shared Socioeconomic Pathway 5-8.5 scenario, with increases in maximum temperature and maximum 1-day precipitation based on a 1986–2005 baseline and SLR based on a 1995–2014 baseline. The indicated locations represent changes in the general region rather than in specific point locations. The projected changes in roadway damage at mid-century vary across the globe.

is needed to explore the dynamics, processes and consequences of the effect of climate change on roadways and pavements and the resulting economic, social, emergency response and operational impacts. An appropriate functional unit must be defined to enable operational impacts to be consistently measured. Although delay times and detour distances provide location- or region-specific measures, they do not capture traffic volumes, origin–destination distances or the number of people affected.

More clarity is needed regarding the evaluation of adaptation strategies. NNBFs do not always have clear, directly predictable impacts, and work is needed to model the roadway and environmental systems together under various climate conditions to quantify the benefits for the environment and roadway. A systematic process should be developed to analyse the transport system to identify where investment should be made to ensure that the community benefits. Combining operational and structural adaptation strategies might provide the most beneficial and equitable solution and flexibility under uncertain future conditions. Such an approach will require an integrated method to account for the structural, functional and operational impacts of climate change on roadways. In addition, methods to quantify return on investment that account for environmental and socioeconomic factors need to be developed.

There are several key areas in which policy is needed to adequately respond to the effects of climate change and correct problems from past practices²³³. First, people must be brought into the workforce and prepared and inspired to meet these challenges. Second, data presentation tools should be built to map complex data from various sources to support decision-making. Third, technology tools, codes and specifications must be developed to meet new demands along with guidance for how to use them. Fourth, there must be changes to how risk of innovation is assigned and mitigated for roadway owners and the professionals licensed to work in and for them. Fifth, funding levels must be increased to support climate resilience and improve climate and infrastructure justice, and performance measures should be developed for that funding. Finally, people must learn to work together to adapt to climate change in ways that meet functional and equity goals, while avoiding actions that exacerbate climate change. These goals can be completed through various national grant programmes, local resilience-based implementation projects and special provisions that allow climate change adaptation techniques and technologies to be implemented, while being approved through the traditional specification adoption process.

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