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DEALING WITH THE EFFECTS OF CLIMATE CHANGE ON ROAD PAVEMENTS

PIARC Technical Committee D.2
Road Pavements

WORLD ROAD ASSOCIATION
MONDIALE DE LA ROUTE
AIPCR PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2008 – 2011 approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.

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SUMMARY

The majority of the scientific community is in agreement that increasing atmospheric concentrations of carbon dioxide and other greenhouse gases as a direct result of human activity is causing a global change in climate. Between 1906 and 2005, the global average near-surface air temperature increased by 0.74°C. It is expected that global average near-surface air temperature will further increase in the years to come, despite efforts to reduce greenhouse gas emissions through mitigation actions.

Climate change is highly likely and almost certain to result in reduced ice and snow coverage, changes in freeze-thaw cycles, rising sea levels, more frequent and intense storms, with rises in average surface temperature and more severe heat waves and prolonged droughts, directly impacting on the performance of our infrastructure, depending on its location.

Climate change can have a direct impact on the performance of our transportation infrastructure. More frequent and intense rainfalls in certain parts of the world may result in flooding and higher groundwater levels, which in turn may lead to erosion, slope instability and reduced structural strength and bearing capacity of road structures. In other parts of the world, the structural strength of road structures may also decrease as a result of thawing of permafrost. Yet in other locations, roads may become exposed to higher incidence of freeze-thaw cycling which will accelerate pavement deterioration which results in increased maintenance costs. Conversely, increases in the ambient temperature may cause bituminous-bound materials to become susceptible to permanent deformation in the form of rutting. In the years to come, climate change will impact on the way roads are planned, designed, constructed, operated and maintained.

The purpose of this report produced by Technical Committee D.2 *Road Pavements* of the World Road Association, is to sensitise the road sector to the likely impacts of climate change on road pavements and to provide guidance on how to go about:

1. Assessing the vulnerability of road pavements to the direct impacts of climate change, and;
2. Identifying and prioritising possible adaptation measures for road pavements that could be applied immediately or phased in over time, so as to avert the negative consequences of climate change on the serviceability of road networks.

In order to better understand the vulnerability of road pavements to the direct impacts of climate change, and to assess the degree of concern and level of readiness of the roads sector, a questionnaire was prepared. Based on the responses received from 21 countries, it became clear that most countries were concerned about the levels of precipitation, where increased levels could cause flooding

and impact on the structural integrity of pavements (and may necessitate the imposition of load restrictions), and decreased levels of precipitation could dry out the subgrade impacting on the overall durability of the pavement. Most coastal countries raised concern about rising sea levels which, when combined with storm surges, could lead to flooding and therefore also road closures. The likely increase in road closures as a consequence of land slides caused by higher precipitation levels was also raised. Several countries expressed concern about an increased frequency in the number of freeze-thaw cycles, leading to frost heave, cracking and potholing. With regard to increased temperatures, several countries, including those with cold winter conditions, raised concern about increased potential for rutting and bleeding in bituminous-bound pavement layers during summer.

In the document, guidance has been provided on how to conduct risk and vulnerability assessments, and on how to deal with the effects of climate change on road pavements. Feedback received, supported by literature on the subject, led to the following observations and recommendations:

- there is sufficient scientific evidence confirming that climate change is happening. Climate change projections are readily available and are being improved upon on a continuous basis so as to empower decision makers, such as road owners/ operators, with information enabling them to assess the vulnerability of their assets and assisting them to improve their planning for the future;
- short and long-term effects of climate change may necessitate more frequent maintenance/ rehabilitation/reconstruction, impacting on the budgets of road owners/operators. Overall, climate change is expected to increase the cost of road maintenance and rehabilitation;
- road owners/operators should implement a systematic approach to define risks and assess the consequences thereof at network level, and should initiate the development of strategies to mitigate these risks in a cost-effective manner using whole-life costing models that incorporate climate change scenarios;
- together with the latest available climate change projections, use should be made of climate analogues to gain a better understanding of the likely pavement engineering solutions that could be adopted from elsewhere to be able to plan ahead and to cope with the projected impacts of climate change;
- differentiation should be made between existing infrastructure, which cannot be changed overnight, and new infrastructure that needs to be constructed. The outcomes of the risk analysis would dictate which actions would require immediate attention (e.g. redesigning drainage systems and adapting design temperatures). For existing infrastructure, assuming that climate will only change gradually over time, adaptation strategies could be phased in over time (e.g. during periodic maintenance or rehabilitation);

- besides protecting the value of assets, road user safety should also feature as a prominent issue in any climate change risk assessment and response strategy. Similarly, the protection of road workers should be looked after, particularly during extreme weather events where they may be tasked to clear debris, redirect traffic or institute emergency repairs;
- apart from adapting design rules and specifications, operational response to climate extremes may have to be improved, where warranted. This may include managerial and emergency teams having to be on standby to impose load restrictions on certain roads, clear debris on roads, divert traffic to alternative routes, and so on. It also includes the necessity to have effective and efficient communication strategies in place to inform road users;
- education on climate change should be promoted in order to create a greater awareness of the importance of both climate change mitigation and climate change adaptation.

Given the strategic role of transport to support socio-economic development, planning for the already known and projected impacts should be pursued without delay.

TERMINOLOGY AND ABBREVIATIONS

TERMINOLOGY

(within the context of this document)

Adaptation: Autonomous or policy-driven adjustments in practices, processes or structures to take account of changing [climatic] conditions.

Adaptive Capacity: The degree to which adjustments in practices, processes and structures can moderate or offset the potential for damage or take advantage of opportunities created by a given change [in climate].

Climate Analogue: A climate analogue refers to a current climate in one location that is similar to the projected future climate in another location.

Climate Change: A change in climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability over comparable time periods.

Cool Pavements: Cool pavements refer to technologies that tend to store less heat and may have lower surface temperatures compared with conventional products. Current cool pavements are those that have increased solar reflectance or that use a permeable material.

High Albedo Pavement Materials: Materials that are light in colour and reflect sunlight away from the surface. With less sunlight absorbed by the pavement, less heat is radiated by the pavement. High albedo pavements therefore reduce the urban heat island effect, which in turn reduces cooling costs, helps the survival of urban vegetation and improves air quality.

Resilience: The extend to which a natural or social system is not sensitive to [climate] variability and change and has the capacity to adapt.

Solar Energy: solar energy is composed of ultraviolet (UV) rays, visible light, and infrared energy, each reaching the Earth in different percentages: 5% of solar energy is in the UV spectrum, 43% of solar energy is visible light (colours ranging from violet to red), and the remaining 52% of solar energy is infrared (felt as heat).

Solar Reflectance (Albedo): Solar reflectance, or albedo, is the percentage of solar energy reflected by a surface, and it is the main determinant of a material's maximum surface temperature.

System Sensitivity: The degree to which a system will respond to a given change [in climate], including beneficial and harmful effects.

Thermal emittance: the thermal emittance of a material determines the quantity of heat radiated by the material by surface unit, at a given temperature; i.e. it determines how easily a surface spreads the heat.

Vulnerability: The extent to which a natural, social or economic system is susceptible to sustaining damage [from climate change]. It is a function of the sensitivity of a system [to a change in climate], adaptive capacity and the degree of exposure of the system to [climatic] hazards.

ABBREVIATIONS

CBA	Cost-Benefit Analysis
CBR	California Bearing Ratio
EPS	Expanded Polystyrene
EVT	Extreme Value Theory
GCM	Global Climate Model
GDP	Gross Domestic Product
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
ITS	Intelligent Transport System
LCA	Life Cycle Assessment
LCCA	Life-Cycle Cost Analysis
MCA	Multi-Criterion Analysis
U.S.	United States (of America)

1. INTRODUCTION

Climate change is often coined as the *"greatest challenge of our time"*. Global warming, sea level rise and the intensity and frequency of extreme climatic events pose a serious threat to both the natural and the built environment. Gradual changes over time as well as abrupt changes to the climate may also cause road pavements to become vulnerable to the effects of a changing climate. If significant climate change impacts are projected and the risk profile justifies it, processes should be initiated to adapt road design, maintenance and construction guidelines and standards. Also, planning, design, construction and maintenance operations may have to be adjusted to take cognisance of these potential impacts so as to reduce risks and to protect the long-term serviceability of road infrastructure.

Climate change is expected to have various environmental, social and economic effects, the severity of which may vary by geographic location, country and region. To better understand these effects, and also to assess the degree of concern and level of readiness of the roads sector, a questionnaire was sent out to the membership of PIARC Technical Committee D.2. The following four basic questions were asked:

1. What are the main concerns your country has about the potential impact of climate change on road pavements?
2. Is anything being done in your country to assess and/or address the consequences of climate change on road pavements, and if not, why not?
3. Are climate change impact and adaptation studies currently being undertaken in your country or region, and if so, can you list them?
4. Can you list pavement-specific issues associated with climate change that would require more evaluation/understanding?

Overall, concern was expressed about the uncertainties associated with the nature and extent of climate change and the lack of understanding of the vulnerability of transport networks to extreme weather events, as well as the risk exposure to both road owners/operators and road users. Linked to those were also the uncertainties associated with the indirect impacts of climate change, such as the potential changes in traffic volumes due to shifts in population and relocation of industrial activities as a consequence of climate change, which may impact on the demand for road infrastructure.

The purpose of this document is to sensitise the road sector as to the likely impacts of climate change on road pavements and to provide guidance on how to go about: (1) assessing the vulnerability of road pavements to the direct impacts of climate change, and; (2) identifying and prioritising possible adaptation measures for road pavements which could be applied immediately or phased in over time, so as to avert the negative consequences of climate change on the serviceability of road networks.

Although the primary focus of this document is on road pavements, the findings of this report apply equally well to other pavement applications such as airport pavements.

Climate change mitigation, namely the combination of activities aimed at stabilising or, ideally, reducing atmospheric greenhouse gas concentrations, does not form part of the scope of this document. While there is an urgent need to mitigate climate change, it has now been widely accepted that climate change is unavoidable, even if global greenhouse gas emissions were to be reduced in accordance with the Kyoto Protocol, and that society will need to prepare itself for the consequences thereof and learn to adapt.

2. CLIMATE CHANGE AND ITS IMPACT ON ROAD PAVEMENTS

2.1. OVERVIEW ON CLIMATE CHANGE AND WHY IT MATTERS TO ROAD OWNERS/OPERATORS

Climate change is real. Some greenhouse gasses such as carbon dioxide, methane, nitrous oxide and fluorocarbon, are proliferating in the atmosphere because of human activities and are increasingly trapping more heat. The increased atmospheric concentration of particularly carbon dioxide has been validated by direct atmospheric measurements performed in the 20th century and the evaluation of ice cores going back 10,000 years (IPCC, 2007a), proving that a change is underway in the greenhouse radiation balance.

Between 1906 and 2005, the global mean near-surface air temperature increased by 0.74°C (IPCC, 2007a). Without concerted actions to cut emissions, the rate of increase in global mean surface air temperatures is expected to accelerate in the future. Under a business-as-usual scenario, greenhouse gas emissions could rise by 25 to 90% between 2000 and 2030, resulting in a global mean surface temperature increase of 1.4 to 5.8°C between 1990 and 2100. This is a much more rapid rate of warming than during the 20th century and very likely to be unprecedented in at least the last 10,000 years. Using the results from formal economic models, the Stern Review (Stern, 2007) estimated that the costs of business-as-usual will be equivalent to losing at least 5% of global Gross Domestic Product (GDP) each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more. On the other hand, if greenhouse gas concentrations could be stabilised at a level not exceeding 550 parts per million, which equates to limiting the increase in temperature to between 2 and 3°C, the annual cost would be limited to approximately one% of global GDP per annum.

Regional changes in temperature have already resulted in discernible impacts on the natural environment such as the shrinkage of glaciers, thawing of permafrost, heat waves, change in cloud cover, heavy precipitation events, and a higher frequency of extreme weather events such as tropical cyclones, hurricanes and typhoons. There is also emerging evidence that some social and economic systems have been affected by the recent increased frequency of floods and droughts in some areas. The nature and severity of changes to the climate are, however, difficult to predict. Climate change may not necessarily occur gradually. Scientists are, for instance, continually revising their forecasts for the rate by which glaciers recede. With the prospect of accelerating climate change in the future, impacts on natural and human systems are likely to become profound *(see figure 1)*.

Climate change will also impact on roads. Many of the activities performed by road owners/operators are either directly affected or influenced by climate. In fact, weather and climate-related factors, which are usually obtained from historical climate records, form an integral part of routine design of road pavements and drainage systems, and these factors also influence the maintenance frequencies of infrastructure assets. What if climate were to change? What if historical climate records are no longer reliable to predict future climate? What if, for instance, heavy precipitation events were to occur more often than predicted within the planning horizon or the support structure of a road were to become undermined within the structural design period by the melting of permafrost or changes in the freeze-thaw cycles? Since a road network is an essential ingredient of a country's economic system and social well-being, how will climate change impact on the functionality of a road and, therefore, on socio-economic development and society?

In view of the challenges that are likely to be posed by gradual as well as abrupt change to the climate, processes should be initiated by which the vulnerability of road networks to the potential impacts of climate change can be assessed and, where warranted, adaptation of planning, design, construction and maintenance operations can be instituted to limit future risks and ensure long-term serviceability of road infrastructure. If significant climate change impacts are foreseen, processes should be initiated to adapt road design, maintenance and construction guidelines and standards to take cognisance of these potential impacts. Denying this may lead to costly consequences, not only for road owners/operators but also to the economy as a whole.

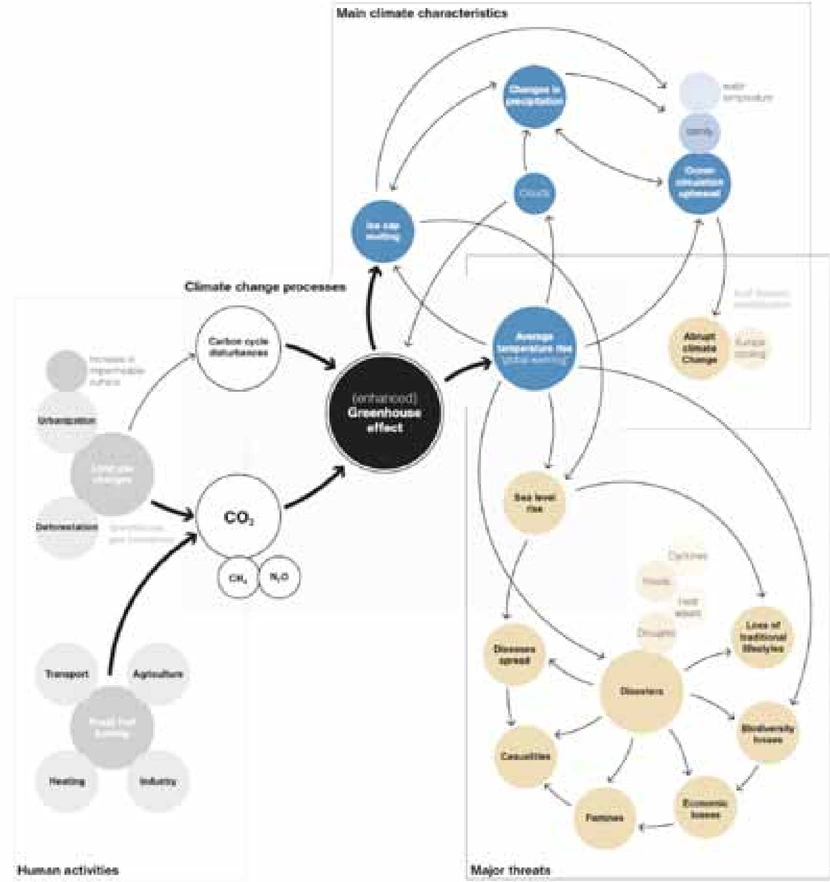


FIGURE 1 - CLIMATE CHANGE – PROCESSES, CHARACTERISTICS AND THREATS (UNEP/GRID, 2005)[1]

2.2. POTENTIAL CLIMATE CHANGE IMPACTS ON ROAD PAVEMENTS

The potential impacts of climate change on road pavements will vary regionally, reflecting differences in both the magnitude of climate changes and environmental conditions. Hence, the latest available probability-based regional climate change scenarios should be consulted for the identification of potential climate change effects and for the appraisal of their likely impacts on road pavements.

So, what are the likely impacts of climate change on road pavements? To answer this question, four regional examples are used, namely Canada, Netherlands/United Kingdom, Australia and Tokyo, Japan.

[1] *“Climat en Péril : Guide grand public des derniers rapports du GIEC”*, PNUE/GRID–Arendal – Design by Philippe Rekacewicz, 2009.

Canada: Warmer winters

There is sufficient evidence, based on climatic data gathered over a 50-year period, that both minimum and maximum temperatures have been warming, particularly during winter time, and it is expected that this trend will continue, if not accelerate.

In summer months, an increase in the frequency and severity of hot days raises concerns that Canada's flexible pavements could experience more problems related to pavement softening and traffic-related rutting on heavily-trafficked roads, as well as bleeding.

However, of greater concern are the warmer temperatures in winter, particularly to the northern parts of Canada. Over 50% of the distresses observed on Canadian roads are attributed to freeze-thaw cycles. Milder winters, with higher frequencies of freeze-thaw cycles, would accelerate road deterioration and increase maintenance costs. Also, permafrost, which underlies 35 to 40% of Canada and provides structural stability for transportation infrastructure, is degrading as a result of climate warming. This will result in an increased depth of the seasonal thaw layer and warming of the frozen zone which reduces its bearing capacity. Finally, milder winters will shorten the ice road season by several weeks. These roads provide transportation routes across frozen ground, lakes and rivers to supply and support communities and resource industries (e.g. mining activities),

Higher and more frequent precipitation events are expected in the southern parts of Canada (in July 2009, Ontario experienced the highest rainfall in its recorded history). Future increases in the intensity and frequency of heavy rainfall events will not only increase the risk for debris flows, landslides, avalanches and floods, but will also have implications for the design of roads, highways, bridges and culverts with respect to stormwater management and protection of the pavement structure. This change to precipitation is likely to require the use of larger drainage structures to convey the higher flow rates anticipated during the more extreme storm events. While some areas are getting wetter, others will become dryer. The Southern region of British Columbia recently experienced a record dry spell which contributed to massive forest fires burning out of control.

Sea levels are also expected to rise. It is estimated that the sea level could rise by between 90 and 900 mm by 2100. This, together with land subsidence, would imply that many causeways, bridges, marine facilities and municipal infrastructure are at risk of being inundated or damaged. The replacement value of the affected infrastructure has been estimated in the hundreds of millions of Canadian dollars, unless appropriate adaptations are made over the coming decades.

Netherlands/United Kingdom: Increased frequency of intense precipitation events

The primary water related climatic changes predicted for the United Kingdom and the Netherlands are an increase in winter rainfall, a reduction in summer rainfall, more extreme rainfall events, a reduction in snowfall and sea level rise. For the Netherlands, which is exposed to both the sea and three main rivers of Europe (Rhine, Meuse and Scheldt) as well as extreme precipitation in mainland Europe, water discharge and rapidly changing water levels in the rivers are relevant issues. The secondary precipitation related climatic change impacts predicted for the United Kingdom and the Netherlands are changes in soil moisture, changes in groundwater level, increased flooding and increased frequency of extreme storm surges.

These predicted flooding related changes mean that the drainage systems of the road network must be capable of draining larger amounts of water and in extreme cases in relatively short periods of time. Existing drainage systems are designed and constructed on the basis of previous precipitation events (statistics). More net precipitation leads to larger water stream flows; existing culverts that are designed based on outdated statistics of high flow events may not be able to cope with these increased flows. Ongoing work in this area in the United Kingdom has included: (i) identifying the risk associated with flooding of third party properties and the road network due to the inadequate capacity of existing culverts; (ii) drawing together existing knowledge on the vulnerability of the network to flooding (particularly developing a better understanding of the relationship between critical weather conditions and vulnerability, and targeted mitigation and prevention measures); and (iii) related water quality issues. Ultimately, this will lead to amended design standards for long-life assets to address the predicted changes. Newly designed drainage structures are now required to take account of increased flows due to climate change and this is increasing the size of culverts, attenuation facilities and drainage systems.

Water quality effects may be encountered during the drier summers when rivers flows may be lower (especially small rivers with a large base flow from groundwater); this may limit the capacity of the river to receive and dilute road runoff from a subsequent storm event following a dry period. Higher drainage flows from increased rainfall may also affect discharges to groundwater via infiltration systems such as soakaways and filter drains. These devices may need to be re-designed and replaced to cope with the higher infiltration flows and the risk of groundwater flooding would have to be considered.

Already in the Netherlands, the design manuals for culverts have been changed based on expected rain intensities in the future; water storage capacity will also have to be increased. A study is currently taking place into the vulnerability of the network to: (i) increased precipitation, including defining black spots where water drainage problems on the network will occur (and what the water levels might be), and identifying where flooding might take place, and; (ii) the effects on extreme ground water levels, on extreme heat waves (number of tropical days) and on less cold (number of zero frost) days.

Severe winter weather is predicted to become less likely with time, with reduced melt-water flooding and frost heave damage; by 2080, large areas of England are likely to have long runs of snow-less winters. These impacts are largely beneficial, especially in mountainous parts of the country.

The effects of climate change on groundwater level are likely to vary depending on geographical location and season. The likely implications for pavement bearing capacity are that unusually high levels may weaken the substructure, whereas unusually low levels may cause volumetric changes in susceptible soils and consequent cracking in the overlying bound pavement surface. These changes may challenge the underlying design assumption in the United Kingdom that the bearing capacity of the pavement foundation remains static or increases over the life time of the road. There is no systematic work being carried out in this area in the United Kingdom at present.

In the Netherlands, because of its specific polder situation, there are risks of very rapid water level rise in the case of a dam-burst. Rising groundwater levels and flooding have an impact on special constructions where light materials, such as Expanded Polystyrene (EPS) foam, are used as light subbase materials. In such situations, floating of the road might occur. In addition, specific secondary materials (such as incinerator bottom ash, used as a sub base material), which are prohibited from use in contact with ground water, may leach in such situations with a resultant threat to the environment. In the Netherlands, the risk of deformation of roads caused by lower ground water levels is considered to be minor. Deformation is a risk when ground water level is lowered more then 0,50 m over a period longer then 3 months; dry summers in the Netherlands will have a limited influence. Nevertheless, in many locations a thick layer of peat is present just below ground water level. Structural lowering of ground water levels will have an impact, as a recent collapse of a peat dike has demonstrated.

Australia: Higher temperatures, drier conditions

Austroads (2004) includes discussion on the potential impacts of climate change on road pavements in Australia. Historical observations show that Australia's continental-average temperature rose by 0.7°C between 1910 and 1999, with most of the increase occurring after 1950. Climate simulations forecast that Australia is expected to become even hotter and drier in the future. Various studies have predicted annual average temperature increases of between 1.0 and 6.0ºC over most of Australia over the next 70 to 100 years. These simulations also forecast that more extremely hot days and less cold days can be expected.

Additionally, forecasts indicate a general reduction in rainfall over most of Australia, except for the far north where significant increases are forecast. In these northern areas, more extreme conditions are expected, with more frequent and heavier rainfall events, and more intense tropical cyclones. However, the vast majority of Australia is likely to experience drier conditions and greater frequency of drought.

Where drier conditions are experienced, the rate of pavement deterioration should, theoretically, reduce due to better subgrade support and more favourable moisture conditions for the pavement layers. However, the associated hotter temperatures in these areas may reduce the life of bituminous materials due to more rapid oxidation, which may also result in secondary impacts such as moisture ingress into the pavement layers through surface cracks. Such impacts can be expected to be greater in the far north where increased rainfall is predicted.

For the majority of the Australian rural road network, which consists of bituminous sprayed seal surface (surface dressing), higher temperatures and in particular more extreme maximum temperatures, may result in pavement problems associated with binder softening. In urban areas, where asphalt is more common, permanent deformation of the asphalt due to binder softening will be more likely.

The indirect impacts of climate change on roads may also be significant: most notably, the effects due to the changing location of the population and human activity altering the demand for roads.

Tokyo, Japan: Urban heat island effects

Temperatures in Tokyo are significantly warmer than those in its surrounding rural areas. The city is a prime example of the urban heat island phenomenon, in that:

- annual mean air temperatures have risen by approximately 3°C over the last century, and the city is thus heating up at four to five times the pace of global warming;
- all 23 wards of Tokyo have recorded year-on-year temperature rises;
- the number of days with recorded temperatures over 35°C in summer months has more than doubled over the past 30 years *(see also figure 2, page 20)*;
- the number of tropical nights (i.e. nights in which the temperature does not drop below 25°C) has increased from less than six a century ago to more than 30 today;
- subtropical plants are starting to displace temperate plants.

Tokyo's urban heat island phenomenon is attributed to its rapid urban development since the Second World War, where the rapid expansion of roads and buildings has resulted in more of the sun's heat being retained during the day and expelled at night. Secondary factors, such as waste heat generated by energy usage (e.g. transport and air conditioners) have also contributed to this phenomenon.

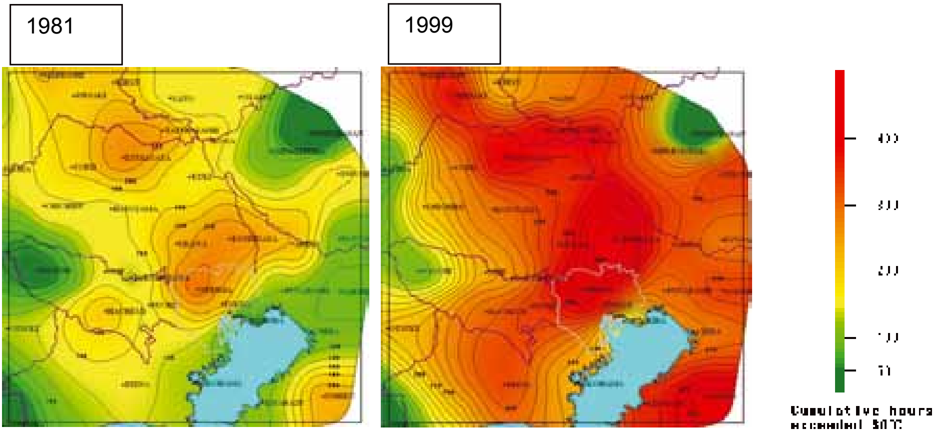


FIGURE 2 - NUMBER OF DAYS WITH A TEMPERATURE ABOVE 30°C (TOKYO) (IMCCMUHI, 2004)

With the rise in temperature and high humidity levels of around 70% on average, summers have become uncomfortable for the 12.8 million residents of Tokyo. Deaths as a result of severe heat exhaustion have steadily risen. During the period June to mid-August 2010, 31,000 people were rushed to hospital in Japan due to heat stroke. Over 130 people died shortly after having been hospitalised (96 in Tokyo). In July alone, over 17,500 people were taken to hospital, of whom 94 died. The relationship between the number of incidences of hot days in Tokyo, the peak daily temperature on these hot days and heat stroke mortality is shown in *figure 3*.

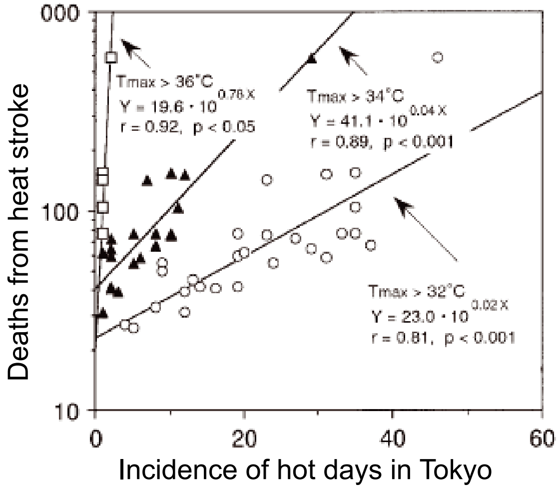


FIGURE 3 - RELATIONSHIP BETWEEN HEAT-STROKE MORTALITY AND THE OCCURRENCE OF HOT DAYS IN TOKYO (TMAX DENOTES THE PEAK DAILY TEMPERATURE) (NAKAI ET AL, 1999)

Climate change, together with the urban heat island phenomenon, has contributed to an increase in extreme precipitation events, which often occur downwind of cities. Two examples are shown *figure 4*.

FIGURE 4 - FLOOD DISASTER IN URBAN AREAS

Mitigation actions are being undertaken to reduce the urban heat island effects by albedo increase, vegetation increase and anthropogenic heat reduction. In terms of road pavements, one of the main contributors to heat retention, two novel approaches have been adopted to cool down pavements. One approach is the Water Retentive Pavement which has a sub-layer consisting of water retentive materials that absorb moisture and then evaporate it through capillary action when the pavement heats up. Another approach used is the Heat-Shield Pavement which reflects near-infrared radiation by the application of special coating materials on its surface. Both these approaches are capable of reducing the maximum surface temperature by approximately 10°C (reduction from 60°C to 50°C), which translates to an approximate 1°C decrease in air temperature. Both these technologies are further expanded upon in *section 4.1.1, page 34*.

2.3. MAIN CONCERNS RAISED BY ROAD OWNERS/OPERATORS

A questionnaire was sent out to the membership of PIARC Technical Committee D.2 to gain a better understanding of:

1. the main concerns raised by road owners/operators about the potential impact of climate change on their road pavements;
2. whether anything was being done by road owners/operators to assess and/or address the consequences of climate change on road pavements, and if not, why not;
3. climate change impact and adaptation studies currently being undertaken in their countries and regions;
4. pavement-specific issues associated with climate change that would require more work.

Representatives of the following countries responded to the questionnaire:

- Australia
- Belgium
- Canada
- China
- Colombia
- Denmark
- Estonia
- Finland
- France
- Hungary
- Japan
- Lithuania
- Mexico
- Netherlands
- New Zealand
- Norway
- Philippines
- Slovakia
- South Africa
- Sweden
- USA

The full results of the questionnaire are presented in Appendix A. In terms of item 1 above ("Main concerns raised by road owners/operators"), these concerns could be classified into two categories, namely (a) general concerns that mainly deal with the uncertainties associated with climate change, and (b) specific concerns which relate to the geographical location of the country.

2.3.1. General concerns raised by road owners/operators

General concerns were expressed about the uncertainties associated with the nature and extent of climate change and the lack of understanding of the vulnerability of the transport network to extreme weather events, as well as the risk exposure to both road owners/operators and road users. Linked to those are also the uncertainties associated with the indirect impacts of climate change, such as the potential changes in traffic volumes due to shifts in population and relocation of industrial activities as a consequence of climate change, which may impact on the demand for road infrastructure.

Following the above, needs were expressed for:

- addressing the biggest unknown, namely the current uncertainty of predicting the rate of change of various climatic influences on road pavements and thus where to focus immediate attention – the need for local intelligence on likely effects of climate change;
- methodologies for assessing the risks associated with climate change and how to conduct vulnerability assessments;
- methodologies for the mapping of critical/vulnerable infrastructure and estimating the costs of adapting to climate change;
- greater sharing of knowledge amongst key stakeholders on how to deal with the effects of climate change on road infrastructure;
- methodologies on how to design and implement adaptation strategies;
- greater exchange of experience and development of practical solutions;
- better linkage of climate change impacts to asset management;
- adaptation in the design for future protection of bridges, tunnels, transit entrances and critical evacuation routes, and the provision of alternative routes;
- capacity building in the field of rapid response to incidents and protection of key assets.

Guidance will be presented in the following chapters, and more particularly in *chapters 3 and 5,* on how to deal with the above.

2.3.2. Specific concerns raised by road owners/operators

Specific concerns raised by road owners/operators differed in accordance with the climate zone in which their country (or parts thereof) is located. In order to summarise the outcomes of the survey, use has been made of the five main climate groups of the Köppen-Geiger climate classification system, these being *(see figures 5a page 24 and 5b page 25)*:

- **Group A:** Tropical/megathermal climates,
- **Group B:** Dry (arid and semiarid) climates,
- **Group C:** Temperate/mesothermal climates,
- **Group D:** Continental/microthermal climates,
- **Group E:** Polar climates.

These groups are identifiable by the first letter of the alphabetical symbols in *figures 5a and 5b*. (Note that figure 5a presents the Köppen-Geiger climate zones for the period 1976 to 2000, whereas figure 5b presents the projected climate zones for the period 2076 to 2100, based on the IPCC's A1F1 scenario.)

Although this approach is imperfect since it does not address the various climate types and sub-types (represented by the second and third letters of the alphabetic symbols in figures 5a and 5b) associated with each of the main climate groups, it nevertheless provides an indication of the specific pavement engineering concerns associated with each of these main climate groups.

The questionnaire responses are summarised in *table 1, page 26*. It is clear from the table that most countries are concerned about the levels of precipitation, where increased levels could cause flooding and impact on the structural integrity of pavements (and may necessitate the imposition of load restrictions), and decreased levels of precipitation could dry out the subgrade impacting on the overall durability of the pavement. Most coastal countries raised concern about rising sea levels which, when combined with storm surges, could lead to flooding and therefore also road closures. The likely increase in road closures as a consequence of land slides caused by higher precipitation levels was also raised. Several countries expressed concern about an increased frequency in the number of freeze-thaw cycles, leading to frost heave, cracking and potholing. With regard to increased temperatures, several countries, including those with cold winter conditions, raised concern about increased potential for rutting and bleeding in bituminous-bound pavement layers during periods of warmer weather.

Chapter 4 provides some guidance on how to deal with the above concerns.

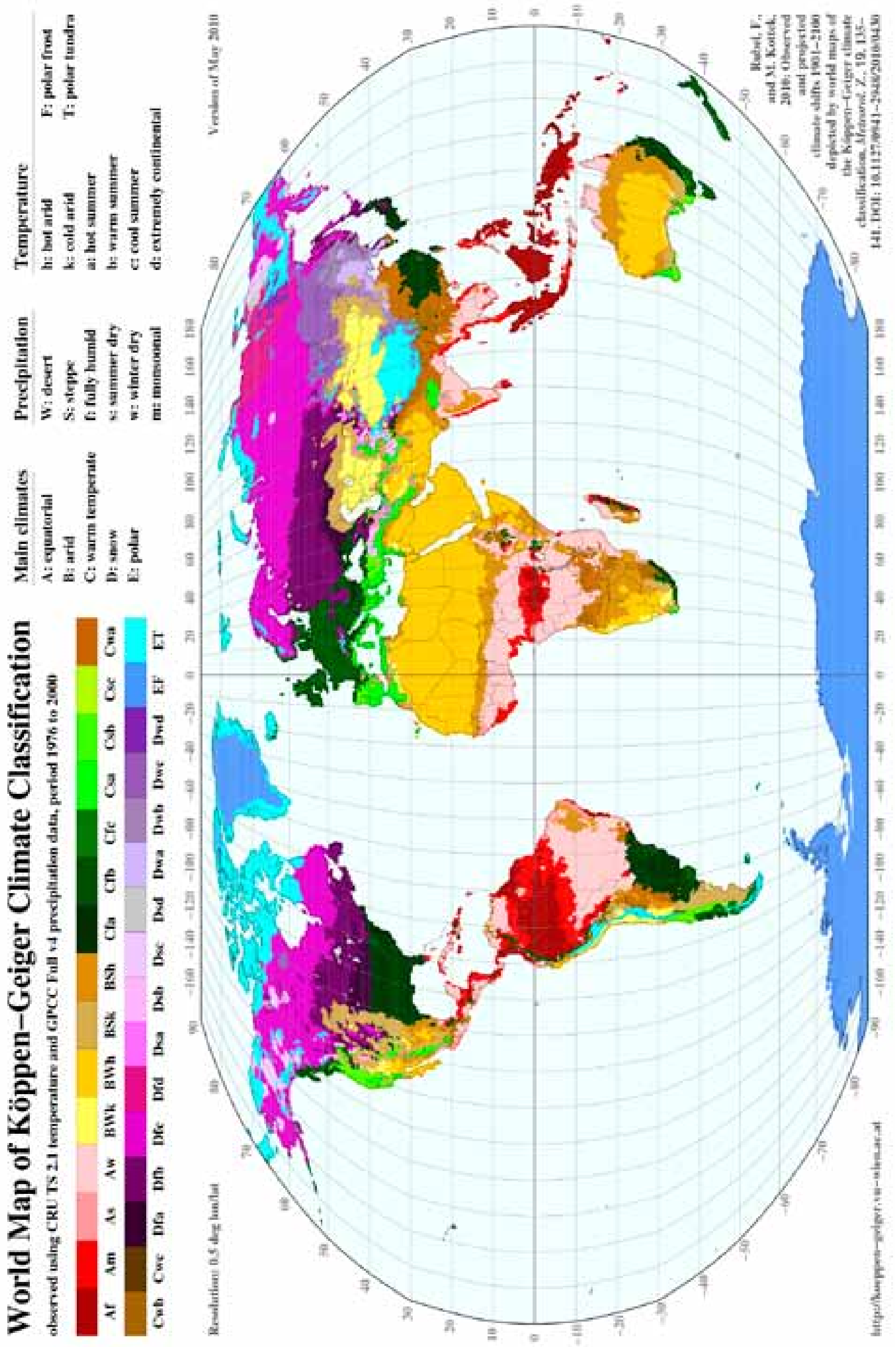


FIGURE 5a - WORLD MAP OF KÖPPEN-GEIGER CLIMATE CLASSIFICATION FOR PERIOD 1976 TO 2000 (RUBEL & KOTTEK, 2007)

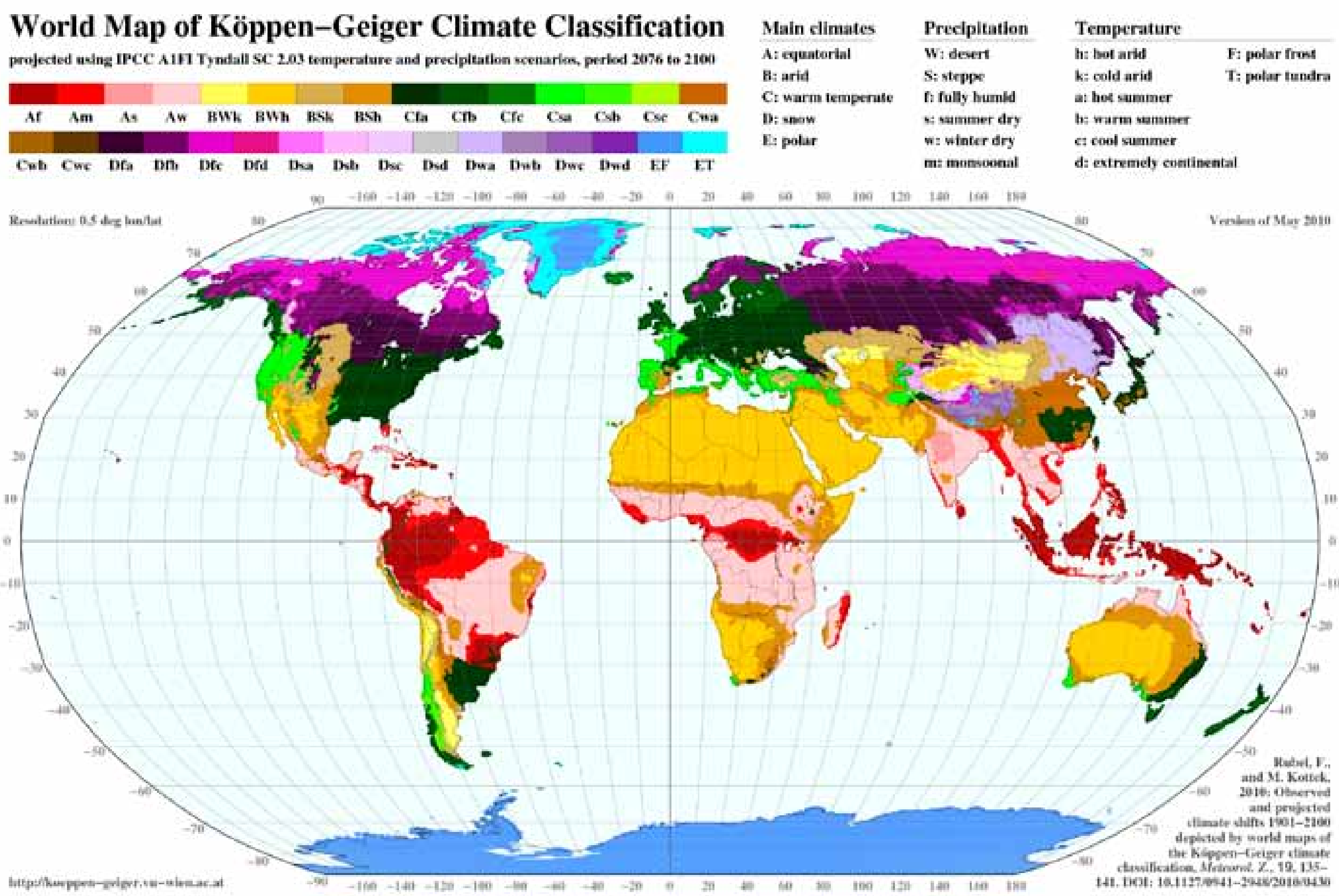


FIGURE 5b - WORLD MAP OF KÖPPEN-GEIGER CLIMATE CLASSIFICATION FOR PERIOD 2076 TO 2100 FOR IPCC A1F1 SCENARIO (RUBEL & KOTTEK, 2007)

TABLE 1 - A SAMPLE OF COUNTRIES, WHO RAISED SPECIFIC CONCERNS ABOUT THE IMPACT OF CLIMATE CHANGE, CLASSIFIED ACCORDING TO THEIR CONCERNS AND FIVE MAIN CLIMATE GROUPS OF THE KÖPPEN-GEIGER CLIMATE CLASSIFICATION SYSTEM

Climate effects	Impacts raising concern (from questionnaire responses)	Five Main Köppen-Geiger Climate Groups (1976-2000; See Figure 5a)				
		Group A	Group B	Group C	Group D	Group E
Increased upper temperatures	• Increased rutting of flexible pavements • Bleeding of bituminous pavements • More rapid ageing of bituminous layers • More frequent maintenance • Bushfires	Northern Australia Mexico	Central Australia Mexico South Africa	Eastern Australia Japon The Netherlands New Zealand South Africa	Lithuania Slovakia	
Increased lower temperatures, increased number of freeze-thaw cycles	• Reduced bearing capacity (e.g. loss of frozen support) • Cracking, ravelling and potholing of bituminous pavements				Canada Estonia Finland Lithuania Norway Sweden	Canada Norway
Increased rainfall, wetter climates, increased storm frequencies	• Higher water tables • Inadequacy of drainage systems • Flooding • Reduced bearing capacity • Cracking & permanent deformation • Slope failures; road closures • Disaster mitigation measures • Alternative roads	Northern Australia The Philippines		Eastern Australia The Netherlands New Zealand South Africa	Canada Danemark Estonia Finland Lithuania Norway Slovakia Sweden	Canada Norway
Reduced rainfall	• Reduced subgrade moisture levels • Salinity problems • Increased roughness		Central Australia South Africa			
Sea level rise	• Road closures • Disaster mitigation measures • Alternative roads	Northern Australia The Philippines		Eastern Australia The Netherlands New Zealand South Africa	Canada Denmark Norway Sweden	Canada Norway
Increased wind velocity	• Damage to road furniture			New Zealand	Denmark	

3. SYSTEMATIC APPROACH FOR CONDUCTING RISK AND VULNERABILITY ASSESSMENTS

The development of a typical climate change adaptation plan would consist of the following five basic steps *(see also sections 5.1 to 5.3)*:

1. Assess current climate trends and future projections for the geographical region, and identify climate change effects and trends that would impact on road pavements and quantify/qualify their degree of uncertainty.
2. Undertake a climate vulnerability assessment of road pavements within the geographic region:
   a. Identify current vulnerabilities based on current climate variability risks and trends;
   b. Identify future potential vulnerabilities based on future projected climate scenarios and future climate risks;
   c. Utilise a design program to evaluate the effects of varying climatic conditions on the performance of user-defined pavement structures.
3. Develop adaptation action plans: undertake a risk appraisal to categorise the nature of risk associated with each vulnerability, and identify, assess and prioritise available options to respond to the risks associated with each of the vulnerabilities.
4. Implement adaptation action plans.
5. Monitor and evaluate the interventions on an ongoing basis, and regularly review and modify the plans at predefined intervals.

3.1. STEP 1: IDENTIFICATION OF POTENTIAL CLIMATE CHANGE EFFECTS

Climate scientists and organisations such as the Intergovernmental Panel on Climate Change (IPCC) continuously assess the state of our understanding on climate change and are continuously striving to improve the confidence with which projections can be made of climate change and its impacts. These projections are reassessed on a regular basis. On account of the uncertainty associated with these projections and scenarios, they are often expressed with upper and lower limits of confidence.

Uncertainties associated with climate change arise from factors such as lack of knowledge of basic scientific relationships, linguistic imprecision, statistical variation, measurement error, variability, approximation and subjective judgement. These problems are compounded by the global scale of climate change, but local scales of impacts, long time lags between environmental forcing (e.g. as a result of greenhouse gas emissions) and climatic response, low-frequency variability with characteristic times that are greater than the length of most instrumental records, and the impossibility of before-the-fact experimental controls also come into play.

Because of the uncertainties, projections are used instead of predictions to emphasise that they do not represent attempts to forecast the most likely evolution of climate in the future, only possible evolutions. Hence, a climate projection should be viewed as a single trajectory of a subset of scenarios. When used as input into impact assessments, the same climate projections commonly are referred to as climate scenarios, with conditional probabilities attached to each scenario.

Climate change events can be characterised into primary climatic changes and secondary climate change effects. Examples of these are listed below:

Primary climatic changes:
- increase in average temperature,
- increase in maximum temperature,
- changes in permafrost and frost depth penetration,
- reduction in snowfall,
- increase/decrease in rainfall,
- more extreme rainfall events,
- sea level rise,
- increased wind velocity.

Secondary climate change effects, such as:
- longer/shorter growing season,
- increase/reduction in soil moisture,
- changes in groundwater level,
- changes in vegetation,
- flooding,
- reduction in icy days in winter,
- frequency of extreme storm surges,
- changes in ecological equilibrium,
- changes in the construction season.

The degree of confidence attached to any given climate change scenario, or to primary and secondary events, could be expressed quantitatively and/or by verbal characterisation. For instance, a combination of both these methods was used by the Transportation Research Board's study on the Potential Impacts of Climate Change on U.S. Transportation to express the level of uncertainty associated with potential climate changes, as illustrated in *table 2*:

TABLE 2 - LEVEL OF UNCERTAINTY ASSOCIATED WITH POTENTIAL CLIMATE CHANGES OF GREATEST RELEVANCE TO TRANSPORTATION (TRB, 2008)

Potential climate changes of relevance to U.S. transportation		Level of uncertainty
Temperature	increases in very hot days and heat waves	Very likely
	decreases in very cold days	Virtually certain
	increases in Arctic temperatures	Virtually certain
	later onset of seasonal freeze and earlier onset of seasonal thaw	Virtually certain
Sea level rise		Virtually certain
Precipitation	increase in intense precipitation events	Very likely
	increases in drought conditions for some regions	Likely
	changes in seasonal precipitation and flooding patterns	Likely
Storms	increases in hurricane intensity	Likely
	increased intensity of cold season storms, with increases in wind and in waves and storm surges	Likely

Notes: Italicised uncertainty designations are those indentified by the IPCC in 2007. Others reflect the study committee's judgement, based on the available literature. Based on IPCC, the following terminology was used to describe uncertainty in terms of probability of occurrence: virtually certain ≥ 99%; extremely likely ≥ 95%; very likely ≥ 90%; likely ≥ 66%; more likely than not ≥ 50%; unlikely ≤ 33%; very unlikely ≤ 10%; extremely unlikely ≤ 5%

There are uncertainties associated with climate change, but these should not inhibit decision making – they should be understood and taken into account. The latest regional climate change scenarios should be consulted to assimilate the likely impacts of the projected changes in climatic conditions over time, assess the vulnerability of assets in view of these changes and, if required, adapt current practices to safeguard the future performance of road pavements. Ideally, information needs to be obtained on:

- regional climate change events that are likely to impact on road pavements (future projections);
- the rate of change in each weather element over time, expressed as ranges rather than single values, as well as the projected extreme values for each weather element;
- projected periodicity of extreme weather events;
- degree of confidence of the projections for each weather element.

3.2. STEP 2: ASSESSMENT OF THE IMPACT OF CLIMATE CHANGE ON THE VULNERABILITY OF ROAD PAVEMENTS

Having obtained the most recent geographical projections and scenarios for climate change effects of greatest relevance for road pavements, and the uncertainties and timescales associated with these (step 1), the next step is to undertake a climate vulnerability assessment of road pavements. The identification of vulnerabilities of road pavements to climate change effects is key to defining how the design, maintenance and operation of road pavements should be adapted to meet the challenges of a changing climate. In assessing vulnerability, three aspects need to be considered, namely:

- the degree of exposure of road pavements to climatic hazards;
- the sensitivity of road pavements to changes in climate, and;
- the degree by which adjustments can be made to offset the potential for damage (i.e. adaptive capacity).

The degree of exposure of road pavements to climatic hazards is primarily a function of the combined nature and severity of each hazard, as discussed in Step 1. However, it is the sensitivity as well as the embedded resistance of road pavement layers and/or of the pavement system as a whole to these climatic hazards that will define the level of damage (i.e. decrease in serviceability) the pavement structure is likely to sustain from climate change.

Different climatic hazards will result in different road pavement responses if the threshold strength of the pavement structure is exceeded. For instance, increased temperatures combined with more frequent heat waves could lead to a greater potential for rutting in bituminous-bound layers that are located near the pavement surface. Similarly, higher groundwater levels could soak the subgrade resulting in a greater potential for structural rutting and/or fatigue cracking. Structural pavement design software packages based on mechanistic-empirical principles could be used to assess the effects of changes in climatic conditions on the performance of pavement structures.

Despite the many available tools and methods, both qualitative and quantitative, for undertaking vulnerability assessments, assessing vulnerability to even current climate variability remains challenging because of the range of factors, in addition to climate, which contribute to vulnerability. Assessing vulnerability to climate change is even more challenging because of the dynamic nature of vulnerability. Although it may be difficult to unequivocally define future vulnerability, some tools, such as scenarios, may help to evaluate future pathways of vulnerability.

Climate change effects (step 1), the exposure of potential vulnerabilities of road pavements to these climate change effects (step 2), as well as possible remedial actions which could be considered to improve and/or enhance the resistance of road pavements to the impact of these climatic hazards (step 3) are presented in *chapter 4, page 32.*

3.3. STEP 3: APPRAISAL OF RISKS AND IDENTIFICATION OF POTENTIAL SOLUTION AND STRATEGIES TO ADDRESS VULNERABILITIES

Once the key vulnerabilities are identified, it is necessary to appraise the risks associated with these vulnerabilities. Ideally, the risk appraisal should be done by experts in the roads sector working together with climate scientists who can comment on the nature of climate variability and uncertainties associated with climate change projections and scenarios. The latter is important since the time horizon for climate change effects to become material needs to be understood, which, together with the functional/structural life expectancy of assets, needs to be integrated in the risk appraisal.

One way by which risks can be appraised is through a probabilistic risk assessment which provides an estimate of total risk and the most important sources of that risk. In essence, risk would be defined as the product of the magnitude of adverse consequences associated with a particular vulnerability or combination of vulnerabilities and the probability that those consequences would occur. Typically, these are expressed in monetary terms. This is further elaborated upon in *section 5.2, page 75*.

For road pavements, these risks should reflect both the impact on road owners/operators in terms of asset deterioration and the increased cost required to maintain a safe, serviceable network, and the impact on road users (and on the economy) in terms of reduced network availability/functionality, increased road user costs and decreased road safety, amongst others. In most if not all cases, the impact on road users would be significantly greater than that on road owners/operators when risks are quantified in monetary terms.

Following the risk appraisal, and if found warranted, an adaptation strategy would have to be formulated, consisting of a range of plausible adaptation actions and solutions that would address vulnerabilities and mitigate risks. Weather is, however, a complex system subject to continuous fluctuations. Hence, adaptation strategies will most likely not be able to eliminate all risks arising from extreme weather conditions, but they should be designed to bring risks in line with acceptable levels.

Various examples of potential actions and solutions that could be considered for addressing the impact of a number of climate change effects are presented in *chapter 4*.

Once adaptation actions have been identified, they need to be prioritised. One method of evaluating which actions might be pursued first is multi-criterion analysis (MCA). This allows options to be evaluated using a range of criteria that could also include the analysis of unquantifiable factors. The purpose of MCA is to aid decision making rather than to evaluate options on monetary terms. It is useful in assessing options for adapting to climate change, as there are many factors that need to be considered, including equity, efficiency, short- and long-term benefits as well as many other non-monetary factors. Tools such as cost-benefit analysis (CBA) are useful when determining the financial implications of an intervention, both in terms of cost and socio-economic benefit to society.

3.4. STEP 4: IMPLEMENTATION OF ADAPTATION PLANS AND STRATEGIES

Having identified the preferred options and solutions from Step 3, they would then be further developed and integrated into a detailed adaptation plan and strategy for deployment. The adaptation plan should contain timelines for the implementation of actions as well as provide triggers for future review of actions that at present require no immediate action. The plan should also define those actions that would necessitate modification of standards, specifications and operational procedures *(see section 5.3, page 80)*, and should identify current issues of uncertainty that would require further study before action plans could be formulated.

3.5. STEP 5: MONITOR AND REVIEW

A key component of a framework for a climate change adaptation strategy is the ongoing monitoring of the programmes and projects that are prioritised and implemented. The effectiveness of the interventions should be regularly assessed and modifications made if necessary.

Adaptation to climate change is not an event but rather an ongoing process of learning. Continuous development and refinement of the strategy is key to adaptation, since adaptation should be an extension of good practices aimed at reducing the vulnerability of road pavements to the impacts of a changing traffic and natural environment.

4. MANAGING CLIMATE CHANGE IMPACTS ON THE OPERATION AND PERFORMANCE OF ROAD PAVEMENTS

Road owners/operators have to be aware that climate change can have both short-term and long-term impacts on road pavements, but also realise that adaptation can be a lengthy process since the parameters of an existing road cannot be changed overnight. Long-term impacts such as increased or decreased average temperatures by a few degrees can be managed by small changes to the specifications that can be phased in over time. However, the impact of (repeated) short-term events such as an increased frequency in the occurrence of heat waves or heavy precipitation events can be more severe.

Also, climate change may impact road pavements in different ways. Many of the impacts may be adverse, but some may actually be positive. Hence, road owners/operators need to manage the adverse effect but should also capitalise on the positive impacts.

Ideally, adaptation strategies should be sustainable and take into consideration appropriate climate change mitigation strategies and policies aimed at reducing greenhouse gas emissions. This can be achieved by, for instance, opting for design and maintenance strategies that focus on (technical) quality and/or adopting long-life pavement design concepts to minimise road construction material usage and to reduce traffic delays considerably by minimising maintenance interventions over the life of the facility. Minimising material usage is important since the amount of material used during the life of a facility has a greater impact on the carbon footprint than, for instance, the construction and maintenance methods adopted. Instruments such as life-cycle costing and life-cycle analysis could be used to optimise the design and maintenance strategies.

Besides the above, the use of more energy efficient materials and construction/ maintenance techniques would also contribute towards the reduction of the carbon footprint. Although their impact depends on local conditions, some general recommendations can be provided:

- minimise transportation of materials;
- use construction techniques that are more energy efficient, taking into account the whole life cycle (e.g. in-plant or in-place recycling);
- use materials with a lower energy content, provided that the functional performance attributes of these materials are at least on par with those of conventional materials (e.g. cold, semi-warm and warm-mix asphalt, recycled asphalt, replacement of Portland cement with supplementary cementitious materials such as fly-ash, blast furnace slag and silica fume, and replacement of clinker with limestone in order to reduce the energy content of Portland cement concrete pavements).

In all cases, potential side effects should be taken into consideration. A narrow focus on reducing greenhouse gas emissions during initial construction without considering the long term impacts could have adverse effects on the sustainability of the facility (e.g. more regular maintenance interventions and associated road user delays, resulting in greater energy usage and greenhouse gas emissions over the life of the facility).

Other road design/construction related techniques that could be employed to mitigate climate change or the effects thereof include:

- the adoption of technologies that have the potential to reduce heat island effects in urban environments (e.g. high-albedo surfacings);
- the utilisation of pavement solutions aimed at reducing rolling resistance (roughness) and thereby decreasing vehicle fuel consumption, and
- the use of reservoir pavements (pervious and permeable pavements) that can provide temporary storage for large volumes of rain water.

In order to give guidance on how to deal with the issues relating to adaptation, this chapter has been divided into weather-related subcategories.

4.1. HOW TO DEAL WITH CHANGES IN TEMPERATURE

4.1.1. Increase in frequency of very hot days (and heat waves)

4.1.1.1 Primary and secondary impacts

Primary impacts
The primary impacts of an increase in frequency of very hot days and heat waves on bituminous pavement layers are manifested by an increased risk of: (1) asphalt rutting; (2) flushing and bleeding of bituminous surfacings, and/or; (3) cracking.

As the temperature of an asphalt mixture increases, the binder phase loses stiffness. Hence, at the same stress level and load duration, the irrecoverable creep deformations (rutting) caused by static or dynamic traffic loading will accumulate at a faster rate.

Deep ruts in asphalt pavements are in general a danger to drivers and excess bitumen smearing the surface of the pavement also becomes a driving hazard as both affect pavement friction.

The consequences include the need for increased maintenance and repair and also a higher frequency of disruption to traffic flow, which impacts on road user costs.

Higher surface temperatures accompanied by increased intensity and duration of ultraviolet radiation cause an increase in the rate and severity of oxidation and/or hardening of the binder phase especially in the upper exposed parts of a bituminous surfacing. The net result is that the binding ability of the bitumen eventually decreases (as it becomes harder and less flexible) and is then less able to withstand the forces induced by traffic and climate. This results in cracking, progressing from micro to macro size, and material loss. Severely cracked surfaces will have reduced bearing capacity, exacerbated by water permeation. Conversely, binder hardening may lead to an increase in mixture stiffness with a potential beneficial effect on pavement load spreading ability.

Significant diurnal temperature fluctuations may also increase the extent of warping in particularly thin concrete pavements. Increased warping will result in increased tensile stresses in concrete pavements under traffic loading and ultimately lead to a reduced fatigue life unless the joint spacing is decreased.

Secondary Impacts
Increased ambient temperatures result in lower asphalt layer stiffness, which results in a greater proportion of the traffic stresses being transmitted to the lower, more vulnerable granular or foundation layers, potentially leading to structural rutting. Unlike surface damage, it is not viable to cosmetically repair or strengthen damage that accumulates in the lower layers of a pavement and major reconstruction operations would be required.

With an increased need for maintenance and resurfacing, the amount of reclaimed asphalt surfacing materials is likely to increase substantially. This may in turn place added pressure on material designers and contractors to attempt to recycle as much of this material as possible into new asphalt mixtures.

Extended dry summers can lead to the risk of bush fires. The extent, magnitude and speed at which these wind fuelled fires can spread out of control and engulf housing estates and roads is all too evident from recent examples from the USA, Australia and Greece.

Global warming is likely to lead to greater shortages of water in some geographical areas; this will drive up the cost of water and simultaneously the cost of construction projects.

Increased global average temperatures may lead to gradual desertification and extinction of certain plant and tree species which, if in the vicinity of road structures, will have consequences on the sub-surface moisture profile of these road foundations. Excessive drying of some soil types may cause shrinkage cracks, which in thinly surfaced roads may reflect through the asphalt bound layers. Vegetation deprived areas are more prone to flash floods following even brief intense downpours. Furthermore, arid climates with sparse or diminishing vegetation suffer more frequently from sand storms (e.g. Arabian Gulf Area). The very fine sand/silt particles can stay suspended in the atmosphere for several days, restricting visibility on roads.

4.1.1.2 Possible short- to medium-term solutions and mitigation techniques

To a large extent, engineers already know how to accommodate temperatures both in pavement design and in mixture design. A number of possible solutions exist, including the following:

- adjustment of bituminous mixture design (performance-related binder selection, including polymer modification of bitumen; selection of stronger aggregate skeleton; optimisation of volumetric criteria);
- adjustment of structural design (flexible, semi-rigid and rigid/composite designs);
- adjustment of maintenance plan (e.g. more frequent surfacing);
- adjustment of traffic management (e.g. temporary road closures or imposing temporary load restrictions);

- making greater use of concrete (less sensitive to temperature), while optimising mixture composition and the application and curing of concrete at higher temperatures;
- changing the design of the concrete pavement mixture to reduce the amount of water required;
- adoption of binders with higher softening point for surface dressings and asphalt;
- adjustment of construction processes and timing;
- forced cooling of pavements;
- adoption of solutions from localities that have already experienced the projected climate scenarios.

This last point relates to a climate analogue, which is a current climate that is similar to the projected future climate of a given location. One such climate analogue for London (Hallegate et al, 2007) suggests that the climate in London at the end of the century might be like that of Nantes according to one model, or Lisbon according to another. If it is assumed that Nantes and Lisbon are well adapted to their current climates, then by studying their current road networks and the way they are managed, it is possible to gain an insight into the possible adaptation measures that could be required in the south of the United Kingdom. In reality, any temperature change will be gradual and structural design is less important in the short to medium term; the most significant imminent risk is likely to be rutting, resulting from (short term) heat waves.

Current pavement design methodologies make use of historical climate data to predict the diurnal temperature and precipitation regimes. A case can be made to perform sensitivity analyses of the influence of climate change on the long-term performance of pavements instead of only using static climate data. This type of analysis would allow a better understanding of the potential influence of a future increase in rutting, freeze-thaw cycles, frost heave and thermal cracking on the functional life of the pavement. However, current design methods are mainly empirical and are unable to predict, for example, rutting. A better model for predicting degradation and therefore a better understanding of degradation mechanisms is therefore needed in the long term.

The importance of good construction practice cannot be over-stated, particularly when introducing harsher/drier mixtures or stiffer binders. For example, with such mixtures there may come a point beyond which modified or upgraded asphalt mixtures become too difficult (unworkable) to compact in the field using conventional compaction equipment, and a new generation of ultra-heavy compaction equipment may need to be introduced. A related issue is that, in service, the performance of some asphalt mixtures is adversely affected by their inability to resist densification, especially during the initial stages of their lives. A key feature of future design and construction practice should be the production of asphalt mixtures that can be laid and compacted at their final (refusal) density on day one, i.e. mixtures designed, laid and compacted to achieve instantaneous full interlock, and that will not densify any further as a result of loss of air voids content caused by traffic loading. It should be noted that in some locations and with some mixtures (porous asphalt) this problem of densification is not experienced; other countries may be able to learn from this experience.

Various techniques are available for reducing the temperature of the surfacing which, in addition to mitigating rutting, flushing and thermal cracking, could be beneficial to reduce the heat island effects in urban areas. These techniques include:

- cooling pavements with water. Trials in Japan have shown that by simply spraying pavements with water during the day, it may be possible to keep the pavement temperature low. Some cities have also used treated wastewater (EPA, 2008);
- using pervious surface courses. Due to the open structure of this material, the layer is not heated in the same way as in dense asphalt mixtures and, to a certain extent, the mixture is cooled by the ambient air so preventing heat accumulation in the surface course and lower layers *(see box 2, page 40)*. This can also include permeable concrete and permeable concrete block paving;
- improving the reflectance of the pavement surface:
  - application of chip seals. These consist of aggregate bound in liquid bitumen. These are often used to resurface low-volume asphalt roads and sometimes highways. Solar reflectance of chip seals will correlate with the albedo of the aggregate used thus reducing pavement temperatures;
  - application of concrete surfaces. These can be overlays over existing asphalt, as well as the construction of concrete pavements in new alignments and widening of roadways. Such surfacing can offer good solar reflectance thus reducing pavement temperatures;
  - application of microsurfacings. These are thin sealing layers used for road maintenance. Light coloured materials can be used to increase the solar reflectance of the asphalt. One trial has shown that the application of light-coloured microsurfacing material consisting of cement, sand, other fillers and a liquid blend of emulsified polymer resin, has produced solar reflectance values comparable to that of new concrete (EPA, 2008);
  - increasing the solar reflectance of pavements. This can be achieved by the use of light-coloured aggregate, colour pigments or coloured sealants. Solar reflectance can also be effectively improved by the use of alternative resin-based binders (clear coloured tree derived resins). Using clear resins, albedo becomes mainly determined by aggregate colour.

4.1.1.3 Possible longer-term solutions

In addition to the above, a number of other, probably more long-term, solutions could be adopted to deal with the increase in frequency of very hot days and heat waves. These include:

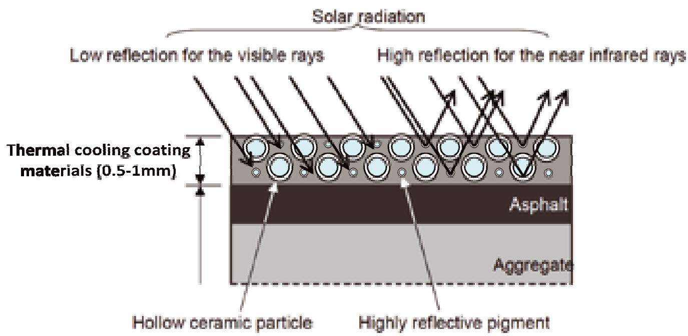
Material technologies:

- the application of purpose designed solar reflective coatings that can be sprayed on existing surfacings (Heat-Shield Pavements). The coatings have high reflectivity in the near infrared spectra and low reflectivity in the visible light spectra *(see box 1)*;
- greater use of transparent bitumen derived binders. Colourable binders have been manufactured from petroleum resins, petroleum oils and thermoplastic elastomers. The components are well mixed and dispersed to produce a stable product. Adhesion promoters and antioxidants can be introduced into the formulations if needed (Seo et al, 2008);
- use of concrete surfaces which naturally have a significantly higher albedo value;

BOX 1 - PAVEMENT SURFACES COATED WITH SOLAR REFLECTIVE TECHNOLOGY (IWAMA ET AL, 2008; KAWAKAMI & KUBO, 2008)

The innovative technology behind this Japanese spray-on coating is based on higher reflectivity for near infrared rays and lower reflectivity for the visible rays. The advantage is that normal road markings can be used since the pavement surface appears dark. The coating formulations essentially consist of high albedo paints which reduce the ability of the pavement surface to absorb infrared rays; furthermore the compositions contain fine hollow ceramic particles to reduce the thermal conductivity of the coating. The technology has also been referred to in the literature as *"Heat-Shield Pavements"*. In one investigation, the albedo of a Heat-Shield surfacing has been measured to be as high as 0.57 (compared to 0.07 for a conventional drainage pavement).

In another set of week-long outdoor exposure trials it was demonstrated that during the summer season with air temperatures reaching approximately 35°C (no rain), the surface temperature of conventional (uncoated) asphalt slabs peaked at around 60°C, whilst identical slabs that had been pre-coated with the solar reflective technology had maximum surface temperatures of around 40°C. The paints were shown to have adequate adhesion to both old and new asphalt surfacing and full scale trials have shown the pavement friction to be comparable to conventional asphalt surfacings. Accelerated ultraviolet weathering tests also showed good weather resistance. The pavement friction of these spray-on coatings was enhanced by introducing a thin layer of ceramic sand sandwiched in between two reflective coating layers.



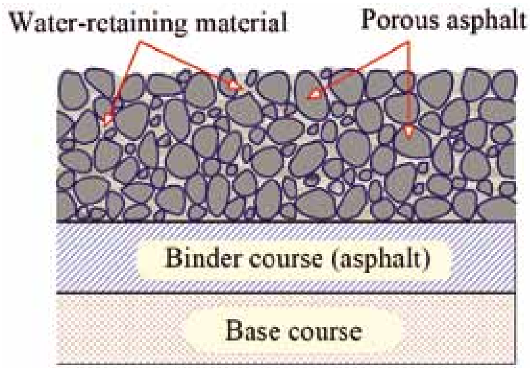
SCHEMATIC OF SOLAR REFLECTIVE TECHNOLOGY

Pavement technologies and the roads environment:

- design and implementation of new road friendly tyre designs, which reduce contact stresses on road surfaces;
- the use of more rigid pavements which have been shown to reduce rolling resistance and are not subject to problems such as bleeding, softening and rutting (i.e. they are less affected by high temperatures);
- the use of pervious concrete pavements for lower trafficked areas and pervious concrete shoulders for higher trafficked areas. Interlocking concrete pavers could also be used for roadway applications;
- the use of Water Retention Pavements (see Box 2). Trials in some Japanese cities have shown that pavement temperatures may be effectively kept low by using water retention pavements. Water retention pavements are porous asphalt or concrete based pavements, which have a sub-layer that consists of water retentive materials that absorb moisture and then evaporate it through capillary action when the pavement heats up. Some of these systems involve underground water piping to ensure the pavement stays moist;
- the use of non-vegetated and vegetated permeable pavements to mitigate heat island effects *(see Box 3 in section 4.2.1.3, page 60)*;
- the use of pavement surfaces with a higher albedo value;
- more sophisticated cooling of roads in summer and using the stored heat to warm the road in winter and/or generate energy;
- urban geometry - the dimensions and spacing of buildings within a city, or urban geometry, can influence how much heat pavements and other infrastructure absorb. For example, tall buildings along narrow streets create an "urban canyon", the effect of which is to limit heat gain to the pavement during the day when the buildings provide shade;
- selection and planting of more dry-climate acclimatised type plant and vegetation for soil stabilisation and moisture control measures of areas adjacent to roads;
- re-assessment of the safety of road users if the frequency of sand storms is to increase, possibly requiring wind breakers (to trap dust), road re-alignment and signage redesigns to enhance visibility.

BOX 2 - WATER RETENTION PAVEMENTS (KUBO ET AL, 2006)

Water retention pavements, another Japanese development, are in essence porous asphalt pavements with the voids filled with water-retaining materials. This type of pavement reduces temperature through the mechanism of evaporation as the water draws heat from the surroundings when it evaporates, which results in a temperature reduction. The structure of a water-retention pavement is shown below. In one comparative investigation, the surface temperature of a water retention pavement on a day following rain was up to 16.4°C lower than that of a conventional dense graded pavement, and up to 13.7°C cooler than a drainage pavement. The mechanical resistance of such pavement types to rutting was also tested using full-scale accelerated vehicle loading and the performance was shown to be comparable to that of conventional asphalts.



STRUCTURE OF WATER RETENTION PAVEMENTS

Traffic management:

- the removal of as much as possible of the heavy goods traffic from the road network onto other means of transportation (particularly rail, inland waterways and sea);
- traffic management so as to prevent very slow moving/standing heavy goods traffic and distribute the traffic loading more uniformly across all traffic lanes;
- the application of lower and stricter limits on maximum permissible axle loads and tyre pressures in combination with tougher measures to monitor traffic loading on flexible pavements (note: not necessarily relevant for concrete pavements);
- encouraging/incentivising heavy traffic to travel exclusively at nighttimes, when the ambient temperatures are lower and the asphalt surfacings are thus stiffer and more rut resistant.

4.1.2. Decrease in frequency of very cold days

4.1.2.1 Main impacts

Three main types of cold-weather associated thermal regimes impact on roads. They are: (a) sustained winter thermal regime during winter months; (b) fluctuating thermal regimes during autumn and spring, and (c) sustained summer thermal regime starting off in spring. The potential impact of these on flexible road pavements are summarised below:

a. under sustained sub-zero temperatures during winter, and depending on the prevailing moisture content in the pavement structure and the nature of the pavement materials (e.g. frost susceptible soils such as silts and clayey silts), the subgrade and/or pavement layers can freeze, increase in volume and subject the pavement to swelling pressures, which eventually can lead to frost heave. The pavement may also crack due to the extensive tensile stresses produced under the effects of sustained sub-zero temperatures in winter;
b. fluctuating thermal regimes, when temperatures repeatedly fluctuate above and below freezing point, may cause thermal fatigue, which can result in pavement distress, particularly in the upper layers of the pavement;
c. when a frozen pavement start thawing in spring, the moist and sometimes saturated conditions in the unbound layers, when combined with traffic loading, may cause substantial damage to a pavement in the form of rutting and cracking;
d. surface deterioration (scaling of concrete surfaces, fretting of asphalt surfaces).

Rigid road pavements are less susceptible to the swelling of the subgrade. The fluctuating thermal regimes, especially when de-icing salts are applied on the surface, may lead to scaling at the surface of the concrete pavement. By optimising the concrete composition (e.g. by using air-entraining agents, higher cement contents, lower water-cement ratios), the influence of the de-icing salts can be minimised.

A significant and sustained decrease in the frequency of very cold days could reduce the risk of pavement damage caused by frost heave, freeze-thaw cycling and thawing, and could therefore reduce road maintenance costs. However, it is not that simple. As winters become gradually warmer, the pavement will be exposed to more frequent cycles of freezing and thawing, leading to premature deterioration of especially the upper layers of the pavement (i.e. cracking and ravelling). This allows more water to ingress the pavement structure, which in turn may lead to higher incidences of expansion and contraction of water during subsequent freeze-thaw cycles, resulting in ravelling, potholing and increased surface roughness. Such conditions were prevalent in Sweden during the winter of 2007/08, which was the warmest winter on record. On the other hand, the unusually cold European winter of 2009/10 resulted in a higher frequency of freeze-thaw cycling causing more potholes to appear than usual on roads in countries such as the United Kingdom, the Netherlands and Belgium, increasing the overall cost of maintenance.

Hence, in areas where roads are usually frozen in winter, a decrease in the number of very cold days could result in the following impacts:

- potentially, a higher frequency of freeze-thaw cycles, causing durability and fatigue problems, and greater incidence of *"black ice"*;
- increased demand for de-icing chemicals on account of the higher frequency of freeze-thaw cycles, including potential damage from adverse effects of repeated application;
- wet surface conditions occurring more frequently, allowing more water to ingress the pavement through cracks with consequential effects;
- reduced bearing capacity as a result of moisture ingress and/or thawing of an otherwise frozen pavement;
- although a reduced frequency of very cold days could reduce the occurrence of low-temperature cracking, one long, cold winter can cause a road to fail;
- winter maintenance costs may be lower during warmer winters, especially since less snow needs to be removed, but road owners/operators would still need to be properly prepared to cater for a cold winter when it comes;
- if studded tires are used *(see figure 6)*, road wear will increase, particularly when the surface is wet *(see figure 7)*.

FIGURE 6 - STUDDED TIRES, NORMALLY USED IN NORDIC COUNTRIES (PICTURE FROM SWEDEN)

FIGURE 7 - EXAMPLE OF A ROAD WITH SEVERE LOSS OF AGGREGATES DUE TO DURABILITY PROBLEMS

4.1.2.2 Possible short- to medium-term solutions and mitigation techniques

Maintenance operations prior to the onset of winter should be geared towards preventative maintenance, such as crack and joint sealing and the repair of other defects, in order to protect the pavement structure against moisture ingress. Impermeable surface dressings, such as single, double or Cape seals, could be used as a holding action if the extent of cracking on the surface renders crack sealing impractical or uneconomical.

When roads are constructed in areas with very cold climates and/or in areas subjected to freeze-thaw cycling, good drainage should be provided both underneath and on the surface of the road. Moisture resistant and frost resistant materials should be used to alleviate bearing capacity problems and the risk of frost heave. The selection of asphalt mixtures that can resist frequent exposure to surface moisture and freeze-thaw cycles is particularly critical. In order to achieve this, suitable laboratory tests should be conducted to qualify the asphalt mixtures. Concrete mixtures should contain air entrainers in order to insert small air bubbles in the concrete structure which reduce the stresses due to freezing of water in the pores and due to differences in salt content in the pore water. Higher cement contents and lower water-cement ratios will also lead to more durable concrete pavements.

Anti-stripping agents can be used in asphalt mixtures to increase resistance to moisture damage. Asphalt mixtures containing higher binder content and low in situ air voids, and that are still able to resist plastic deformation, particularly in hot summers[2], would also perform better under such conditions. The lower air voids would also prevent de-icing chemicals from penetrating the asphalt layer. Alternatively, modification of the bituminous binder by means of polymers or heterogeneous modifiers such as crumb rubber could render the mixture more resistant to moisture-associated damage. For concrete pavements in freeze-thaw environments, aggregates are tested to ensure they are not susceptible to D-cracking.

The reduced bearing capacity of especially low-volume roads as a result of moisture ingress and/or thawing of an otherwise frozen pavement can be a problem in areas subjected to heavy transport during winter. If these roads remain unfrozen or ice starts to melt during the winter season, they can be severely damaged by heavy vehicles. Therefore, road owners/operators may need to restrict the allowable maximum and/or axle weight of such vehicles. If roads were to freeze at night, the road owner/operator may choose to restrict heavy transport movements to nighttimes, but this needs to be closely monitored. If weeks of warm weather were to occur during winter, roads might suffer from a reduced bearing capacity. Trucks with tyre pressure controls such as inflatable/deflatable tyres might offer a short-term solution for such cases.

[2] Countries such as Hungary can not only have severe winters (-15 to -25°C), but also high summer temperatures of more than 40°C. Hence, pavements should be designed carefully to cater for both extremes.

It is important that winter maintenance operations are carried out in accordance with best practices. For instance, snow or slush that has accumulated alongside the road needs to be removed. *Figure 7* illustrates the entrapment of melting snow and ice on the surface. This could cause pumping of water in the pores of the asphalt layer, which may result in higher incidences of ravelling.

If studded tyres are allowed to be used on flexible or rigid pavements, high quality hard aggregate, preferably with a maximum aggregate size of up to 16 mm, would be required to resist the abrasion caused by such tyres. The higher the amount of large stones, the better the resistance to abrasion, but one has to be aware that large aggregate protruding from the surface may increase noise levels. Concrete pavement mixtures can also be made more abrasion resistance by increasing the concrete strength and the aggregate hardness to resist potential wear due to studded tires.

4.1.2.3 Possible longer-term solutions

The implementation of longer-term actions, such as a relaxation of design and construction standards for cold-weather roads, depends on whether or not the frequency of very cold days will decrease substantially and sustainably, as well as the frequency of freeze-thaw cycles. This is unlikely to happen in the short term, and as mentioned earlier, one cold winter could cause severe cold-weather associated road damages.

Adjustments to both structural design and material composition to prolong the life of cold-weather roads should be properly tested in the field and should have been proven to work under very cold winter conditions before they could be incorporated into specifications.

Countries with very cold climates are encouraged to exchange information about their best practices and success criteria in order to make it easier to adopt solutions from elsewhere. In general, technology is available to meet these challenges; the key is selecting the most appropriate solution.

4.1.3. Increases in arctic temperatures

4.1.3.1 The Arctic, climate change and frozen ground

The cryosphere is those places where low temperatures freeze water into its solid form (snow and ice), essentially the Arctic, Antarctic and high alpine regions (mountain ranges of Canada, Chile, Peru, China, Russia and United States, for instance), with focus here on the Arctic. The northern polar region consists of a vast ocean surrounded by land. Snow and ice cover much of the Arctic sea and land surface, particularly the Northern Arctic. A wide expanse of tundra (treeless plains over frozen ground) lies between the icy High Arctic and the forested (boreal) Subarctic. Almost four million people live in the Arctic. Unlike many parts of the world, Arctic land is generally more accessible in the winter when the tundra is frozen and ice roads and bridges are available. Many community and industrial activities depend on frozen ground surfaces, including ice roads and bridges, for the transport of supplies, fuels and materials. In the summer, when the top layer of the permafrost thaws and the terrain becomes boggy, travel over land and construction activities can be difficult (ACIA, 2004; IPCC, 2007). The roads and airports of the Arctic are critical to the viability of often small communities, with the airports particularly important for year-round access to life-support systems such as hospitals.

The Arctic is extremely vulnerable to observed and projected climate change (some of the most severe experienced) and its impacts. Changes in the Arctic climate also profoundly affect the rest of the world through increased global warming and rising sea levels. The annual average Arctic temperature has increased at almost twice the rate of the rest of the world over the past few decades, with some regional variability. Increasing precipitation, shorter and warmer winters, substantial decreases in snow and ice cover and/or thickness, and a significant rise in sea levels (effect of melting ice and thermal expansion of oceans) are the main projected changes, some of which are clearly already underway, that are very likely to persist for centuries (ACIA, 2004; IPCC, 2007). It should be noted that, in addition to the United Nations Intergovernmental Panel on Climate Change's comprehensively researched, referenced and reviewed evaluations of Arctic climate change and its impact, mitigation and adaptation (IPCC, 2001; IPCC, 2007), the Arctic Council[3] provides an intergovernmental, high-level forum and mechanism to address common Arctic climate change concerns, such as land transport over thawing permafrost, faced by Arctic people and governments (ACIA, 2004).

The Arctic's frozen water is in the form of snow, ice, glaciers, and frozen ground (permafrost, seasonally frozen ground and intermittently frozen ground). Permafrost, or permanently frozen ground, is soil, sediment, organic terrain, or bedrock that remains at or below 0°C for at least two years, unless physically or environmentally disturbed. It occurs both on land and beneath offshore Arctic continental shelves, and its thickness ranges from less than one metre to greater than 1,000 metres. Seasonally frozen ground is near-surface soil that freezes for more than 15 days per year. Intermittently frozen ground is near-surface soil that freezes from one to 15 days per year. With climate warming, permafrost (frozen ground) will thaw and the amount and thickness of seasonally frozen ground will decrease. The active layer, where the ground freezes and thaws each year, will get thicker and the extent of permafrost

[3] The Artic Council comprises eight Arctic nations (Canada, Denmark/Greenland/Faroe Islands, Finland, Iceland, Norway, Russia, Sweden, and United States), six Indigenous Peoples organisations, and official observers).

and seasonally frozen ground will not reach as far south as it does now in the Northern Hemisphere. Permafrost regions occupy approximately 23 million square kilometres (about 24% of the exposed land surface) of the Northern Hemisphere. Permafrost occurs as far north as 84°N in northern Greenland, and as far south as 26°N in the Himalayas.

The surface of snow and ice is white, so it reflects most solar energy (high albedo) back into space. A small change in temperature can start the melting of snow and ice, exposing increasing areas of ocean and ground. As the ocean and ground surface are darker in colour they then absorb more solar energy (low albedo). The continuing climate change impact transition from white reflecting surfaces to dark absorbing surfaces (sometimes in combination with atmospheric pollution such as soot) causes warming to occur faster in the Arctic than in warmer regions.

Frozen ground data are critical to understanding environmental change, validating climate models, and constructing and maintaining infrastructure such as road and airport pavements in permafrost and seasonal frost regions. Rising temperatures are already leading to a shortening of the season during which ice roads can be used and are creating increasing challenges on many routes. These problems are projected to increase as temperatures continue to rise. Frost heave and thaw-induced weakening are major factors affecting roadway performance with Arctic climatic warming conditions. In addition, the incidence of landslides and avalanches is sensitive to climate change impacts, such as an increase in heavy precipitation events, which are projected to accompany warming. Fortunately, applied engineering and construction experience dealing with permafrost issues has evolved over the past seventy years (painting runway surfaces white in Thule, Greenland, in the early 1940s, for higher albedo/reduced permafrost thaw, for example) (Berg and Aitken, 1973) and is the continuing subject of considerable applied research, particularly in and between the member countries of the Arctic Council. From a permafrost areas technology perspective for the design, construction and maintenance of road and airport pavements, including adaptation to deal with climate change impacts, the activities of the International Permafrost Association, particularly their International Conferences on Permafrost (for instance the 9th International Conference on Permafrost *"Permafrost on a Warming Planet: Impacts on Ecosystems, Infrastructure and Climate"*, 2008, University of Alaska Fairbanks, http://nicop.org), are also particularly important [www.ipa-permafrost.org]. The continuing development of circumpolar[4] regional transportation infrastructure engineering expertise is also very important to technically-sound, cost-effective and environment-friendly adaptation to Arctic climate change impacts.

[4] This includes the University of Alaska Anchorage Arctic Engineering Programme and proposed Government of the Yukon led research programme on climate change and transportation infrastructure on permafrost (Government of Yukon and Laval University, Canada, University of Alaska Transportation Centre, Fairbanks, United States, Colas Group, International, Yakut Design and Research Institute for Construction, Russia, and Arctic Technology Centre, Greenland).

4.1.3.2 Primary and secondary impacts on pavement structures in the Arctic and Subarctic

Primary impacts

The observed and projected climate change effects in the Arctic include rising temperatures, increasing precipitation, thawing permafrost, declining snow cover, rising river flows, diminishing lake and river ice, melting glaciers and ice sheets, retreating summer sea ice, and rising sea levels. The three primary detrimental, and relatively costly for adaptation, impacts of the observed and projected rapid and relatively severe Arctic climate change effects on road and airport pavement structures (including associated embankments, cuts and fills, slopes, drainage systems, and bridges) are, in decreasing order of Arctic and Subarctic extent (ACIA, 2004; IPCC, 2007):

1. thawing of frozen ground, together with increasing freeze-thaw cycles and frost heaving will decrease load bearing capacity and lead to subsidence and destabilisation of existing pavement structures. This will require substantial maintenance, rehabilitation, and reconstruction of existing pavement structures, with new and reconstructed pavement structures requiring relatively more costly adaptive planning, design, materials, construction, maintenance, and operations technology implementation (including maintenance and operations facilities such as equipment and materials storage buildings);
2. delayed ice formation and reduced ice thickness of winter ice roads and bridges, and a reduced frozen tundra period, will increasingly shorten and disrupt the winter ice roads and bridges, and frozen ground (compacted snow) roads. It will also impact on the operating season and capacity for northern communities and industries (e.g. mining). This would require the implementation of more adaptive construction and operations technology with increased maintenance and monitoring, including safety and overall risk reduction (particularly for life-support routes), and;
3. inundation and damage (e.g. erosion) of pavement structures due to rising sea levels, particularly when coupled with high tides, storm surges, heavy rainfalls, strong winds and thawing permafrost in some coastal areas. This impact is covered in *section 4.3.1* (*"Sea Level Rise, added to storm surges"*, noting that coastal airports are particularly vulnerable), and will not be considered further here.

It should be noted that these three primary impacts, coupled with secondary impacts, will often be interactive and cascading, along with other Arctic climate change affects on components of the terrestrial cryosphere and hydrology (e.g. thermokarst formation, changes in freshwater seasonal runoff and routings, and increased ice flows) (ACIA, 2004; IPCC, 2007).

Secondary impacts

There are secondary impacts on pavement structures associated with Arctic climate warming trends and primary impacts discussed above, such as (USACE, 2002; ACIA, 2004; UFC, 2004; CIER, 2006; Northwest Territories Transportation, 2007; Doré and Zubeck, 2009):

- increasing freeze-thaw cycles and frost action will result in more environmental deterioration of flexible pavements (noting that Portland cement concrete pavements are not commonly used in the Arctic) such as cracking (may extend a metre or more down into the base course and become wider and raised/depressed with age), ravelling and spalling at edges of cracks (FOD potential for airports);
- shortening winter construction season when the frozen ground surface makes road construction equipment movement most effective (e.g. embankment fill construction) with minimal disturbance of the underlying surface and damage to adjacent vegetation and water courses (highly desirable to take advantage of the natural thermal and physical adjustment capabilities of permafrost terrain);
- increasing river, stream and lake winter ice accumulation that can, during "summer" breakup, result in ice jams, flooding, riprap damage, scour and bank erosion impacting on pavement, drainage and bridge structures;
- increasing winter road maintenance requirements (ice and snow control) in the Subarctic – standard Southern winter road maintenance practices are essentially moving further North, and;
- Increasing attention to the safety of road users, maintenance staff and construction workers with increased freeze-thaw and slippery conditions.

It should be noted that this list of secondary impacts on pavement structures is not inclusive and comprehensive details are given in the cited references, particularly Doré and Zubeck (2009), which presents the state-of-the-art for pavement engineering in cold regions like the Arctic.

4.1.3.3 Adaptation technology for pavement structures and winter roads in the Arctic and Subarctic

Overview

It may appear, to the non-specialist on infrastructure engineering, construction and operation in cold regions (Arctic and Subarctic), that implementing appropriate pavement structure adaptation technology to deal with Arctic climate change trends will be a draconian task. However, this implementation has been an on-going, albeit accelerated now, activity since the 1950s of civil and military infrastructure engineers and contractors with permafrost expertise and practical experience with all stages of road and airport pavements planning, design, materials, construction, maintenance, and operations. For instance, airport asphalt pavements have been constructed successfully on permafrost and have been operated without significant problems at

Thule, Greenland and Norman Wells, Canada. This expertise, practical experience, and continuing applied research on infrastructure engineering in cold regions is well covered in the technical literature, and increasingly in northern engineering education and training programmes (TAC, 2010). It also includes risk-based design procedures and improved climatic data prediction models. The key point is quite simply the importance of involving engineers and contractors with northern regions (permafrost) expertise and experience, typically for the specific site(s) involved, at all stages of developing, constructing, operating and managing transportation infrastructure in the Arctic and Subarctic.

There are a number of applicable and informative technical references on transportation infrastructure in northern regions that cover the subject in considerable detail, such as:

- *Arctic and Subarctic climate change impacts on northern region transportation infrastructure* (ACIA, 2004; Natural Resources Canada, 2004; IPCC, 2007; TRB, 2008);
- *Ice and snow in polar and mountain regions of the world* (UNEP, 2007; Lamar, 2010);
- *Building science and frozen ground engineering for cold climates* (Hutcheson and Handegord, 1983; Andersland and Ladanyi, 2004; Anon, 2009; Kenter, 2010);
- *Ice engineering for ice control structures and ice suppression, and coastal engineering for sea-level changes* (USACE, 2002; USACE, 2009);
- *Impact of climate change on road earthworks* (PIARC, 2008);
- *Development, operation and management of transportation infrastructure in cold regions with permafrost terrain* (CSA, 2010; TAC, 2010a);
- *Pavement engineering, construction, maintenance and operation in cold regions* (Berg and Aitken, 1973; UFC, 2004; Grondin et al, 2005; FHWA, 2007; McGregor et al, 2008; Doré, 2009; Doré and Zubeck, 2009; Krashinsky, 2009, and;
- *Climate change impacts on winter roads – ice roads, ice bridges and frozen ground (compacted snow) roads and adaptation technology* (CIER, 2006; Northwest Territories Transportation, 2007; McGregor et al, 2008; Wise, 2009).

For the non-specialist, Doré and Zubeck's *Cold Regions Pavement Engineering* is recommended as a starting point (Doré and Zubeck, 2009). This document provides current, comprehensive information for designing, constructing and maintaining cost-effective pavement structures where freezing temperatures, unstable soils, precipitation, ice, permafrost, materials availability, materials selection, construction conditions, construction techniques, environmental protection, remote and small communities, and climate change impacts are complicating factors that must be considered.

Pavement structures

The engineering and construction of pavement structures in northern regions (permafrost areas) has generally included a consideration of the following parameters for the specific site involved:

- determining the distribution (vertically and horizontally), type (richness, source, formation, thermal properties) and load-bearing capacity (frozen and thawed states) of the permafrost;
- determining the surface and groundwater hydrology;
- minimising potential thermal and erosion impacts;
- minimising cuts (particularly of ice-rich soils) and utilising embankments (fills) where possible;
- maintaining natural drainage systems and providing for surface drainage;
- designing for anticipated differential settlements;
- avoiding surface and groundwater seepage areas;
- avoiding subgrade and embankment frost susceptible soils;
- stabilising (thermally and/or mechanically) cuts and fills;
- designing drainage structures to minimise erosion and plugging, and;
- designing embankment, cut and fill surface drainage for all weather service.

New adaptation technologies being implemented and/or developed to deal with climate change impacts on pavement structures on permafrost include (Doré and Zubeck, 2009; TAC, 2010a):

- use of artificial cooling to ensure that subgrades and embankments remain frozen;
- use of thermosyphons to enhance winter heat extraction from the ground (these devices have already been used to stabilise railway embankments on thawing permafrost);
- use of insulation within embankments (fills) to minimise thermal disturbance in thaw-sensitive permafrost;
- use of open-graded rock embankment materials to mobilise effective heat transfer within embankments (natural air convection within a dry rock fill embankment is an effective supplementary heat removal mechanism in winter);
- excavation of frozen ice-rich material and replacement with thaw-stable material;
- intentional thawing of permafrost (e.g. clearing vegetation), with postponement of construction until after the ground has settled;
- use of light-coloured coatings, reflective surface coatings and/or light coloured aggregates (high albedo) on asphalt concrete and chip-seal surfaces (low albedo) to decrease pavement surface temperatures and reduce potential permafrost thawing, and;
- use of enhanced pavement maintenance monitoring to detect potential problem areas so that they can be properly repaired before they interfere with road use (e.g. ground penetrating radar use).

Winter roads
The construction of ice roads, ice bridges and frozen ground (compacted snow) roads is highly developed in northern regions. By careful ice road monitoring (e.g. using ground penetrating radar to profile the ice), recording ice conditions, establishing truck operating rules and training truck drivers in the need for speed limits and

spacing requirements, it has been possible to generally maintain the truck loadings and to control the risk involved over the past thirty years. However, with climate warming in the Arctic and Subarctic, the operating season has been shortening and increasing maintenance is required. New adaptive technology is being developed and implemented for winter roads to improve their performance and extend their operating season, such as (McGregor et al, 2008):

- technical improvements in ice stress analyses to allow greater truck loadings;
- technical improvements for assessing the ice capacity and locating discontinuities in the ice (e.g. ground penetrating radar);
- traffic management improvements such as separate lanes for loaded trucks and returning empty trucks, allowing the general speed restrictions (for ice-wave and bending- stress control) on ice roads to be relaxed for the empty trucks;
- development of contingency ice road routes across areas with known potential ice instability to allow rapid traffic redirection if necessary due to monitored ice deterioration;
- greater vigilance and driver education to maintain safe truck operating speeds, and;
- more use of surface flooding and/or spray ice techniques to create rapid ice thickness increases.

It may not be possible to operate ice roads in some areas of the north in the future when the climate warming precludes the establishment and maintenance of satisfactory ice thicknesses and/or strengths. Long-term adaptive technology is being considered for these areas, such as (McGregor et al, 2008):

- gradual shift away from lake ice roads to roads on frozen ground (combination of all season and winter roads), including all-season truck routes to ports and mines;
- increased reliance on alternative transportation methods such as barges during the summer and shallow draft vessels to northern ports, and;
- transportation of heavy equipment and freight over winter roads with the assistance of heavy-lift balloons (innovation in the Arctic based on many years of similar use in the North American logging industry).

It is clear from the above that cost-effective adaptive technology to deal with climate change impacts on transportation infrastructure is already being implemented and the development of further technologies is being encouraged by the overall Arctic and Subarctic transportation infrastructure sector engineers and contractors.

4.2. HOW TO DEAL WITH CHANGES IN PRECIPITATION

4.2.1. Increase in frequency of intense precipitation events

4.2.1.1 Primary and secondary impacts

Primary impacts
The primary impacts of an increase in frequency of intense precipitation events on pavement constructions are manifested by increased risk, with potential impact on both the pavement structure and on the use of the pavement. The key risks include: (1) water damage to asphalt; (2) reduced bearing capacity of lower pavement layers, and/or; (3) reduced safety and comfort for the user (less friction, less comfort, reduced capacity of the road).

Water damage to asphalt
Water damage to asphalt is still an imperfectly understood phenomenon, and it is likely that a number of different mechanisms operate to different degrees in different situations. These include: (i) failure of binder adhesion to aggregate, especially with *"acidic"* type aggregates and unsuitable fines to which adhesion of *"acidic"* bitumen is weak (in the classic situation leading to *"stripping"* (complete detachment) of the binder from the aggregate), as the asphalt frets, ravels and, in the extreme case, eventually becomes unbound; and (ii) scouring of binder from the aggregate under repeated elevated hydraulic pressures caused by traffic loading, once water has entered the pavement and become trapped between layers. In the Netherlands, fundamental research is being performed into the modelling of adhesive and cohesive failure in asphalt including the effect of water and ageing of bitumen/mortar mixtures (Hagos, 2008; Huurman, 2008; Scarpas et al, 2007).

Water damage can result in a reduced lifetime for a bituminous pavement, although in some countries with temperate/mesothermal climates the impact may be negligible since roads are normally wet for a certain period and an increase in the amount of precipitation may not change this period of time (or its impact on the asphalt) significantly. In other countries where there will be a significant change in the length of time a road will be wet, the effects may be more pronounced. These countries will have to review their specifications and take advantage of the knowledge in countries already dealing with this phenomenon.

Reduced bearing capacity
Higher precipitation levels could increase the risk that (on a temporary basis) water is present in base or sub base layers (e.g. as a result of rising ground water levels). With regard to lower pavement layers comprising conventional construction aggregates, the risk lies with degradation of the base/sub base layer, particularly when unbound or weakly bound; hydraulically bound secondary materials like crushed concrete

are similarly vulnerable. In addition, if water is allowed to infiltrate and remain in these lower pavement layers and in the sub base, saturation may occur, with the consequence that their stiffness (and bearing capacity) will reduce, with potentially disastrous consequences for the overall pavement *(see figure 8)*. In the extreme case, unbound or weakly bound material may suffer permanent damage in the form of wash-out (especially of fines). Furthermore, chemical reactions may take place in the environmental conditions that occur in a base course layer, resulting in a weakening of the bond or in a total loss of bond between aggregate particles. In some materials these chemical processes can result in the formation of deleterious minerals. More strongly bound lower pavement layer materials are less exposed to such damage; equally, they are not generally designed to be saturated in service, and the effects of prolonged saturation may be deleterious, depending on the binder used. The saturation of a sub base could have a disastrous effect on the bearing capacity of the pavement. Where conventional construction aggregates are replaced by lightweight materials such as expanded polystyrene foam, the stability of the whole pavement structure may be influenced by saturation with water.

FIGURE 8 - PAVEMENT DAMAGE CAUSED BY FLOODING
(DEPARTMENT OF TRANSPORT AND MAIN ROADS, QUEENSLAND, AUSTRALIA)

Reduced safety

The higher precipitation will result in more water on the road. This has an effect on safety (pavement friction), comfort (visibility) and capacity of the road. The general understanding of the term *"skid resistance"* refers to the frictional properties of the road surface measured using a specified measurement device under standardised conditions. In most countries, the term always refers to measurements made on wetted roads, unless specifically stated otherwise, and while these measurements are used to characterise the road surface and assess the need for maintenance, they cannot be related directly to the friction available to a road user making a particular manoeuvre at a particular time. The skid resistance of a wet or damp road surface will be substantially lower than that of the same surface when dry, and is more dependent on the condition of the surfacing material, including its surface texture. Hence, the term "pavement friction" is preferred to that of *"skid resistance"*. The objective of design and maintenance standards is to manage the risk of skidding accidents in wet conditions. Based on accidents analyses, countries determine a certain level of pavement friction for their network and adopt a maintenance strategy. Although the amount of water used in skid resistance measurements simulates a severe rain situation, our understanding is based on the status quo, and with an increase in intense precipitation events there is a level of uncertainty regarding what the "appropriate" levels of pavement friction are, potentially requiring re-evaluation for these new conditions. In addition to the possible need to determine appropriate levels of pavement friction where surface water is more prevalent than historically, there is also the associated increased risk of aquaplaning; in the extreme case, this can cause a vehicle to skid out of control at high speed on a surface that is so wet that it causes the vehicle's tyres to lose contact with the road especially in situations were rutting occurs. It is important to try and increase the tyre-pavement interface during wet conditions.

For countries with temperate/mesothermal climates where roads are already frequently wetted, there may be no need to adapt pavement friction levels at the present time, although periodic analyses of safety will be needed. For other countries where there will be a significant change in the length of time a road will be wet, the situation could be different.

Reduced comfort

The presence of water causes splash and spray, limiting visibility and increasing discomfort. This could have an impact on safety. Generally, roads are designed to transport water as quickly as possible from the road surface to the road verges and drainage systems. High precipitation rates especially in hilly areas can cause roads to have a thick surface water layer or even to be flooded to a certain extent, not only because the water can not be transported quickly enough but also because water flows to the road from the surrounding environment. The latter especially transports not only water but also other materials, as mud, resulting in a sudden drop of pavement friction.

In Europe, the ERA-NET ROAD project SWAMP (Storm WAter prevention - Methods to predict damage from water stream in and near road Pavements in lowland areas), has provided a systematic approach at network level to identify so-called blue spots, namely roads that are prone to flooding, and guidelines on how to reduce the vulnerability of roads to flooding (Hansson et al, 2010). The methodology adopted by SWAMP could have more general application in helping transport professionals to deal with the effects of climate change.

Reduced road capacity

As a result of an increase in frequency of intense precipitation events, the capacity of the road to transport vehicles reduces considerably. This can result in more traffic congestion with associated social costs.

Secondary impacts
Where water penetrates and begins to damage asphalt material, this is frequently accompanied by a reduction in, or the complete absence of, bond at layer interfaces; this discontinuity provides a location where water can pond, accelerating the pavement deterioration described above.

Erosion and pumping of material by the action of water under a jointed concrete pavement can result in faulting.

Apart from inadequate storage capacity, there is a range of water quality effects associated with an increase in frequency of intense precipitation events:

- Water quality effects may be encountered during the drier summers when rivers flows may be lower; this may limit the capacity of the river to receive and dilute road runoff from a subsequent storm event following a dry period. However, it is worth noting that:
  - this effect can be reduced if treatment of runoff is dimensioned correctly;
  - in the case of ditches and canals, the water level is less dependant on rainfall, and the described effects can be less than in rivers.

- Higher drainage flows from increased rainfall may affect discharges to groundwater via infiltration systems such as soakaways and filter drains;
  - if runoff is infiltrated in the verge soil, contamination of surface water in adjacent ditches or canals is prevented. However, in the case of heavy and sustained rainfall the soil will become soaked, and runoff will flow over the soil and into the surface water, potentially causing contamination;
  - when infiltration into the verge soil is not possible, the water is usually discharged through drainage / gutters and is treated for example by sedimentation before the water is discharged into the surface water or sewage system. In the case of heavy and sustained rainfall the dimensioning of the treatment can be insufficient, potentially causing contamination of surface water;
  - the total contamination load coming from a road will not be changed by an increase in frequency of intense precipitation events. After a dry period, however, the concentration and amount of runoff could be relatively high (and may not penetrate a desiccated soil), compared to a situation with a more evenly distributed discharge. This could cause effects especially in smaller water systems, which would not occur with a more evenly distributed year-round discharge of the runoff. A well designed verge or water drainage and treatment system is essential to prevent this.

- In many countries, the use of secondary materials in base courses is common and sometimes materials are used that could potentially leach deleterious substances. To prevent this, the materials can be either bound (immobilised) or isolated. In the case of the former, loss of bond as described earlier could then create environmental problems. In addition, a rise in ground water level may lead to leaching of contaminant materials, such as from Incinerator Bottom Ash. Application is only allowed if there is no contact with the ground water. Where special isolating measures are in use, the design parameters of these measures should be re-investigated where there is an increase in the frequency of intense precipitation events.

- Rising ground water levels may also lead to increased salinity in certain locations.

As already indicated, the existing drainage infrastructure may be inadequate to convey the higher flow rates anticipated during the more extreme storm events and these changes in precipitation are likely to require the use of larger drainage structures in the future. Where the drainage is inadequate and leads to standing water, then in the worst case scenario road closure may be necessary for safety reasons.

Finally, there is a range of impacts on the pavement foundation and underlying earthworks related to the presence of increased water. While these impacts are beyond the scope of the present report, they cannot be ignored because the road pavement sits directly upon and is intimate contact with these materials. Impacts include an increased likelihood of landslides and instability of road embankments due to water pressure in overflow areas.

4.2.1.2 Possible short- to medium-term solutions and mitigation techniques

As with temperature, a great deal of knowledge already exists regarding how to accommodate greater amounts of water resulting from an increased frequency of intense precipitation events, both in pavement and material design as well as in the geometrical design of the road. Possible solutions include the following;

- adjustment of asphalt mixture designs (improved resistance to water damage), although, as noted earlier, in some countries with temperate/mesothermal climates the impact may be negligible. In other countries where the period that roads will be wet will be increased considerably, there may be good reason to look into this. Concrete pavement materials would generally be expected to be more resistant to water damage than asphalt pavement materials, although knowledge of how to increase water resistance in bituminous pavements is available, including the use of special additives and fillers (asphalt is used in waterworks and water reservoirs and can be made resistant to water in the long term);
- increasing the water bearing capacity by the use of porous pavements or porous wearing courses;
- implementation of restrictions on building with secondary materials for which specific environmental conditions related to possible leaching apply (for example, use of Incineration Bottom Ash in road embankments). It should be noted that our

understanding of the water quality effects associated with changes in historical precipitation levels is a developing story, and long term assessment is a necessary precursor to informed decision making;
- informed material selection (improved resistance to water damage) linked to structural design (for example, greater use of bound foundations, linked to appropriate drainage provisions);
- adapting the drainage capacity of roads, including cross fall adaptation as well as transportation of the water via drainage systems or other means away from the road and preventing water from penetrating into the lower layers;
- green verge maintenance, to ensure that water can be transported from the road to the verge (too often maintenance is neglected resulting in a barrier preventing water from flowing away);
- in the case of infiltration of the runoff into the soil, redesign of the verges (both the width of the verge and the composition of the soil) may be necessary to maximise infiltration of the runoff into the soil and prevent discharge into the surface water systems after heavy rainfall;
- improvement or upgrading of stormwater systems, including the water treatment facilities;
- increased temporary water storage, for example by use of eco-balancing ponds;
- greater ground water level control or restrictions on building with lightweight materials such as expanded polystyrene foam;
- adjustment of traffic management (e.g. temporary road closures of inundated areas or load restrictions for flood affected pavements);
- adoption of solutions from elsewhere (climate analogues).

Water resistant asphalt mixtures are an essential first line of defence to withstand the effects of water. In this, the period of time that water will be present is more relevant than the amount of water due to an increased frequency of intense precipitation events. Our understanding of the effect of water is limited, particularly regarding the processes taking place at the micro-mechanical level (at the aggregate/binder interface); a better understanding of water damage would help to appreciate the value of components like hydrated lime, anti-stripping additives and polymer modified binders, which are conceived and marketed as beneficial, often with little positive evidence. Nevertheless, empirical knowledge is available. Many countries already experiencing frequent and intense rainfall build durable asphalt roads. For example, in the Netherlands the positive effect of hydrated lime on the durability of porous asphalt has been observed.

Current pavement design methodologies make little use of precipitation data. Rather than just using static climate data, more knowledge of the influence of climate change on the long-term performance of pavements would be beneficial, as already noted in the case of temperature. Unfortunately, current design methods are mainly empirical and are unable to predict, for example, durability parameters such as water related damage. However, as already noted, fundamental research is being done in the Netherlands to understand degradation mechanisms in porous asphalt, the mixture types that are most exposed to the effects of water and other climatological influences (Hagos, 2008; Huurman, 2008; Scarpas et al, 2007). Other recent work in this area includes the *"Pavement Performance and Remediation Requirements following Climate Change"* (P2R2C2) research project, carried out under the ERA-NET ROAD *"Road Owners Getting to Grips with Climate Change"* initiative. This project examined the likely differences in moisture (water) condition in the pavements of roads in Europe, from the Alps northwards, as a consequence of climate change, and estimated, for a range of representative pavement types and climatic zones, the likely consequences for pavement and subgrade material behaviour and for whole pavement needs in terms of:

- reformulation of material composition;
- new and modified drainage practice;
- modification to maintenance practice and rehabilitation.

The P2R2C2 project (completed in November 2010) concluded that it is neither economical, nor sensible, to look at short-term climate changes and thus start to modify maintenance methods at the present time, because climate change uncertainty (and year to year variability) is too high; rather, road design methods should be changed in order to introduce climate changes in the design models in order to overcome the possibility of climate change-related lower performance of current road designs. The study also noted that other uncertainties, especially economic and demographic, are likely to have a bigger impact on pavement maintenance and pavement need than is climate change.

In many countries, the design manuals for culverts are being changed to accommodate expected future increases in intense precipitation events; at the same time, water storage capacity will also have to be increased. Studies are also taking place into network vulnerability, defining 'black spots' where water drainage problems on the network are likely to occur, identifying where flooding might take place and the effects on ground water levels. The capability of pavement surface and sub-surface drainage systems to cope with these new circumstances, and the potential elevation of the water table within the pavement structure, is likely to require modified pavement design and drainage practice in the medium to long term.

4.2.1.3 Possible longer-term solutions

A number of other strategies could be adopted to deal with an increase in the frequency of intense precipitation events. These are probably more long term, in many cases because of the need to assess the (safety) risk associated with the proposed changes:

- the application of appropriate pavement friction criteria for situations where surface water is more prevalent (this would need to be combined with a better understanding of pavement friction under these conditions);
- related to pavement friction and with similar caveats, the implementation of appropriate surface texture levels. There may be lessons that can be learnt from other fields, for example airfield engineering and concrete pavements, where grooving has been successfully used to shed excess surface water and could have an application for (say) concrete surfaced pavements. The effects on noise should nevertheless be considered;
- the use of porous top layers can facilitate the drainage of the water to the sides of the road and prevent aquaplaning;
- the development of hydrophobic coatings suitable for use at the micro-mechanical and/or pavement surfacing level;
- better modelling of landslide risk, building on developing knowledge regarding network vulnerability;
- in areas where soils do not drain freely, permeable pavements can be used in combination with subsurface drainage systems to slow runoff and reduce stress on the storm-water system (for example, reservoir pavements *(Box 3, page 60)*). It should be noted that the existing track record for such pavements is mainly in lightly trafficked situations, and adaptation for heavily trafficked roads will require structural design input;
- improvements in road geometry, including the implementation of appropriate cross-fall requirements (for example, >1.5%);
- modifications and improvements to the pavement surface and sub-surface drainage system;
- in the Netherlands, some parts of the country are being set aside to act as temporary water storage areas in the case of high river levels and river water discharge. This will require adaptations to the design of roads and infrastructure in these areas.

4.2.1.4 Conclusions

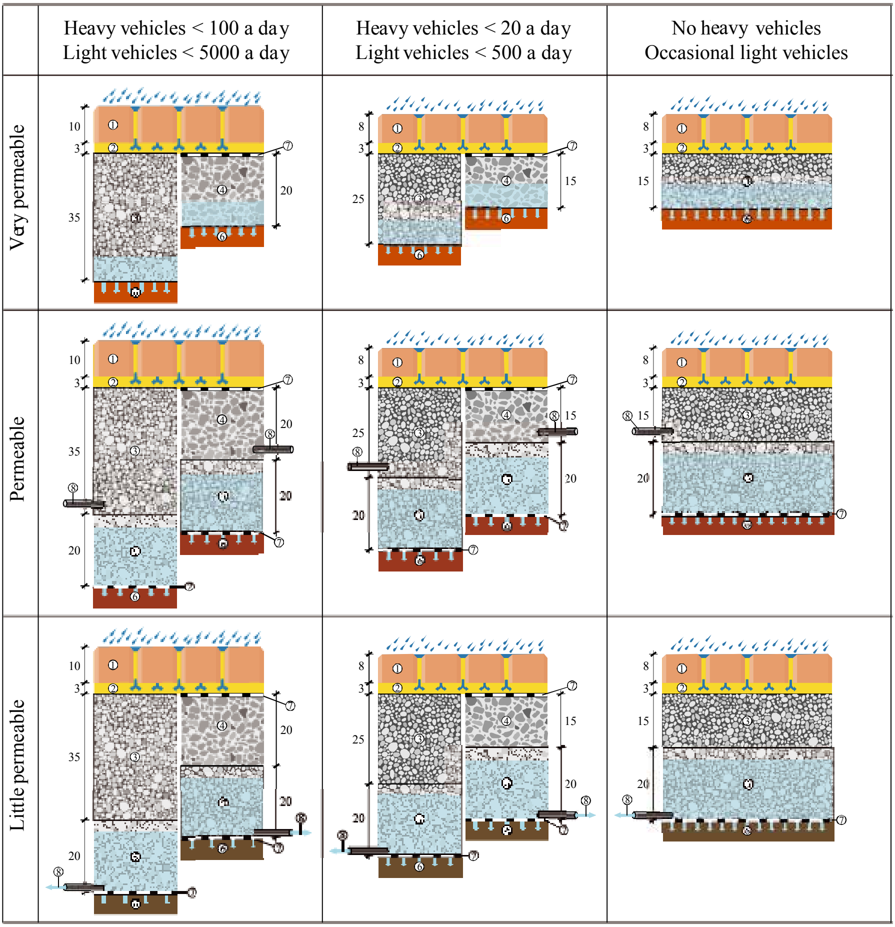
The most severe effect seems to be the presence of water on or in the road. The latter results in a possible loss of bearing capacity due to several reasons, depending on the way the construction is built and the materials used. Effects on the performance of asphalt and concrete are in general limited; however, for all these effects solutions are already in place.

Water on the road, directly or caused by flow of water to the road from the surrounding environment, can have a severe impact on safety, comfort and capacity. Improved water drainage systems and good cross-fall of the road should help to deal with this.

BOX 3 - PERMEABLE/RESERVOIR PAVEMENTS

Permeable/reservoir pavements provide durable and ecological solutions to prevent water run-off, minimise the risk of flooding and increase the efficiency of water purification by controlling water upstream and allowing it to infiltrate immediately into the soil.
Water is stored in the pavement structure and infiltrated into the soil or discharged by a drainage system at a reduced flow. Important for a durable and well-functioning reservoir pavement is the combination of bearing capacity and permeability. To this end, a structure has been developed by which water is stored in the subbase, and which is designed to protect the bearing capacity of both the base course and the pervious surfacing. In colder regions, frost protection of the soil beneath the structure has to be provided.
Depending on the permeability of the soil, additional drainage with flow reduction may have to be installed at the bottom of the structure. Standard structures used in Belgium for permeable concrete block pavements, expressed as a function of traffic volume and soil permeability, are shown below. Important for good efficiency are the permeability of the entire structure, storage capacity of the subbase layer and the infiltration or delayed drainage at the bottom of the structure.

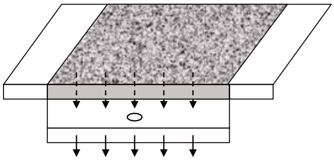
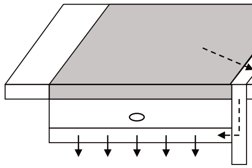
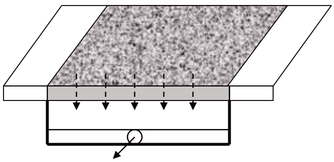
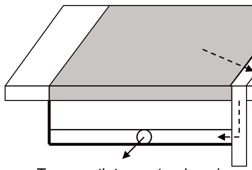
The working principle of a permeable pavement is as follows: the pavement allows water to ingress into the pavement structure through the surface, which aims to prevent water run-off over the surface of the pavement *(see figures following page)*, or allows for localised water ingress alongside an impermeable surfacing layer. In the case of the former, pavement blocks, porous asphalt or porous concrete could be used to allow water to ingress through the surface of the pavement. Water is stored at the bottom of the structure, preferably in the subbase layer. This protects the bearing capacity of the structure since pumping, which could occur at the surface of the structure in the presence of water and traffic, is largely eliminated. Also, reduction in bearing capacity of the base layer due to saturation by water is minimised. Evacuation of water is achieved by infiltration or by drainage or by a combination of both. From an environmental point of view, infiltration into the soil is desirable, unless the paving structure is situated in a water collecting area. In the latter case, a water impermeable membrane has to be placed beneath the structure, and the permeable paving will only serve as buffering system.



1. Water permeable pavement blocks
2. Beddinglayer
3. Unbound base layer
4. Porous lean concrete
5. Unbound sub base layer
6. Soil
7. Permeable geotextile
8. Drainage tube.

Dimensions in cm

OVERVIEW OF STANDARD STRUCTURES FOR PERMEABLE CONCRETE BLOCK PAVEMENTS (BEELDENS ET AL, 2009)

	WATER INGRESS ACROSS FULL SURFACE AREA (permeable surfacing layer)	**LOCALISED WATER INGRESS** (impermeable surfacing layer)
Distributed Drainage (infiltration)		
	A drain is installed centrally in the pavement structure to drain water to a safety overflow.	
Localised Drainage (regulated flow to an outlet)	 To an outlet or natural environment	 To an outlet or natural environment
	An outlet drain is installed within the pavement structure. Manholes with sumps should be positioned every 75 metres to provide access to the outlet drain for maintenance purposes. A manhole with sump should be positioned at each stormwater inlet.	

SCHEMATICS OF FOUR TYPES OF RESEVOIR PAVEMENTS (CITY OF LYON, FRANCE)

4.2.2. Increase in frequency of drought conditions

4.2.2.1 Direct and indirect impacts

Climate change projections indicate that drier climatic conditions are likely in areas such as central and Mediterranean Europe, southern and central Australia, southern and Mediterranean Africa, northern China, southwest USA and Central America.

The effect of drought is already familiar in these areas. However, climate change projections generally suggest that more frequent, more widespread and more severe droughts will be experienced.

Drought conditions may have impacts on the construction and performance of geotechnical structures and road pavements. Possible impacts include both adverse and beneficial impacts.

Construction
Water is a key ingredient used in the construction of road pavements and earthworks, in particular to achieve the required compaction density. Traditional compaction processes used in the construction of geotechnical structures and roads require

that the moisture content of materials is raised to the "optimum moisture content" (OMC) of that material at which point the shear strength created by soil suction at low moisture contents is minimised and the rearrangement of soil particles during the essential process of compaction requires less energy to achieve. In broad terms, this typically requires the use of about 200 litres of water per cubic metre of material (or between 150 and 200 thousand litres of water per pavement layer per kilometre of conventional road pavement). The amount of water required to reach OMC is increased in arid areas where the natural moisture content of soil is very low and high temperatures result in a significant loss of water by evaporation during the mixing and compaction process.

Drought brings with it a scarcity of water and competing community demands for whatever water is available. Use of existing water sources for road construction may not be given as high a priority as other uses. Where suitable alternative sources are not available, it may not be possible to utilise traditional construction methods.

Whilst a lack of water is likely to be an impediment to some construction procedures, it also presents the benefit of reducing the probability of construction delays due to inclement weather conditions.

Post-compaction volume changes as a result of changes in moisture conditions
Drying of the subgrade and fill can be of some benefit to pavements, as drier materials generally have greater bearing capacity and therefore provide better support to the pavement layers. If the water table is close to ground level, and within the stressed zone beneath the pavement, then any lowering of the water table during drought is likely to be of benefit to the support provided to the pavement. In certain areas, the lowering of the water table may also reduce exposure of pavements to saline conditions.

However, some of the most prevalent impacts on the performance of road pavements and earthworks are likely to be those resulting from changing moisture conditions in materials which are volumetrically sensitive to such changes. Such materials are often referred to as expansive or reactive materials, and generally these are materials which contain clay. Drying of such materials during drought results in their volume reducing, which can lead to pavement roughness and cracking.

Drying of expansive clay subgrade and fill materials can lead to volume changes which are not uniform across the full width and length of the pavement. This is a particular concern where the composition of the earth structure is not uniform or if its geometry is asymmetrical (for example, a fill on a cross-slope). The differential deformations that occur may be large enough to result in deformation of the pavement surface, which can be quantified in terms of increased pavement roughness. Wetting of these materials at the end of a period of drought can lead to differential expansion, further exacerbating the increase in roughness.

A secondary impact of these volume changes is the effect on drainage structures which may be damaged, misaligned or made redundant due to moving ground levels. Likewise, the connections between the earth structure and structures which are not deformable or only slightly deformable (e.g. bridge abutment fills and retaining walls) may be subjected to severe damage which may pose a threat to users when the fill settles excessively.

Stability design methods for earth structures could be regarded as being rather conservative with respect to severe drought situations. This is because design calculations are based on the characteristics of saturated soils which are more unfavourable than when the soil is in a dry state. However, this is not the case if major shrinkage cracks develop *(see figure 9, following page)*.

Cracking as a result of shrinkage
During the drying phase, shrinkage of these materials can result in cracking. Such cracking may be sufficiently severe to reflect through the pavement (figure 9). The cracks may also be a source of rapid moisture entry following rainfall. This can weaken the pavement further and reduce subgrade support.

It is obvious that if the network of cracks develops as a consequence of drought, damage will occur as a result of a loss of cohesion. One can also raise questions about the effect of shear on the subgrade when sections of earth structures, such as fills, are separated by very wide cracks. The above considerations apply only to the risks of instability in the mass of structures.

It may be prudent and reasonable for the stability design of soil structures on compressible soils to ignore the cohesion of the soil because if cracking occurs it will eliminate the effect of cohesion.

Clockwise from top left: drying shrinkage cracks in expansive embankment material; cracks from embankment reflected through pavement; repairs to cracked pavement and embankment; damage to drainage culvert due to volume changes in subgrade material. (Photos courtesy Jothi Ramanujam)

FIGURE 9 - MATERIAL DRYING SHRINKAGE IMPACTS ON PAVEMENTS

Erosion

"Skin effects" must also be considered. The soils which dry out the most are those nearest the surface on slopes. If they are sandy-silty soils they become extremely erodible and devoid of cohesion when dry. They are subject to rain-wash due to rainwater or runoff from the pavement, but may also undergo damage due to displacement caused by high winds.

Surface conditions

Drought conditions may be beneficial to the performance of the pavement in that moisture-induced damage, such as potholing of granular pavements and stripping in asphalt, is less likely to occur.

Increased frequency of drought conditions, like any other climatic changes, may affect pavement friction. During drought periods the pavement friction may not be an issue as the pavement is always dry. This may be beneficial to accident rates but may also change driver behaviour to become accustomed to dry weather driving. Some research suggests that pavement friction is at its lowest immediately after the first rainfall event which follows a period of dry weather. A contributing factor to this phenomenon is the accumulations of oils and other lubricants on the surface of the pavement. Drivers who do not adjust their behaviour for the changing conditions will increase the potential for skid related accidents to occur.

As drought conditions can be linked to increased sunshine, and in some areas higher temperatures, impacts on bituminous materials such as oxidation and deformation may become more common. These are discussed in detail in *section 4.1.1*.

Indirect impacts on land use and vegetation
An indirect impact on pavements that could result from increased drought conditions is a change in traffic loading due to shifts in freight transport routes as a result of changing land use (for example, agriculture). Likewise, population shifts are possible away from drought affected areas as a result of harsher living conditions, due to lesser availability of water, possibly hotter weather and increased frequency of dust storms.

Effects on vegetation adjacent to the road could have secondary impacts on pavements due to competition for moisture within the subgrade, root growth, and durability of drainage channels and batter slopes which may rely on grass or ground covers to prevent erosion.

4.2.2.2 Possible solutions and mitigation techniques

Design
Design of pavements may be able to exploit the drier subgrade conditions by reducing pavement thicknesses in response to the increased bearing capacity.

Design standards for drainage will require some consideration to ensure future integrity of surface and sub-surface drainage.

Compaction
Different soils have different optimum moisture contents, mostly related to the fines (and particularly clay minerals) content of the material, although aspects such as material porosity/absorptivity can also have an effect. The selection of materials for construction based on those with the lowest optimum moisture contents can have a significant effect on water usage.

Where normal sources of water used for construction purposes become limited or unavailable, it will be necessary to investigate alternative sources or use alternative construction practices that utilise less water. Possible alternative sources of water include bore water, recycled water and desalinated river/sea water. Each source must be consider on its own merits, including the assessment of the presence of dissolved salts, bacteria, oils or other substances that may be detrimental to the pavement, worker health or the natural environment.

Resistance to compaction can be reduced by adding surfactant (soap) to the mix water to reduce the component of intergranular stress derived from capillary tension. The decrease in capillary tension permits greater dry-side compaction density and an increase in soaked California bearing ratio strength (Berney et al, 2003).

The potential poor strength and water susceptibility of low-moisture compacted soils could be solved by the addition of minor amounts of stabilising agents. These could either be added in dry form or be mixed with what water is still added to the soil.

Alternatively, construction practices could be adjusted to be less reliant on water. In schematic terms, the drier the soil the more compaction energy is required in order to compensate for the lack of water and its lubricating role. High-energy impact compaction which makes use of heavy non-circular rollers (square or triangular), that impart energy to the layer being compacted as the rollers fall from their corners or apices, have been used successfully to compact drier soils.

When the soil is too dry, which can easily be determined from Proctor and CBR tests, the thickness of the individual compacted layers must be reduced and the power of compactors must be increased, but the limits of the effectiveness of this method are soon reached. If fills, for instance, are not considerably moistened subsequently, there is no danger of damage due to abnormal settlement. However, if a fill of this type is moistened, it becomes "collapsible" and will exhibit damage in proportion to its thickness.

The classical solution is therefore to moisten the materials employed in order to attain the desired level of compaction, but this solution is confronted by at least three major constraints:

- in the case of dry soils, the adjacent wells and rivers are usually at a low level themselves and it is not realistic to imagine that the administrative authorities will accept a further lowering of the water level for the construction of earth structures;
- when soils are dry, the meteorological conditions are frequently also responsible for high evaporation which makes attempts to moisten the soils by watering ineffective (wind may be an additional factor that increases the effect of evaporation);
- adding a large amount of water to the soil in order to make adequate compaction possible may transform the soil into mud if it is performed too suddenly. This, however, can be overcome by applying an appropriate and carefully controlled mixing technique, or by using *"sprinkler-buryer"* type plants.

Drying of materials in fills and subgrades
Problems associated with drying of material in fills, which could lead to shrinkage problems, non-uniform deformations and surface drying, could be addressed by moistening the material, reaching an optimal level of compaction to avoid subsequent settlement, and/or by covering the fill with protective soil (e.g. granular materials) or by establishing plant cover.

Similarly, problems associated with drying of subgrade materials, which could lead to transverse instability and the development of cracks that could reflect through the upper pavement layers, could be addressed by ignoring soil cohesion in the structural stability calculations, and hence opting for a more conservative design of the pavement structure.

Expansive soils
To satisfy performance and future maintenance requirements, the use of flexible pavement structures rather than rigid pavements in areas of expansive soils should be considered.

Options for designers to consider include use of low-swell fill materials, removal and replacement of expansive materials, provision of adequate cover thickness over expansive subgrades, lime stabilisation of clays, use of geogrids/geocells, and additional drainage provisions in an attempt to maintain a more constant moisture regime in the pavement and subgrade. The use of zoned embankments, where material that is prone to volume change is placed in the centre of the embankment, beyond the influence of seasonal moisture effects, is an option to consider when making use of expansive fill materials.

For the stabilisation of clay, soil treatments are often not appropriate if the soil is excessively dry, as performance will be unsatisfactory and the soil will remain unstable if there is a subsequent rainy period (i.e. risk for collapse). In the case of the re-use of clayey soils, specifications differ quite markedly in different parts of the world. The level of plasticity that is allowable in a given country for the reuse of such soils in fills has been established on the basis of past experience of climatic conditions and the available soils, and in some cases measures are taken to encourage re-use. The level of plasticity is closely linked to the shrinking and swelling capacity of the soils.

Soil erosion
Where soil erosion is a possibility, the erodible soils, which are often devoid of cohesion when dry, can be protected by covering them with a protective soil (granular material for example) or, preferably, establish plant cover. The last approach may, however, fail if the climate is too dry or the soil is too infertile.

Pavement friction

Where climatic conditions change, road administrators should consider their policies for pavement friction and make adjustments if needed. In conjunction with this, driver education campaigns may be necessary to remind drivers to adjust their behaviour when wet weather conditions occur.

4.2.3. Changes in seasonal precipitation

Much of the foregoing text on increases in frequency of intense precipitation events and drought conditions *(sections 4.2.1/4.2.2)* can be referenced when considering the impact and potential solutions to changes in seasonal precipitation, since intense precipitation events/drought conditions represent the extremes of wet and dry conditions that may occur to varying degrees as a result of changes in seasonal precipitation. Managing climate change impacts on the operation and performance of road pavements as a consequence of changes in seasonal precipitation thus requires a balanced view to be taken between these two extremes.

4.2.3.1 Primary and secondary impacts

The key impacts of changes in seasonal precipitation are likely to be manifested by:

- more/less stripping of binder from aggregate in bituminous layers;
- more/less delamination at layer interfaces in flexible pavements;
- reduced/increased bearing capacity;
- reduced/improved friction, depending on prevalent road condition;
- related to the above, increased/reduced oil and rubber deposits on pavements;
- changes in pavement roughness due to expansion (on wetting) and shrinkage (on drying) of reactive clay subgrades;
- changes in salinity (cycles of wetting and drying of the groundwater leading to more precipitation salts);
- shorter/longer construction times.

4.2.3.2 Possible solutions and mitigation techniques

To a large extent, the solutions to dealing with changes in seasonal precipitation have been covered by the forgoing text. The primary solutions include:

- adjustments to mixture design;
- adjustments to structural design;
- the application of appropriate pavement friction and surface texture criteria (combined with a better understanding of the requirements) under these conditions.

4.3. HOW TO DEAL WITH OTHER EFFECTS

4.3.1. Sea level rise, added to storm surges

The increase in the amount of liquid water at global level, combined with the increase in sea water temperature, will result in a rise in sea levels. Some islands may disappear and some regions that are near sea level may be flooded. This risk requires a detailed assessment of the elevation of current transport infrastructure and of that which is planned in flat coastal areas or in the vicinity of deltas and estuaries. However, while a rise in sea level is projected, there is still uncertainty about the magnitude and rate thereof.

This raising of sea level poses two potential threats to road pavements and earthworks structures:

- rises in water levels may make trafficked areas unusable, and;
- the rise in the water table may reduce the bearing capacity of the pavement structure in a way that is incompatible with its function.

It is particularly important to take these two effects into account for infrastructure that must provide high levels of service (urban and inter-urban roads, as well as railway tracks and airport runways), especially in view of the fact that the investment involves a very long service life and an interruption in traffic will impact on both road users and the regional economy, which interruption is expected to become more common in future.

Storm surges, particularly during high tides, would further intensify the risk of flooding in low-lying coastal areas or the closure of roads by the accumulation of debris on their surface *(see figure 10, following page)*. Greater protection of infrastructure will be required against sea level rise combined with storm surges.

Improved designs will be required for road pavements that are likely to be subjected to flooding. The simplest way of coping with this risk is to increase the depth of fills during construction and raise the infrastructure, but in areas where there is a shortage of natural materials (with the exception of sea sand), fill material is expensive, as it may have to be transported over long distances. Another alternative is submersible pavements, but these are frequently too rigid for areas that tend to be compressible, and they will nevertheless be unusable if the traffic lane is submerged.

The stormwater drainage system may also need to be resized or relocated for road pavements that are likely to be subjected to flooding.

Alternatively, roads (and other transport infrastructure) may have to be relocated further inland, or seawalls and dykes may have to be erected or strengthened to protect the infrastructure against storm surges.

FIGURE 10 - IMPACT OF A STORM SURGE (SOUTH AFRICA, OCTOBER 2008)

4.3.2. Increased wind velocity

The frequency of strong winds or severe storms may increase as a consequence of climate change. This may: (a) pose a treat to geotechnical structures due to wind erosion; (b) impact on the stability of road furniture, such as road signage and gantries, and/or; (c) create obstacles that may impede traffic flow or create a hazard to road users.

Wind erosion

The main threat posed to geotechnical structures by a change in wind regime or by extreme winds is caused by wind erosion. For wind erosion to occur three conditions must be satisfied:

- the surface soils must be sandy or sandy-silty;
- the surface soils must be dry;
- there must be no or little surface vegetation.

Of course, the presence of a prevailing wind direction (even without storms with strong winds, which would in any case have an effect on erodible zones) is an aggravating risk factor.

It is conceivable that an area that is currently not susceptible to wind erosion (i.e. it does not satisfy all of the above conditions) could become erodible in future as a consequence of climate change (e.g. an increase in frequency of drought conditions which may result in reduced plant cover). Examples of other areas that could be prone to wind erosion are: coastal areas that are particularly vulnerable to windblown sand and dune formation, and slopes of cuts and fills, whose sandy and infertile nature already makes them poor environments to allow the development of vegetation.

One of the most effective ways of combating surface erosion is to establish plant cover over the threatened zones. This, however, may be problematic in areas where the climate is, or is becoming, too unstable and irregular. In such cases, the solution may demand the mobilisation of more elaborate and expensive techniques.

Road furniture
Road furniture could be damaged by strong winds if the road signage and gantries are not adequately designed to withstand the prevailing wind forces. In such cases, the design of the supports and anchorages should be modified on the basis of climatic data as well as projected changes in wind velocities as a consequence of climate change.

Obstacles
Obstacles on the roadway caused by strong winds or severe storms, such as fallen trees, could lead to accidents and road closures. It is therefore imperative that all obstacles be removed as soon as possible from the roadway by an emergency task team.

In order to prevent or minimise the occurrence of fallen trees on the roadway, consideration could be given to cutting down trees adjacent to the roadway that could pose a problem.

4.3.3. Instability of embankments and slopes

For a landslide or slope failure to occur, the slope conditions have to be suitable for the movement of materials down slope. These conditions include the slope dimensions and geometry, geological conditions and climatic conditions as well as the presence of a driving force, e.g., earthquake, exceptional rainfall or interference by man.

Many slopes have such favourable conditions that movement of the materials is almost impossible, even under extreme driving forces. Such slopes are not expected to become unstable due to a change in climatic conditions. However, some slopes are only stable due to the favourable conditions outweighing the unfavourable conditions. Where climatic conditions are one of the favourable conditions a slope could potentially become unstable as climate change occurs.

As climate change occurs, slopes that are currently meta-stable or even stable may be triggered to fail due to an increase in rainfall events (both in frequency and intensity). These events will rapidly induce unfavourable slope conditions, primarily due to temporary high pore water pressures within the slope *(figure 11)*. Such slope failures can be considered to be triggered directly by the changes in climatic conditions and are therefore a primary impact.

Secondary impacts of climate change on slope stability will manifest when long-term changes in slope conditions occur. The conditions most likely to change are those of the water/moisture regime in the slope. As climate change causes precipitation regimes to change and snow/ice to melt over large areas the natural water levels will change accordingly. This will change the water conditions in both embankment and cut slopes and therefore change the design parameters of these features. Over time such slopes could become unstable and fail.

FIGURE 11 - INCREASED GROUNDWATER FLOWS IN CUTTING RESULTING IN PAVEMENT SATURATION AND SUBSEQUENT FAILURE (BARKLY HIGHWAY, CONCURRY – DEPARTMENT OF TRANSPORT AND MAIN ROADS, QUEENSLAND, AUSTRALIA)

A long term effect of climate change on slope stability will be a change in the geological conditions due to a change in the rock weathering regimes. Areas that become drier will be exposed to additional mechanical weathering while those that become wetter (and warmer) will be exposed to additional chemical weathering. Depending on the geological conditions, weathering may progress more rapidly and cause the material properties to deteriorate and ultimately render a slope unstable.

Since it is not possible to accurately predict the exact conditions that will result in an area due to climate change, it is not possible to predict what the effects of climate change in a specific area will be on the slope stability. It is, however, possible to identify those slopes that would be most vulnerable to potential negative effects. Slopes that are currently meta-stable will be vulnerable to any changes that result in the water conditions becoming unfavourable. Additionally, slopes with geological conditions that are prone to rapid deterioration in climatic conditions different to those in which they were designed are potentially vulnerable.

The most viable mitigation measure against slope instabilities causing damage and closures to road infrastructure is therefore to monitor high-risk slopes over time to see if any of the potential triggering mechanisms are developing. If such conditions are seen to be developing, mitigation measures, including slope stabilisation techniques, can be employed accordingly.

5. POLICY IMPLICATIONS

5.1. HOW TO RESPOND TO POTENTIAL IMPACTS OF CLIMATE CHANGE

There is sufficient scientific evidence that climate change is occurring. However, what is still draped in uncertainty are the likely extent of the gradual (and possibly even abrupt) changes in the climate over time and the local and regional impacts thereof. These uncertainties make it difficult to plan and design infrastructure that can accommodate these impacts. It is expected that, over time, climate scientists will improve their climate change projections and therefore empower road owners/operators with better information to assess the vulnerability of their assets and enable them to adapt and plan for the future.

Generally, most road pavements operating in moderate as well as warm and dry climatic zones will be less affected by the impacts of climate change than those located in cold climatic zones, particularly those that are gradually becoming warmer. This said, more regular extreme weather events may necessitate road owners/operators to institute more frequent maintenance and/or to review and adapt their standards and specifications in any region of the World.

Chapter 3 presented a systematic approach for conducting risk and vulnerability assessments for road pavement systems. It provides a broad framework for assessing risks and for the development of adaptation strategies and plans. On project level, tools such as Life-Cycle Cost Analysis (LCCA), could be used in association with a probability risk assessment to explore the financial and economic implications of a *"do nothing"* design option vis-à-vis those of options which accommodate climate change effects in their designs.

A Life Cycle Assessment (LCA) of alternative pavement structures should also be considered. LCA takes into consideration environmental issues such as energy consumption and greenhouse gas emissions over the functional lifespan of a facility (e.g. over a 50-year evaluation period). Combined with an LCCA, the true cost and environmental impacts of different pavement structures can be determined and compared to one another to determine which the best overall option is. Issues such as energy savings and associated reduction in road user costs can also be taken into consideration in LCA evaluations (Taylor, 2002 and 2006).

Since in most cases climate will change only gradually over time, road owners/operators could adapt their design philosophies and operational requirements when periodic maintenance or rehabilitation is scheduled and effected on existing infrastructure, if necessary. This, however, may not be the case for new and particularly long-life infrastructure that is being planned, where the potential long-term impacts of climate change may need to be considered upfront during the design of the facility. Similarly, road owners/operators need to consider the impact of the closure of a main arterial route as a consequence of, for instance, slope instability or flooding, and plan accordingly (e.g. disaster/emergency management plans and the mapping/provision of alternative routes where feasible).

In some cases, climate change may reduce the costs of infrastructure provision (e.g. in areas that are becoming dryer). However, invariably in most other areas, infrastructure costs are likely to escalate as a consequence of climate change. It is therefore important for road owners/operators to understand the likely implication thereof on their maintenance and capital works budgets. If warranted, road owners/operators may have to develop a business case which outlines the socio-economic risks of not (or inadequately) catering for the likely effect of climate change and which is matched against road user and community expectations, and appraise government and/or other funding agencies thereof, with the view to attract more funding to upkeep the serviceability of their road assets.

5.2. HOW TO DEAL WITH UNCERTAINTY AND RISKS

Within the scope of this report, vulnerability is defined as the extent to which a road pavement and its users are susceptible to sustaining damage and harm from adverse climate change effects. Vulnerability is a function of the sensitivity of road pavements to the effects of a change in climate, adaptive capacity and the degree of exposure of road pavements to climatic hazards. Risk is then the probability that a particular climate change event occurs during a stated period of time causing damage to road assets and/or harm to their users and society, thereby adversely impacting on the availability, functionality and safety of a road or road network.

Examples of a road owner/operator's high-level exposure to risks are presented in *Table 3*:

TABLE 3 - EXAMPLES OF A ROAD OWNER/OPERATOR'S HIGH-LEVEL EXPOSURE TO RISKS (UK HIGHWAYS AGENCY, 2008)

Risk	Examples
Reduced asset condition and safety	Assets deteriorate more quickly due to changes in average climatic conditions; assets are more badly damaged as a result of more extreme climatic events.
Reduced network availability and/or functionality	Need for restrictions on the network to maintain safety; increased need for roadworks.
Increased costs to maintain a safe, serviceable network	Construction/maintenance/repairs/renewal required more often; more extensive construction/maintenance/repairs/renewal required; new (more expensive) solutions required e.g. designs and materials/components/construction costs.
Increased safety risk to road workers	Increased risk to construction and maintenance workers and Traffic Officers as a result of climatic change e.g. if need to work on the network more often; if required to work on the network during extreme climatic events or if climatic changes requires them to perform more "risky" activities.
Increased programme and quality risks due to required changes in construction activities	More onerous design requirements; new technical solutions required with higher uncertainty, affecting project programmes and/or quality
Current road owner/operator's internal operational procedures not appropriate	Effects of climate change require new ways of working – changed or new business processes, new skills/competences.
Increased business management costs	Need for more staff; more frequent (expensive) incidents to pay for; need for more research into ways of coping with climate change.

At present, risks are still fairly difficult to quantify in absolute terms on account of the uncertainties associated with climate change predictions and the effects climate change would have on road pavements. However, these uncertainties should not hold back decision-making processes. Knowledge of the risk profile will assist road owners/operators to focus and prioritise its current and future actions to safeguard their infrastructure.

Various tools are available by which uncertainties and risks can be appraised. They range from multi-criteria risk appraisals *(see box 4, page 77)* to more complex probabilistic risk assessments, such as Extreme Value Theory *(see box 5, page 79)*. In Europe, the ERA-NET ROAD project RIMAROCC (Risk Management of Roads in a Changing Climate) provides a comprehensive guide on how to assess and mitigate climate change associated risks (Bles et al, 2010). Whatever method is used, and in view of the uncertainties associated with climate change, sensitivity analyses should be conducted on the probabilities of the occurrence of undesirable events and the impact thereof on the outcomes should be assessed. This approach will identify outcomes that may be particularly sensitive to changes in the probabilistic estimates and will built robustness into the risk assessment process.

BOX 4 - EXAMPLE OF MULTI-CRITERIA RISK APPRAISAL (UK HIGHWAYS AGENCY, 2008)

The Highways Agency of the United Kingdom uses a fairly simple yet rational risk appraisal process to provide a means of scoring the climate change vulnerabilities to form hierarchies and rankings, and to enable the UK Highways Agency to determine where to focus its efforts in adapting to climate change. The risk appraisal for each vulnerability makes use of the following four primary criteria:

- *Uncertainty* – compound measure of current uncertainty in climate change predictions and the effects of climate change on the asset/activity;
- *Rate of climate change* – measure of the time horizon within which any currently predicted climate changes are likely to become material, relative to the expected life/time horizon of the asset or activity;
- *Extent of disruption* – measure taking account of the number of locations across the network where this asset or activity occurs and/or the number of users affected if an associated climate-related event occurs. Therefore, an activity could be important of it affects a high proportion of the network, or a small number of highly strategic points on the network.
- *Severity of disruption* – measure of the recovery time in the event of a climate-related event e.g. flood or landslip. This is separate from 'how bad' the actual event is when it occurs e.g. how many running lanes you lose; it focuses on how easy/difficult it is to recover from the event i.e. how long it takes to get those running lanes back into use.

For each of the vulnerabilities, a High/Medium/Low qualitative score is assigned against the four primary risk appraisal criteria. Scoring is undertaken based on expert opinion, and necessarily involves some judgement. The qualitative score for the four criteria is determined as follows *(figure 12)*:

The qualitative scores are then converted to numerical scores by assigning a value of "3" to *"High"*; "2" to *"Medium"* and "1" to *"Low"*. Instead of adopting a composite measure of extent and severity, the UK Highways Agency rather opted for the following five prioritisation criteria for the identified vulnerabilities, reflecting different reasons for actions to be undertaken:

UNCERTAINTY MATRIX		Uncertainty level – effects of climate change on asset/activity		
		High	Medium	Low
Uncertainty level – Climate change predictions	High	H	H	M
	Medium	H	M	L
	Low	M	L	L

RATE OF CLIMATE CHANGE MATRIX		Asset life/activity time horizon	
		Short term <30 years	Long term >30 years
Time horizon for climate change effects to become material	Short-term (up to 2020)	H	H
	Mid-to-longer term (between 2020 and 2080)	M	H
	Longer-term (beyond 2080)	L	M

EXTENT OF DISRUPTION MATRIX	Criterion: Extent of network affected
High	>80% of network/users affected, or any specific highly strategic routes/locations
Medium	20-80% of network/users affected
Low	<20% of network/users affected

SEVERITY OF DISRUPTION MATRIX	Criterion: Severity of disruption
High	Disruption time > 1 week
Medium	Disruption time 1 day to 1 week
Low	Disruption time < 1 day

FIGURE 12 - QUALITATIVE SCORES FOR THE FOUR PRIMARY RISK CRITERIA

Prioritisation Criteria	Indicator Score
Time criticality	[rate of climate change] divided by 3
High extent	[extent of disruption] divided by 3
High disruption duration	[severity of disruption] divided by 3
Potential research need (asset or activity)	[Uncertainty level – effects of climate change on asset/activity] divided by 3
Highly disruptive, time-critical with high confidence	[Rate of climate change] x [Extent of disruption] x [Severity of disruption] x (4 - [uncertainty]) divided by 81

In support of the prioritisation process, vulnerabilities are flagged in the risk appraisal process as early adaptation action advisable, if any of the following criteria are met:

- long-lead time needed to plan adaptation (e.g. to enable research or required changes to policy / standards to be introduced;
- significant planning/smoothing will be needed because many different locations on the network need to be worked on (e.g. lengthy national programme of works needed in order to adapt);
- adaptation is concerned with a long-life, expensive asset where it is suspected that there will be clear benefits derived from future-proofing new designs now (e.g. because marginal cost implications to future-proof now, but very expensive to address retrospectively).

Vulnerabilities are identified as early adaptation action advisable if some action is required or advisable within 5 years.

BOX 5 - EXTREME VALUE THEORY TO ASSESS THE PROBABILITY OF OCCURRENCE OF EXTREME EVENTS

The basis of risk assessment is to provide the key stakeholders concerned with the occurrence of an extreme event, a quantification of the risk in terms of its recurrence probability, or in terms of return periods of such events. Quantification of risk can be a useful tool for policy makers aiding them to have a better control over planning for future events.

Risk is associated with the occurrence of those events which have a low probability of and a high consequence of occurrence. The Extreme Value Theory (EVT) comprises of a framework of statistical methods to that extrapolate from historical data to extreme event possibilities.

Definition of concepts:
Some of the concepts are introduced via an example. Suppose the intention is to measure daily rainfall levels for n days, and denote the data as uppercase $X_1, X_2, \ldots, X_n$. Until a rainfall has been measured, the exact value of Xi on day i is unknown and is a random quantity. Once rainfall occurs, the observed value of Xi is denoted by lowercase X_i, the measured quantity. Let X represent a random variable whose outcome is uncertain. The set of possible outcomes of X is called the sample space. Random variables can be discreet or continuous variables. An event is a single or a collection of outcomes from the sample space. A probability distribution assigns probabilities to events associated with X, and is denoted by $P\{X = x\}$, where x is the realised value of the random variable X.

The definition of 'risk' that is used here is: An event with low probability and high consequence. Probabilistic risk assessment is defined as the process of estimating the probabilities of the occurrence of undesirable events (which have severe impact) taking place within a specified time period, in a specific context (Brillinger, 2003). It is assumed that such probabilistic risk can be objectively quantified. Thus, probabilistic risk assessment will involve the identification, quantification, and characterisation of such events. An example of a risk event could be maximum rainfall $M_n = \max\{X_1, X_2, \ldots, X_n\}$ exceeding a certain high threshold say, u.

Statistical models that investigate the behaviour of extreme events, without loss of generality, are considered large events, focus on behaviour of $M_n = \max\{X_1, X_2, \ldots, X_n\}$[5].

[5] For extremely small rare events, one would focus on $M_n = \min\{X_1, X_2, \ldots, X_n\}$

Statistical models that investigate the behaviour of extreme events, without loss of generality, are considered large events, focus on behaviour of $M_n = \max\{X_1, X_2, ..., X_n\}$. EVT investigates the probabilistic behaviour of Mn, that is, $P\{M_n \leq z\} = PX_1 \leq z, X_2 \leq z, \ldots, X_n \leq z\} \rightarrow G(z)$ as $n \rightarrow \infty$, for some high threshold of concern z. Here G(z) is a limiting distribution, and turns out to be only one of three distributions of Gumbel, Fréchet and Weibull. These three types of extreme value distributions can be combined into a single family known as the Generalised Extreme Value (GEV) distribution given by:

$$G(z \mid \mu, \psi, \xi) = \exp\left\{ -\left(1 + \xi \frac{z - \mu}{\psi}\right)^{-1/\xi} \right\}, \text{ where: } \left(1 + \xi \frac{z - \mu}{\psi}\right) > 0,$$

μ is the location parameter; ψ is the scale parameter, and ξ is the shape parameter.

The main alternative to the GEV distribution is the idea of exceedances over a *'high'* threshold, say *u*, and to investigate events that exceed *u*. Two issues are involved in this investigation – how many such exceedances over the study period, and by how much over the threshold u. This is the Poisson-Generalised Pareto Distribution. The choice of the threshold value u needs to be such that it ensures the asymptotic validity of the model and the optimal use of information about the extremes (Coles, 2001).

The main difference between the quantification of risk of current events and those under future climate change scenarios will rely on the forecasts of future climate indicators. Properties of these climatic indicators could include substantial temporal records, as well as spatial coverage of study areas.

The risk assessment for the future events will also depend on outputs from Global Climate Models (GCMs), appropriately down-scaled to local climate models, to represent future climate scenarios.

5.3. ADAPTATION OF DESIGN RULES AND SPECIFICATIONS

Since adaptation to climate change is a continuous process, design rules, standards and specifications should also evolve over time to reflect changing realities. The risk profile, linked to cost, reliability and safety implications, will dictate what the most opportune time will be to effect changes to the status quo. All designs have a built-in safety margin. However, for instance, an escalation in yearly maintenance costs to address permanent deformation of bituminous-bound wearing courses, specifically if caused by higher summer pavement temperatures, may necessitate a review of the design standards for such materials, or a move towards alternative materials, to reduce the yearly maintenance costs to an acceptable level. However, if higher design standards were to be required, these might come at a higher cost. Life-cycle cost analyses should be conducted to decide on the most optimal decision and/or timing of interventions.

If the effects of climate change were to result in more regular and abrupt impacts on road pavements (e.g. the gradual melting of the permafrost), more regular re-evaluation and updating of design rules, standards and specifications for road pavements may be required. This will also require more intensive, short- to medium-term research, development and implementation efforts to develop and validate these new design rules, standards and specifications. However, the development and acceptance of these is usually a time-consuming process.

In some cases, the need to effect changes has already been found warranted/justifiable. In Denmark, for instance, concerns about increased precipitation levels leading to flooding, and concerns that existing drainage systems will no longer be able to cope, let to a policy decision that all new drainage systems will be constructed 30% larger than what is currently the norm to ensure that enough capacity will be available to handle future rain intensities. The design rules for drainage systems have also been adapted in the Netherlands.

In other cases, such as the design of long-life pavements, potential climate change effects and their potential impacts should be considered. This also may challenge current design philosophies and practices. For instance, should the designer opt for more robust designs which invariably may cost more, or rather opt for more economical designs of shorter life that could be upgraded or retrofitted in future (e.g. stage construction)?

In most cases, there would be no need to develop and/or implement new design rules, standards and specifications since the *"changing conditions"* would most likely reflect similar conditions currently present in another country or region. Hence, this learning could be transferred, and adopted or adapted for local conditions. The sharing of experiences and best practices for dealing with particular situations should be promoted, which may necessitate the establishment of mechanisms, such as technology-sharing forums, to facilitate this.

5.4. TRAFFIC MANAGEMENT ISSUES AND SAFETY

5.4.1. Operational response

Severe storms, storm surges near low-lying coastal areas, long periods of intense precipitation, extreme winds or other climate extremes, and their associated impacts such as flooding of infrastructure, the undermining of the structural strength of infrastructure or road closures as a result of the accumulation of debris on the road or slope failures, amongst others, all necessitate an emergency response from transportation officials. Climate change is likely to intensify these climate extremes or could increase the frequency of their occurrences over time. This will challenge the preparedness of officials to deal with the impacts of such climate extremes, and may also have a significant impact on their operational budgets.

In future, transportation officials may have to instil more pro-active approaches for dealing with climate extremes. This may include the mapping of vulnerable routes, such as those that could become susceptible to flooding or slope failures, for instance, and the establishment of emergency plans to reinstate access or divert traffic to alternative routes. These pro-active approaches could also include the protection/strengthening of infrastructure to withstand climate extremes, or even the relocation of the infrastructure to more protected locations (e.g. rerouting of critical roads further inland to prevent their closure during storm surges).

In order to protect the road pavement itself, seasonal or temporary load limitations could be imposed. These could be applied, inter alia:

- When the road pavement structure is weakened by excessive moisture or melting of the permafrost and would be at risk of deforming and/or the upper layers would be at risk of cracking under heavy loading, and;
- For flexible pavements, when the surface temperature is high (i.e. well above the softening point of the bituminous binder), rendering the upper bituminous layers susceptible to rutting under heavy loading.

Ideally, these limitations should be condition-based rather than calendar-based. This, however, may require technology installed in situ to monitor road conditions, enable direct (remote) transfer of condition data to road owners/operators and enable real-time analysis of road strengths based on these conditions. The implementation of such technology would provide an early warning system to road owners/operators about the state of their infrastructure and the potential risks imposed by both the natural and traffic environment.

Communication with road users to warn them about potential hazards is of paramount importance. Information about the status of the road network, such as road sections that are or will become subject to strong winds and/or flooding, should be communicated in a timely manner using the most effective and efficient means available, be it signage, radio, ITS, mobile phones or GPS. Improved communication on road closures, load limitations and other relevant issues will also enable the freight industry to better manage its operations.

5.4.2. Safety

The safety of road users should be upheld at all times. In fact, the lack of provision of adequate road user safety should be construed as a failure of the climate change adaptation system. Road user safety should therefore feature prominently in any climate change risk assessment process. Examples of risks that could be attributed directly to climate change effects include:

- aquaplaning of vehicles on water accumulated on the road surface;
- skidding of vehicles caused by lack of friction during or shortly after intense precipitation events, or as a result of bleeding of the bituminous road surface caused by hot summer weather;
- lost control over a vehicle as a result of severe wind conditions, high currents during flooding, and even as a result of potholes formed after several freeze-thaw cycles;
- reduction in visibility during intense precipitation events and sand storms;
- impairment as a result of, for example, flooding, land slides, mud flows and slush avalanches.

Most of these direct risks could be dealt with proactively by improving the functional and structural characteristics of the road pavement as well as the road environment *(see chapter 4)*. Others will require emergency response, such as network restrictions or even road closures to uphold safety *(see section 5.4.1)*.

In addition to the direct risks, there are indirect risks that also need to be considered, such as, for instance, the inability to access disaster areas and emergency facilities as a consequence of road closures. Indirect risks would require a different set of emergency responses such as the provision of alternative access (e.g. alternative roads and air rescue).

It is expected that, as a consequence of extreme climate effects, road pavements and other infrastructure may require more regular maintenance than is currently the norm. This may require road workers to work on the network more often and also may require them to work during extreme climatic events; hence the need to also include the safety of road workers in the risk assessment process.

5.5. EDUCATION FOR CLIMATE CHANGE ADAPTATION

Professionals who are tasked with the responsibility to develop adaptation strategies for pavements may have a general awareness of climate change, but in most cases are unlikely to have an in depth knowledge of climate change. Hence, there is a need for professional development and training on the topic to better equip pavement professionals with the knowledge required to develop adaptation strategies.

A study was conducted in Australia in which education for climate change adaptation in the built environment sector was investigated (Lyth et al, 2007)[6]. The study found that to date the focus of climate change education has predominately been acknowledging climate change as an issue and learning the context and/or science of this phenomenon; and more specifically, education about mitigation, particularly a focus on ways of reducing greenhouse gas emissions from built environment activities and structures.

The study identified that education for climate change adaptation has been the missing component. Education for climate change adaptation is about the development of adaptive capacity - increasing the ability of individuals, groups, or organisations to adapt to changes associated with climate change. This approach promotes the development of critical skills necessary for understanding the complexity associated with climate change issues and the systemic changes needed to address these.

6. CONCLUSIONS AND RECOMMENDATIONS

The contribution of transport to greenhouse gas emissions is well documented and understood, and a significant number of activities are being undertaken to "green" the transport, including the road construction, sector so as to reduce its carbon footprint. However, the potential impacts of climate change on road pavements and ways to lessen these impacts through adaptation have thus far received little attention.

There is overwhelming evidence that climate change is happening. Global warming, sea level rise and the intensity and frequency of extreme climatic events pose a serious threat to both the natural and the built environment.

Gradual changes over time as well as abrupt changes to the climate will cause road pavements to become vulnerable to the effects of a changing climate. The nature and extent of the impact of climate change on road pavements will depend on their geographical location. Several countries surveyed as part of this study expressed concern about increased levels of precipitation, which would cause flooding and impact on the structural integrity of pavements. Most coastal countries raised concern about rising sea levels which, when combined with storm surges, could lead to flooding and therefore also road closures. The likely increase in road closures as a consequence of land slides caused by higher precipitation levels was also raised. Several countries, particularly in northern Europe and northern America (especially Canada), expressed concern about an increased frequency in the number of freeze-thaw cycles, leading to frost heave, cracking and potholing. With respect to increased temperatures, several countries, including those with cold winter conditions (e.g. east-central Europe) raised concern about increased potential for rutting and bleeding in bituminous-bound pavement layers during summer.

[6] Reference: www.aries.mq.edu.au/projects/ClimateChange (in English only)

In regions that are or will become vulnerable to the consequences of a changing climate, the above climate change effects could have a significant impact on the cost of operating a road network. Road owners/operators therefore should quantify their risk profile, not only with respect to the economic value of their road assets but also the cost to society (e.g. increased road user costs as a consequence of a more rapidly deteriorating road network and road closures).

Differentiation should be made between existing infrastructure, which cannot be changed overnight, and new infrastructure that needs to be constructed. The outcomes of the risk analysis would dictate which actions would require immediate attention (e.g. redesigning drainage systems and adapting design temperatures). For existing infrastructure, assuming that climate will only change gradually over time, adaptation strategies could be phased in over time (e.g. during periodic maintenance or rehabilitation). In association with risk analysis, greater use of tools such as life-cycle cost analysis and life-cycle assessment should be made when exploring construction, reconstruction and maintenance options for the roadway.

Technical solutions to deal with the effects of a changing climate are readily available. Use should be made of climate analogues to gain a better understanding on the likely pavement engineering solutions that could be adopted from elsewhere to be able to plan ahead and to cope with the projected impacts of climate change. Greater exchange of existing knowledge and information on how to deal with the effects of a changing climate should be encouraged.

Since climate change is becoming a reality, there is a need to act now.

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8. APPENDIX

8.1. QUESTIONNAIRE

PIARC INFORMATION REQUEST:
POTENTIAL IMPACT OF CLIMATE CHANGE ON ROAD PAVEMENTS

PIARC Committee D2 on Road Pavements has been tasked by the World Road Association to identify aspects of road pavements that would be subject to the impacts of climate change, and study evolving adaptation strategies to alleviate these impacts. To this end, Committee D2 has appointed a Working Group on *"Adaptation to Climate Change"*.

One of the envisaged outcomes of the above study will be a best practice document that will enable road engineering practitioners to better understand the potential impacts of climate change on road pavements and assist them in selecting appropriate solutions to mitigate the present and future effects of climate change on road pavements.

The document will be a synthesis of best practices that have been shown to work or do show great merit, sourced from countries worldwide. The document is intended to address the following:

- Climate change and its impact on road pavements;
- A systematic approach for conducting risk and vulnerability assessments and developing adaptation strategies;
- The management of climate change impacts on the design, construction, maintenance and performance of road pavements;
- Policy implications, including ways to respond to the potential impacts of climate change, ways to deal with uncertainty and risks, and adaptation of design rules and specifications.

In order for this document to have worldwide relevance, information needs to be sourced from an as wide array of countries as possible. The five questions listed below are intended as a framework to initiate discussion and seek information from specific countries as to how they would deal with the impact of climate change on road pavements. This first-level assessment could possibly be followed up by a more targeted second-level assessment in which more specific information will be sought. The five questions for the first-level assessment are as follows:

1. What are the main concerns your country has about the potential impact of climate change on road pavements?
2. Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

3. If nothing is being done, why not?
4. If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?
5. Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

It will be appreciated if you could respond, on behalf of your country, to the above five questions, and that your response could be sent back to the PIARC Committee D2 Working Group Leader by [date].

8.2. RESPONSES

8.2.1. Australia

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

As discussed in Austroads (2004), the main concerns are:

- uncertainty about the nature and extent of future climate change
- changes in traffic volumes due to shifts in population and industry
- wetter climates in northern parts of Australia causing costs of pavement maintenance and construction to increase. Also in these areas, the capacity of existing culverts and waterways may prove inadequate.
- The life of bituminous surface treatments is affected by ambient temperature. An increase in temperature will accelerate the rate of deterioration of seal binders and require earlier surface dressings/reseals, which leads to higher maintenance costs
- Sea level rise could be a concern for low-lying roads in coastal areas
- increased salt concentrations in rivers where rainfall is less. Steel reinforcing in concrete structures in riverine environments may be more prone to corrosion
- changes in flood heights and frequencies, which may change in positive or negative directions depending on the location.

Generally, the implications of climate change are expected to range from increased rainfall in the north to reduced rainfall in other areas; cyclonic activity migrating further south than is currently the case; increased temperatures generally; and rising sea levels. Each of these will potentially impact on the operation, management and maintenance of existing road and bridge infrastructure, and the way that we plan, design and build that infrastructure in the future.

Increased rainfall can be expected to lead to greater flood damage to road pavements including softening leading to failure and/or the need to impose load restrictions for increasingly lengthy periods. Contrast that with expected reduced rainfall which is likely to lead to lowered water tables, and less influence of salinity on pavements (salinity has been a recent problem in those areas). However, reduced rainfall in the form of drought may affect subgrade moisture content leading to a reduced pavement durability and increased roughness with consequential increase in maintenance costs.

In coastal areas projected sea level rise will pose flooding implications for local roads. Higher sea levels are likely to require raised, protected embankments, strengthened pavements and, in more remote areas, even the need for additional/alternative routes to facilitate community evacuation. Problems near the coast will be exacerbated in northern areas where sea level rise coincides with increased rainfall, as there will be less capacity in the rivers to accept increased flooding events and the consequential damage to pavements. This of course will be further complicated by storm surge associated with cyclonic activity.

Increased rainfall will significantly affect unsealed roads in terms of usability and maintenance costs.
Increased temperatures can be expected to lead to an increased likelihood of problems associated with asphalt softening. Bitumen oxidises more quickly under higher temperature and sunlight. A better understanding of temperature changes will contribute to determining future bitumen deterioration rates and road reseal frequencies. These influences, and how we respond to them, will impact on pavement longevity.

Impact of road pavements from bush fire events - burning of surfacings, burning of roadside vegetation, etc.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

1) The Climate Futures Tasmania Infrastructure (CFTI) project. This project covers a broad range of Tasmanian infrastructure, including road pavements.

The Climate Futures Tasmania Infrastructure (CFTI) project will draw climate projection data from the Climate Futures Tasmania (ACE CRC) project. The CTFI project aims to use the most current climate information providing a link for information access and bridging the gap between design data and climate relevant Australian standards.

It is proposed that the CTFI project will use a GIS interface tool on a Tasmanian map with 14km grid cells. Users will click on location of interest and access drop down boxes to refine information on variables and risk.

The CFTI steps include:

1 Identifying the project scope and key climate variables;
2 Identify the sensitivity of infrastructure categories;
3 Determine methodology for applying ACE CRC project data outputs;
4 Development of practical tools for risk management.

The ACE CRC project data can be used to predict a 'likely' future. The CFTI project is intended to be able to provide information on trends and their potential impacts on infrastructure – the bigger picture – but is not intended to make precise predictions on timing of any specific climatic event.
DIER Tasmania is a significant stakeholder with regard to road, bridge, rail, storm water and close to coastal zone assets. DIER's climate change protection for infrastructure is of rising concern. The tool will aim to provide information on predicted impacts on existing infrastructure as well as assisting in new infrastructure planning. Having direct and early access to the outputs of the ACE CRC project modelling during the next 18 months will assist the agency to make realistic decisions as to the protection of its assets from predicted climate change impact.

Various technical reference groups are established to discuss the potential impact on the various elements of infrastructure for the possible range of climate change predictions identified through the ACE CRC project.

(2) Some state road agencies have been investigating ways to better protect steel reinforcing in concrete structures from rusting due to increased salinity.

(3) Extensive mapping of coastal land and sea, including road assets. Commenced associated assessment of economic implications of rising sea levels and associated mitigation measures.

(4) Austroads Project AT1479 *"Impact of Climactic Change on Road Performance"* (this project has not yet commenced).

Project Purpose: To update the Thornthwaite Moisture Index (TMI) map (1960-current) to accommodate climate change, and to expand the use of these maps for planning, policy development and performance prediction with reference to the road infrastructure.

Project Background: Two of the most significant impacts of climate change, particularly lower rainfall and higher temperatures, cause soil drying and reduced run-off. This index was developed by C. W. Thornthwaite in the 1930's -1940's and is a number that indicates the relative *"wetness"* or *"dryness"* of a particular soil-climate system. This index and its derivatives are widely used as climate rating

systems in USA, South Africa and India and has also been adopted for many soil and climate-related studies throughout the world. It categorises the soil moisture regime by balancing the rainfall, potential and a real evapotranspiration and soil water holding capacity. In the 1960's a TMI of Australia was used only to predict the interaction of climate for a better design of the national road system. This project proposes to update this information for planning, policy development and performance prediction with reference to the road infrastructure. This will include updating the TMI map (1960- current) to accommodate the climate change. The process of updating will be on going for every 15-20 years. This project will be in partnership with RMIT and other possibly the SILO (part of Bureau of Meteorology) and the Footing Foundation Society (FFS).
The TMI is an input to pavement deterioration models. An updated index will improve the prediction of pavement performance.

(5) Assessment of the impact of rising water table and increased salinity on road pavements - refer Austroads report AP-T121/08

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

(1) The Australian Government established the Department of Climate Change on 3 December 2007 as part of the Prime Minister and Cabinet Portfolio. The Corporate Plan provides a high level view that can be used to inform our work on a day–to–day basis, showing how we contribute to achieving this framework, based on the three pillars of: reducing Australia's greenhouse gas emissions, adapting to the impacts of climate change we cannot avoid, helping to shape a global solution.

The Department of Climate Change administers the Australian Climate Change Science Program which aims to improve our understanding of the causes, nature, timing and consequences of climate change so that industry, community and government decisions can be better informed.

The National Climate Change Adaptation Program aims to commence preparing Australian governments and vulnerable industries and communities for the unavoidable impacts of climate change

Further information on The Department of Climate Change is available from www.climatechange.gov.au.

(2) Climate change scenarios for initial assessment of risk in accordance with risk management guidance, CSIRO, 2006 (report available from www.climatechange.gov.au).

(3) The Climate Change Adaptation Skills for Professionals Program is providing small grants to tertiary education and training institutions and professional associations to revise or develop professional development and accreditation programs geared towards architects, engineers, natural resource managers and planners. Refer to www.climatechange.gov.au for further information.

(4) Shifting Towards Sustainability - Education for climate change adaptation in the built environment sector.
A scoping study which investigated the professional training and development needs of architects, landscape architects, planners and engineers in climate change adaptation through engaging relevant accrediting institutions in an action inquiry process. The project sought to go further than a normal scoping study would, as it aimed to also assist the professional institutions involved to begin to think about, and take action on, professional development in climate change adaptation.

The Australian Research Institute in Education for Sustainability (ARIES) undertook the study for the Australian Government Department of the Environment and Water Resources (DEW). ARIES was asked to investigate opportunities to improve the capacity of graduate practitioners and existing practitioners to effectively respond to climate change adaptation challenges through accredited university courses and professional development.

For further information refer to Shifting Towards Sustainability - Education for climate change adaptation in the built environment sector, Australian Research Institute in Education for Sustainability (ARIES), Macquarie University, 2007 (available from www.aries.mq.edu.au/projects/ClimateChange).

(5) Climate Futures Tasmania Infrastructure (CFTI) project and Climate Futures Tasmania (ACE CRC) project (cf. question 2).

(6) See the following news items. Note that the consultancy, Parsons Brinckerhoff (PB), covers all infrastructure, not only roads. The report is expected to be completed in December 2009.
http://www.roads.org.au/news/show-arf-insider/46
PB to provide climate change check on infrastructure
PB is undertaking an assessment of the effects of climate on Australia's infrastructure for the Federal Government's Department of Climate Change.
The National Infrastructure Climate Change Adaptation Risk Assessment (NICARRA) will consider the challenges facing key infrastructure to 2070.
PB's Climate Change Business Unit will provide an independent and rigorous report on the strengths and vulnerabilities of the nation's significant infrastructure, and

planned infrastructure, in transport, energy, water, communication, and buildings.
PB's Project Director and National Technical Executive, Climate Change, Arek Sinanian, says the assessment is an urgent task for business and government.
"Key stakeholders in each infrastructure sector will take part in risk assessment workshops," he says.
"PB's final report will provide a basis for the Department of Climate Change and the Australian Government to implement solutions for prevention, adaptation and mitigation as urgently as possible."
KPMG and CSIRO will assist PB with specific aspects of the study.
http://www.environmentbusiness.com.au/n-0811.asp
Parsons Brinckerhoff (PB) was awarded a $600,000 contract to undertake a climate change check on Australian infrastructure
Parsons Brinckerhoff will assess the effects of climate change on Australia's infrastructure on behalf of the Federal Department of Climate Change. The $600,000 National Infrastructure Climate Change Adaptation Risk Assessment (NICARRA) will consider the challenges facing key infrastructure to 2070. PB's Project Director and National Technical Executive, Climate Change Arek Sinanian explained this assessment was an urgent task for government and business. *"The condition and performance of our infrastructure critically influences the growth and international competitiveness of the Australian economy and subsequently, the living standards of Australians. "Australia's infrastructure is a fundamentally important national asset - it represents a large historical investment from both the public and private sectors. PB's Climate Change Business Unit will provide an independent and rigorous report on the strengths and vulnerabilities of Australia's significant infrastructure, or what is termed 'economic infrastructure."* KPMG and CSIRO are also part of the expert team and will assist PB with specific aspects of the study.

(7) There is an Austroads report on this topic
(available for download from www.austroads.com.au)
AP-R243/04 : Impact of Climate Change on Road Infrastructure
AP-R243A/04 : Appendices - Impact of Climate Change on Road Infrastructure

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

All of the above (refer questions 1-4). The biggest unknown is perhaps the inability to predict the rate of change of various climatic influences on road pavements and thus where to focus immediate attention.

Since road travel is a demand derived from land use then it is critical that land use changes associated with climate change are well understood and factored into pavement discussion (as an extreme example if it is chosen to allow a settlement to be inundated, then the road network serving that settlement is no longer required.

8.2.2. Belgium

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

As Belgium has a moderated climate, we do not expect important impact of climate changes on the road pavements.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

No

QUESTION 3: If nothing is being done, why not?

Nothing is done, because there are no important impacts expected in Belgium.

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

At the Agency of Roads and Traffic no studies concerning this topic have been conducted. A student (Tahirou Moustapha from Nigeria) is preparing a thesis at the VUB (University of Brussels with promoter prof. Wastiels) in cooperation with the University of Gent (co-promoter E. De Winne) on *"Influence of bitumen aging on asphalt quality, comparison between bitumen and asphalt aging"*. This study will be available by the end of 2009.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

As a change of climate would lead to a climate actually present on another place of the earth, experience can be exchanged. Consequently, no pavement-specific issues require more work at this moment.

8.2.3. Canada

QUESTION 1: What are the main concerns Canada has about the potential impact of climate change on road pavements?

Global climate change, particularly short-term (anthropogenic), poses two major challenges to the transportation sector: 1.ensuring the transportation infrastructure can withstand the climate change impacts already in progress (adaptation - the focus herein is on road pavements from a Canadian perspective); and 2. reducing the transportation source greenhouse gas emissions (mitigation). Climate change mitigation, which presents considerable political, economic and technical challenges in Canada, is not considered herein (Ragan, 2009). The International Panel on Climate Change (IPCC) 2007 Fourth Assessment Report (AR4), based on a cautious, conservative approach, states *"Warming of the climate system is unequivocal as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level."* and further, *"Most of the observed increase in global average temperatures since the mid-20th century is very likely (>90% probability) due to the observed increase in anthropogenic greenhouse gas concentration."* (IPCC, 2007). It should be noted that the United Nations Environment Programme IPCC Fifth Assessment Report (AR5) has been initiated and is due to be completed in 2013-2014.

Assessing the vulnerability of Canada's road, rail, air and water transportation infrastructure to climate change is a key step to ensuring a safe, efficient, sustainable and resilient future transportation system through technically sound, environment friendly, energy efficient and life-cycle cost effective reactive adaptation and proactive mitigation practices. While the Canadian transportation system is well developed (road system alone has an asset value of about $100 billion), transportation in Canada remains sensitive to a number of weather-related hazards such as storm surges, high wind speeds, fog, heavy snowfalls and ice storms. Future climate changes of the magnitude projected for this century by the IPCC: 1.surface air warming estimates for a low scenario of 1.8°C (likely range of 1.1 to 2.9°C) and for a high scenario of 4.0°C (likely range of 2.4 to 6.4°C), noting that as a high-latitude country, warming in Canada would likely be more pronounced; and 2. sea level rise estimates for a low scenario of 180 to 380 mm and for a high scenario of 260 to 590 mm (IPCC, 2007) – would have both positive and negative impacts on Canada's transportation infrastructure, as summarised in *table C1*. (Bailey et al, 1997; Environment Canada, 1990; Natural Resources Canada, 2004; DOT, 2002; CCSP, 2008; TRB, 2008; ECE (2010).

TABLE C1 - POSSIBLE IMPLICATIONS OF CLIMATE CHANGE FOR CANADA'S TRANSPORTATION SYSTEM		
Expected Changes in Climatic Variables (a)		
Climatic Variable	**Confidence 2001 (b)**	**Probability 2007 (b)**
Increase in mean temperature	High	Virtually Certain,>99%
Sea level rise	High	Virtually Certain,>99%
Changes in temperature extremes	Moderate (e.g. increase in summer, decrease in winter)	Very Likely,>90%
Increases in intense precipitation events	Low	Very Likely,>90%
Increase in storm frequency and severity	Low (e.g. higher wind speeds)	Likely,>66%
Changes in mean precipitation	Moderate	Likely,>66%

TABLE C1 - POSSIBLE IMPLICATIONS OF CLIMATE CHANGE FOR CANADA'S TRANSPORTATION SYSTEM
POTENTIAL IMPACTS ON TRANSPORTATON SYSTEMS (c)
National Changes in fuel efficiencies and payloads (d). Changes in length and quality of construction season (d) Impacts on health and safety (e.g. accidents, heat stress, access to services) (d). Changes in transportation demand and competition (d). Changes to maintenance and design practices (d).
Northern Canada Increased Arctic shipping (Northwest Passage) Infrastructure damage from permafrost degradation and increase in freeze-thaw cycles
Southern Canada Inundation and flooding of coastal infrastructure (Atlantic and Pacific) Increased costs of shipping in Great Lakes – St. Lawrence Seaway system Increased landslide/avalanche activity (e.g. reduced mobility, increased maintenance costs) Increased flooding of inland infrastructure Changes in winter maintenance costs for surface and air transport (d). Decreased damage from fewer freeze-thaw cycles(d).
Notes: a. Adapted from DOT, 2002 and Natural Resources Canada, 2004. While road, rail, air and water transportation systems are considered, the transportation sector also includes other infrastructure such as pipelines, energy transmission and communication networks. b. Refers to agreement among global climate models in accordance with Intergovernmental Panel on Climate Change (IPCC, 2001; IPCC, 2007). c. There is considerable Canadian and American interaction on climate change impacts on transportation infrastructure, particularly through the Transportation Research Board. d. Refers to potential impacts with limited or no completed climate change studies on the topic up to 2004 (Natural Resources Canada, 2004).

Climate and weather affect the design, materials, construction, performance, maintenance and operation of road pavements throughout their service life, which can be forty years, or more, for long-life flexible (asphalt concrete), semi-rigid and rigid (Portland cement concrete) pavements. While most road pavements have some inherent resiliency, the expected short-term climate changes, summarised in table C1, would likely result in impacts on road highway and airport pavements as summarised in *table C2* (National Resources Canada, 2004; DOT, 2002; CCSP, 2008; TRB, 2008; Kenter, 2010).

It should be noted that the parallel Questionnaire response for the United States provides further information, and the close Canadian and American interaction, and considerable Canadian international engineering, construction and technology interaction, extends the climates from the High Arctic (perishing cold) to Tropics (searing heat), so that essentially all of the modified Köppen classification system climatic zones are represented (NGS, 2005); with corresponding North American and International adaptation and practices such as: asphalt materials with high rutting resistance (PIARC, 1995; AI, 2005); flexible pavement materials and designs for heavy loadings and severe climates (PIARC, 2000; NLA, 2004); innovative pavements such as porous pavements (PIARC, 1993; Ferguson, 2005); adaptation for pavement earthworks (PIARC, 2008; TAC, 2010a); performance graded asphalt binders (CSHRP, 1995; FHWA, 1999); and mechanistic-empirical design methods that incorporate pavement thermal spectra) (FHWA, 2006; Doré and Zubeck, 2009; Mallick and El-Korchi, 2009).

TABLE C2 - POTENTIAL CLIMATE CHANGE IMPACTS ON PAVEMENTS (a)
(asphalt cement - AC, surface treatment - ST, asphalt concrete – HMA, Portland cement concrete – PCC, unsurfaced/gravel – UG, ice roads - IR) **This Listing is Not Inclusive or Conclusive** **(Overall, the effects of warming will likely be more pronounced in the winter than in the summer.** **The road pavement impacts will generally also be the same for airport pavements.)**
Increase in the Frequency and Severity of Hot Day • Changes in pavement construction practice (e.g. heat stress, dust control, water supply, compaction moisture content, PCC curing); • Increased thermal expansion and stresses (e.g. expansion joint design, PCC slab curl and cracking, PCC joint design, blow-ups); • Softening/increased temperature susceptibility of AC (e.g. reduced HMA resilient moduli, HMA instability rutting, ST and HMA flushing/ bleeding, ST and HMA albedo decrease due to flushing/ bleeding, reduced ST and HMA micro and macro texture due to flushing/bleeding); • Increased oxidation/hardening of HMA asphalt binder (e.g. reduced resistance to winter thermal cracking, increased potential for top-down cracking (TDC) of long-life HMA flexible pavements (Kuennen, 2007; NCHRP, 2010)); • Increased oxidation/hardening degradation of crack and joint sealants; Increased extent and magnitude of urban heat island effects related to paved surfaces (NGS, 2005; Calkins, 2006; Byers, 2007; Henson, 2010).
Decrease in the Frequency and Severity of Cold Days • Changes in pavement construction and maintenance practices (e.g. longer construction season, less pot-hole repairs, reduced thermal protection); • Changes in the frequency of freeze-thaw cycles; • Premature deterioration of pavements related to high frequencies of freeze-thaw cycles, particularly for saturated, frost susceptible, silty soils.); • Southern Region – fewer freeze-thaw cycles resulting in less frost damage; • Northern Region – milder winters with more freeze-thaw cycles resulting in decreased availability, accelerated deterioration and increased maintenance costs for roads that rely on a frozen subgrade for strength, which might be partially offset by fewer spring thaws; • Reduced costs and use of anti-icing and deicing materials related to snow and ice control (TAC,1999; TAC, 2004; Öberg and Pisano, 2010; PIARC, 2010); • Use of proven Southern Region winter maintenance techniques further North; Probable reduction in the number of accidents related to snow, ice and winter storms.

TABLE C2 - POTENTIAL CLIMATE CHANGE IMPACTS ON PAVEMENTS (a)
Increase in Annual Precipitation and Intense Precipitation Events (With an increase in the proportion of precipitation falling as rain rather than as snow in the Southern Region. The timing, frequency, form and/or intensity of precipitation affects related natural processes such as debris flows, avalanches, landslides, mudslides and floods.) • More damage to pavement structures and embankments due to rainfall-induced landslides (ground movements) (Bjordal, 2009; Parriaux, 2008; PIARC, 2008) (e.g. increased extreme rainfall and snowmelt-induced landslide frequency in alpine areas of western Canada, increased precipitation-triggered instability of embankments and pavement structures underlain by clay-rich sediments in parts of eastern Ontario and southern Québec) • Design implications for embankments, ditches, culverts, drains, street hardware and pavements with respect to heavy precipitation and stormwater management, particularly in urban areas where pavements make up a large component of the land surface (Beersing, 2008/2009; TRCA, 2009).
Coastal Issues Related to Sea Level Rise (Coastal Areas of Atlantic Canada, Québec, South-western British Columbia and Northwest Territories) Higher mean sea levels, particularly coupled with high tides and storm surges, are most likely to inundate and/or damage embankments, pavement structures and municipal infrastructure under roads (the replacement value of impacted infrastructure has been estimated to be in the hundreds of million dollars unless appropriate adaptation is completed (Natural Resources Canada, 2004)) (Clague and Turner, 2003; Savard and Musy, 2008; Turner et al, 1998; World Vision, 2008).
Far Northern Issues Related to Climate Warming (Far northern Canada is where the most significant warming is expected and the physical landscape is highly sensitive to any climate change. Permafrost (ground that remains at or below 0°C for at least two years) underlies almost half of Canada important structural support for infrastructure such as all-season road and airport pavements.) • Degradation of permafrost as a result of climate warming (e.g. increased depth of seasonal thaw layer, melting of ice in thaw layer and warming of frozen zone, reducing its bearing capacity – paved roads and runways particularly vulnerable as they readily absorb solar energy due to low albedos compared to snow and ice – the typical albedo of fresh snow is 0.75 to 0.95, of HMA is 0.05 (fresh) to 0.17 (aged) and PCC 0.27 to 0.17 (aged) (Allaby, 2007; Anon, 2009); • Shortened ice-road seasons by several weeks, unless more intensive and advanced IR construction and maintenance (IRs constructed by clearing and developing routes across frozen ground, lakes and/or rivers are important to northern transportation); • More attention to the safety of road construction and maintenance staff with increased freeze-thaw and slippery conditions (Northwest Territories Transportation, 2007).
Note: The PIARC Technical Committee C4.5 Earthworks 2008 Report *“Anticipating the Impact of Climate Change on Road Earthworks”* provides considerable technical information that supplements and extends the technology given above, including Québec as a regional scenario example and north of Canada and Alaska permafrost thawing (PIARC, 2008).

QUESTION 2: Is anything being done in Canada to assess and/or address the consequences of climate change on road pavements?

A considerable amount of Canadian Federal, Provincial, Territorial and Municipal Agency, Public Association, Academic and Trade Association road pavement climate change assessment, adaptation and mitigation activities, often collaborative, have been completed and reported and/or are in active progress, with most of the activity scopes and reports readily and freely available at their web sites. A listing of the major Canadian participants and their climate change activities is given herein, noting this listing in not inclusive and can be readily extended in scope and detail through web searches, including very active American and International Agencies such as the IPCC, TRB, FHWA, World Bank, Inter-American Development Bank and Asian Development Bank. It should be noted that, in Canada, it is the Provincial, Territorial and Municipal Agencies that have the main responsibility for road pavements. Please note that most of the publications cited below are available on the internet at no cost.

FEDERAL AGENCIES

Natural Resources Canada [www.adaptation.nrcan.gc.ca]

Climate Change Impacts and Adaptation Program

The goal of the Natural Resources Canada Climate Change Impacts and Adaptation Division (CCIAD) Program is to reduce Canada's vulnerability to climate change. The research program supports cost-shared research to address knowledge gaps concerning Canada's vulnerability to climate change and to provide information for adaptation decision-making. The program also supports the Canadian Climate Impacts and Adaptation Research Network (C-CIARN). This network facilitates linkages between stakeholders and researchers, promotes new research techniques and methodologies, disseminates information, and provides a voice for an emerging impacts and adaptation research community. CCID has produced a number of publications, including assessment reports that document recent science and examine key adaptation issues across Canada, for instance:

1. From Impacts to Adaptation: Canada in a Changing Climate (2007);
2. Climate Change Impacts and Adaptation: A Canadian Perspective (Natural Resources Canada, 2004);
3. Adapting to Climate Change: An Introduction for Canadian Municipalities (2006);
4. An Overview of the Risk Management Approach to Adaptation to Climate Change in Canada (2005).

A related publication is *"Aspects of the Potential Impacts of Climate Change on Seasonal Weight Limits and Trucking in the Prairie Region"* (University of Manitoba Transport Information Group and EBA Engineering Consultants Ltd., prepared for Natural Resources Canada, June 2005).

Synthesis of Data on the Use of Supplementary Cementing Materials (SCMs; i.e. fly ash, slag, silica fume and other pozzolans) in Concrete Pavement Applications Exposed to Freeze / Thaw and De-icing Chemical

The development of this Synthesis document has been commissioned and partly funded by the Minerals and Metals Program of the Government of Canada Action

Plan 2000 on Climate Change (Minerals and Metals Sector, Natural Resources Canada). This Program is working towards the reduction of Canada's greenhouse gas (GHG) emissions by enhancing mineral and metal recycling processes and practices, and by assessing alternate materials and production processes. Funding and guidance for the work was also provided by the Cement Association of Canada.

The purpose of the Study is to provide data and information to help establish practical parameters for an enhanced concrete using SCMs that will meet or surpass the performance and durability requirements of a Portland cement concrete pavement (PCCP) in such environments as are experienced in Canada. Establishment of such parameters will provide Agencies, owners, and the design community alike, the opportunity to use this enhanced product as an environmental solution for a pavement material which will contribute to the reduction of GHGs, and thereby help Canada and other countries meet their GHG reduction target.

Environment Canada [www.ec.gc.ca]

Climate Research Activities

Environment Canada's climate research program is an integral part of national and international efforts to understand climate system behaviour, the human influence on climate and future climate change. The results and knowledge produced from these activities provide the scientific basis for services to Canadians and for the development of timely actions to confront the challenges of climate change. These climate research activities are focused in four areas of particular relevance to Canada:

1. Climate Modelling and Analysis;
2. Climate Monitoring and Data Analysis;
3. Cold Climate Processes and Cryosphere;
4. Greenhouse Gases and Aerosols.

Environment Canada is also involved with the environmental management of road salts, sustainable transportation and ice information and services. It was recently announced that a new High Arctic Climate Research Station will be located in Cambridge Bay on Victoria Island. This new Arctic Research Station will focus on the environmental challenge that is transforming vast regions of the North – climate change.

Environment Canada also funded the development of a prototype LCA tool for highways entitled Athena Impact Estimator for Highways. A beta version of the tool was released in April 2010. This program allows the user to define the roadway cross section and the type of materials in each layer and it will perform an LCA to determine the environmental impact of the design.

The National Research Council of Canada (NRC)

The National Research Council of Canada (NRC) performed two detailed studies testing the fuel consumed while driving a 5-axle tanker semi-trailer and 6-axle van semi-trailer on several concrete, asphalt and composite pavements in Ontario and Quebec, Canada. The two studies are entitled *"Additional Analysis of the Effect of Pavement Structure on Truck Fuel Consumption"* and *"Effects of Pavement Structure on Vehicle Fuel Consumption – Phase III"*, and can be found on the Cement Association of Canada website [www.cement.ca].

International Development Research Centre (IDRC) [www.idrc.ca]

The International Development Research Centre (IDRC), a Canadian Crown Corporation based in Ottawa, has climate change and environmental economic programs which support research and developing regions of the world to promote growth and development.

International Civil Aviation Organisation (ICAO) [www.icao.int]

ICAO is based in Montreal and is involved with international aviation action on climate change (aviation and the environment), with focus on mitigation, for instance GHG reduction.

PROVINCIAL AGENCIES

Ontario Ministry of Transportation (MTO) [www.mto.gov.on.ca]

The MTO Strategic Directions for the next five years include building on its reputation as a leader in recycling by incorporating environmental considerations to all aspects of its operations and improving its environmental stewardship (GreenPave LEED based program – the greenest roads in North America).

Province of Quebec [www.gouv.qc.ca]

A Partner to Tackle Climate Change – Quebec has positioned itself as one of the most progressive and responsible jurisdictions worldwide in the fight against climate change. For some years it has recorded the lowest per-capita greenhouse gas emissions in Canada and is also the first federated state in North America to have introduced a levy on fossil fuels.

Consortium on Regional Climatology and Adaptation to Climate Change (Ouranos). [www.ouranos.ca] (Savard and Musy, 2008).

Ouranos' mission is to acquire and develop knowledge on climate change, its impact and related socioeconomic and environmental vulnerabilities. Its main research focus is:

1 improve climate forecasts and better identification of association uncertainties;
2 more accurately quantifying the extent of impacts and vulnerabilities and risks related to extreme events;
3 enhance and significantly improve its analysis of adaptation options (Savard and Musy, 2008; Chaumont and Brown, 2010).

Toronto and Region Conservation Authority (TRCA) [www.trca.on.ca]

Toronto and Region Conservation (TRCA) works with its partners to ensure *The Living City* is built on a natural foundation of healthy rivers and shorelines, greenspace and biodiversity, and sustainable communities. It has recently completed a State of the Practice Report *"Preparing for the Impacts of Climate Change on Stormwater and Floodplain Management: A Review of Adaptation Plans and Practices"*, February 2009, which includes a comprehensive referenced (with sites) review of stormwater and flood plain management and adaptation practices across Canada (TRCA, 2009).

PUBLIC AGENCIES

Transportation Association of Canada (TAC) [www.tac-atc.ca]

Climate Change Task Force

The Climate Change Task Force provides a forum for focussed discussion on the topic of climate change. As the key provider of guidelines and best practices for the planning, design, construction, operation and maintenance of transportation infrastructure, TAC is beginning to incorporate climate change considerations, from both mitigation and adaptation perspectives, in all aspects of its work. The Task Force has established a Current Practices and Innovations Database, which includes climate change documents. TAC has recently completed the Best Practices *"Guidelines for Development and Management of Transportation Infrastructure in Permafrost Regions"* (TAC, 2010a).

Green Guide for Roads "Roadmap" Task Force

The Task Force was established to develop a set of self-evaluation performance measurements criteria incorporating sustainable/green principles and environmental stewardship that may be applied to all aspects of the roadway over its lifecycle. It will provide guidance on roadway planning, design, construction, commissioning, maintenance and operation, and Life Cycle Assessment (LCA) activities.

Federation of Canadian Municipalities (FCM) [www.gmf.fcm.ca]

The Government of Canada endowed the Federation of Canadian Municipalities (FCM) with $550 million to establish the Green Municipal Fund (GMF). The Fund provides below-market loans and grants, as well as education and training services to support municipal initiatives that improve air, water and soil quality, and protect the climate.

The Clean Air Partnership (CAP) [www.cleanairpartnership.org]

The Clean Air Partnership works with many partners – especially municipal governments – on clean air, climate change mitigation and adaptation. CAP's climate change adaptation work is focused on research (e.g. cities preparing for climate change), working with the City of Toronto on its adaptation strategy, urban heat island mapping and related geo-spatial work in the Greater Toronto Area, and the Alliance for Resilient Cities. A recent climate change adaptation publication is *"Cities Preparing for Climate Change, a Study of Six Urban Regions"* (May 2007).

Public Infrastructure Engineering Vulnerability Committee (PIEVC) [www.pievc.ca]
The Public Infrastructure Engineering Vulnerability Committee, also known as Vulnerability Committee, was established by Engineers Canada and its partners. It is guided by expert working groups, and is supported by the PIEVC Secretariat managed by Engineers Canada staff and is co-funded by Natural Resources Canada. Its first mandate was to look broadly and systematically at infrastructure vulnerability to climate change from an engineering perspective, and define adaptive capacity indicators. PIEVC evaluated four categories of public infrastructure: buildings, roads and associated structures; storm water and wastewater systems, and water resources. The PIEVC published the *"First National Engineering Assessment Report"* in June 2008, which includes roads and associated structures across Canada.

Ontario Good Roads Association (OGRA) [www.ogra.org]
Environment Canada's Code of Practice for Environmental Management of Road Salts. OGRA regularly provides workshops on snow and ice control and salt management.

Canadian Standards Association (CSA) [www.csa.ca]
The Canadian Standards Association has been evaluating the current state of knowledge of climate change amongst practising infrastructure engineers and the role of standards in adapting to the impacts of climate change. The CSA is also involved in developing infrastructure technical guides as part of the Municipal Infrastructure Solutions Program supported by the Government of Canada. This has resulted in three publications:

1. The Role of Standards in Adapting Canada's Infrastructure to the Impacts of Climate Change (CSA, 2006);
2. Climate Change and Infrastructure Engineering: Moving Towards a New Curriculum (CSA 2007); and
3. Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation (CSA, 2010).

ACADEMIC
Laval University [http://i3c.gci.ulaval.ca/en/homepage]
NSERC Industrial Research Chair on Heavy Loads/Weather/Pavement Interaction (i3C)
The research on the interaction of heavy loads/climate/pavements at Laval University, is directed by Professor Guy Doré, who is very active in cold regions pavement engineering and is well known for his applied research and engineering, which is reflected in the state-of-the-art book *"Cold Regions Pavement Engineering"*, co-authored with Professor Zubeck of the University of Alaska (Doré and Zubeck, 2009). This Research Chair aims at improving the knowledge of the interaction between heavy loads induced by transportation vehicles, the structural and functional performance of pavements and climatic effects, related to Canadian conditions.

University of Waterloo [www.civil.uwaterloo.ca/cpatt]
Centre for Pavement and Transportation Technology (CPATT)
This research facility is dedicated to pavement research, with focus on emerging and innovative pavement materials and technologies.

Norman W. McLeod Chair in Sustainable Pavements
This Chair has been established to provide the specialised research and training needed to meet the challenges of pavements and transportation engineering in the 21st Century, and nurturing future leaders for the infrastructure industry.

University of Calgary [www.ucalgary.ca]
NSERC/John Lau Husky Energy Industrial Research Chair in Bituminous Materials
Professor Ludo Zanzotto, his team and partners, have patented several new pavement products that are proving to be more durable for Canada's harsh weather as well as techniques for repairing damage to asphalt and new road testing procedures that are being adopted by transportation authorities, including Alberta Transportation. Asphalt products, developed specifically for Husky have become popular with the road paving industry across North America and are being used to surface the Stoney Trail Extension in North West Calgary. Advances in pavement life, construction and maintenance costs add up to considerable savings for tax payers, not to mention the savings for drivers in terms of better fuel efficiency, reduced vehicle maintenance and lower accident rates.

University of Victoria [www.climate.uvic.ca]
Climate Modelling Laboratory
The Climate Modelling Group at the University of Victoria is involved in the modelling and analysis of past, present and future climate, primarily using their locally developed comprehensive Earth System Climate Model, known internationally as the *"UVic coupled model"*. Over the past decade, scientific understanding of the relationships between tropical events and mid-latitude seasonal climatic responses has been well established. These relationships provide a statistical basis to make statements about upcoming seasonal conditions in Western Canada. Such predictions have the potential to assist decision-makers and to benefit economic sectors including agriculture, energy, tourism, transportation, insurance, to name a few. Dr. Andrew Weaver is a Professor and Canada Research Chair in Climate Modelling and Analysis in the School of Earth and Ocean Sciences, and a lead author of the IPCC. His book *"Keeping our Cool: Canada in a Warming World"* was published by Viking Canada in September 2008.

Canadian Institute for Climate Studies (CICS) [www.cics.uvic.ca]
The Canadian Institute for Climate Studies' mission is to further the understanding of the climate system, its variability and potential for change and to further the application of that understanding to decision making in both the public and private sectors. The CICS is the Secretariat for the Pacific Climate Impacts Consortium (PCIC).

Pacific Climate Impacts Consortium (PCIC) [http://pacificclimate.org]
The Vision of the Pacific Climate Impacts Consortium is to stimulate collaboration among government, academe and industry to reduce vulnerability to extreme weather events, climate variability and the threat of global change. The consortium for climate impacts bridges the gap between climate research and climate applications and makes practical information available to government, industry and the public.

TRADE ASSOCIATIONS
A Life Cycle Perspective on Concrete and Asphalt Pavement Roadways: Embodied Primary Energy and Global Warming Potential
The Athena Institute performed a 50-year Life Cycle Assessment (LCA) comparing several concrete and asphalt pavement structures on an energy use and CO_2 created basis. The 2006 report can be found on the Cement Association of Canada website: www.cement.ca.

QUESTION 3: If nothing is being done, why not?

Not Applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in Canada, can you please list these and provide references as to where more information can be obtained?

In addition to the research and resulting publications outlined above for Question 2, some of the completed Canadian studies with specific relevance to adaptation to the impacts of climate changes on road and airport pavements are:

Rutting of HMA
Rut Mitigation Techniques at Intersections (Infraguide, 2003)

Moisture Damage of HMA
Moisture Damage of Asphalt Pavements and Anti-stripping Additives: Causes, Identification, Testing and Mitigation (TAC, 1997)

Top-Down Cracking of HMA
Evaluation and Mitigation of Asphalt Surface Course Top-Down Cracking (Emery, 2005)

Quality of HMA
Synthesis of Quality Management Practices for Canadian Flexible Pavement Materials and Construction (TAC, 2007)

Waterproofing of Bridge Decks
Structural Concrete Deck Protection Systems (TAC, 2010b)

Sulphur Extended Asphalt Modifier (SEAM) www.shell.ca/seam
SEAM is a patented Shell additive for use in asphalt paving mixtures, both as a binder extender and an asphalt mix modifier. It improves road strength and reduces pavement rutting and cracking, which results in safer roads and longer road life. SEAM is also used for paving in places, such as container ports and truck terminal yards, where heavy, concentrated loads exceed the capabilities of conventional asphalt pavements.

Grey Asphalt Surfaces
Surface colour effects on the thermal behaviour and mechanistic properties of asphalt pavements are being studied at the McMaster University Department of Civil Engineering by Professors Dieter Stolle and Peijun Guo, and Adjunct Professor John Emery. The asphalt pavement performance advantages of lighter coloured surfaces (grey asphalt surface developed by a light hydrated lime coating of the polymer modified HMA) with less black body absorption and lower temperature lead to more life cycle performance and cost effective pavements for both highways and runways. This has a significant impact on both costs and reduced use of energy resources. Lighter coloured pavement surfaces also reduce the environmental impact of warm drainage runoff from the surface and can be used to reduce heat island effects in urban areas. This research on grey asphalt surfaces and its application during the design of the HMA for a Superpave and long life flexible pavement demonstration project in China was presented at the Canadian User Producer Group in 2007 (Emery, 2007) and this PowerPoint is available at the Canadian Technical Asphalt Association site: www.ctaa.ca. Similar technology is being developed by Professor Guy Doré, with government and commercial colleagues (Krashinksky, 2009), and the overall approach of lighter coloured pavement surfaces (increased albedo) is covered under the topic of Reflective Surfaces in *"Cold Regions Pavement Engineering"* (Doré and Zubeck, 2009).

Salt Management
The Transportation Association of Canada has developed a Salt Management Guide and Salt Smart learning material that is widely used across Canada. The Guide is currently under revision to reflect advances in winter maintenance technology, particularly reducing the amount of road salt being used (TAC, 1999; TAC, 2004).

Cold Regions Paving Engineering
This is covered in *"Cold Regions Paving Engineering"*, particularly with respect to permafrost (Doré and Zubeck, 2009).

Surface Climate of Canada
The surface properties at a site, in combination with its synoptic setting (macroclimate), establish its surface climate (microclimate). The site properties of relevance in this regard, in a rather complex fashion, are radiative (albedo), aerodynamic, thermal and moisture. These properties determine the response of the site to the flows of heat, water and momentum brought to it by the external influences of the sun, wind and

rain. Effective modelling of the site surface climate would be most helpful to the pavement engineer, and this is the subject of considerable Canadian research, such as the activities of the Canadian Association of Geographers, as reviewed in *"The Surface Climates of Canada"* (Bailey et al, 1997).

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

From the above, it is clear that most of the road pavement-specific issues associated with climate change have been studied or reported or the necessary additional studies are under way. However, the Transportation Association of Canada (TAC) is concerned that many of the climate-related design values currently used in Standards are already dated and are not being regularly updated to reflect a changing climate (TAC, 2010c). For instance, the CSA Canadian Highway Bridge Design Standard (CAN-CSA-S6-06 CSA Standard) used by TAC members contains climatic design information dating from the 1960s. The implication is that engineers are currently designing new transport infrastructure systems without the benefit of recent climatic data and without considering the changing climate conditions being reported by Environment Canada and other scientists. However, these TAC concerns transportation infrastructure designs not reflecting a changing climate could probably be readily resolved by working more closely with specialists such as the University of Victoria based Climate Modelling Laboratory and the Canadian Institute for Climate Studies. The extensive climate change activities of the US National Centre for Atmospheric Research (NCAR) and the NASA Earth System Science Data and Services National Snow and Ice Data Centre (NSIDC), particularly computer models for projecting future North American weather and climate, should also be considered in this regard. Please see the United States of America Section for more details on these NCAR and NSIDC activities and services.

8.2.4. China

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The major potential impacts on Asian infrastructure identified in the International Panel on Climate Change (IPCC) 2007 Fourth Assessment Report (AR4) are: 1. Central and Northern Asia – widespread thawing of permafrost causing damage to transportation infrastructure and buildings and some coastal erosion due to sea ice retreat; and 2. Southern Asia – increase in flooding of deltas and coastal plains due to sea level rise and increased cyclone intensity (IPCC, 2007; ECE, 2010). It should be noted, that coastal communities in South Asia are particularly vulnerable to sea level rise and natural catastrophes such as earthquakes, and international agencies are now focusing more on proactive adaptation (World Vision, 2008).

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

The major transportation sector climate change focus of the Peoples Republic (China) is currently almost exclusively on mitigation and the road pavement adaptation activities will over time undoubtedly mirror the European and North American pavement materials, design and construction adaptation activities, as is already a growing practice. China is actually, with respect to the transportation sector, an international leader in mitigation (Reguly, 2009) and one of the major government energy conservation activities is to conserve and substitute for petroleum in the power, petrochemical, building materials and transportation industries (FLP, 2007). There are also laws in China with respect to the promotion of cleaner production and the evaluation of environmental effects (LPC, 2004). For the reader with little experience with the Chinese geography, climate and transportation systems, China 2008 (FLP, 2008) and Federal Highway Administration Freight Mobility and Intermodal Connectivity in China (FHWA, 2008), are recommended.

With respect to China's growing use of current European and North American pavement technology, the current focus is on Superpave and long-life (perpetual pavements) flexible pavements technology in China (Timm et al, 2006). The first Superpave long-life (asphalt) flexible pavements in China were completed in November 2008 by Henan Ruxin Expressway Limited, with JEGEL/McMaster University acting as technology advisors, pavement designers and quality verification engineers for a new 27 km Expressway in Ruyang County, Henan Province.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

There are considerable Chinese Government, World Bank, Asian Development Bank and Pew Center on Global Change activities, often collaborative, on climate change impacts on China, mitigation and some adaptation activities. Comprehensive reports on these activities, in English, are generally available on-line. These reports include:

- Understanding Extreme Weather and Climate Impacts in China (PC, 2010)
- China's National Climate Change Programme (PRC, 2007)
- The Costs to Developing Countries of Adapting to Climate Change (World Bank, 2009)
- A Roadmap for U.S. China Cooperation on Energy and Climate Change (PCAS, 2009)

- Promoting Environmentally Sustainable Transport in the People's Republic of China, (ADB, 2008)
- The Economics of Climate Change in Southeast Asia (ADB, 2009)
- Reducing Carbon Emissions from Transport Projects (ADB, 2010)
- Green Transport Resource Optimisation in the Road Sector in the People's Republic of China (ADBPRC, 2008)
- Fixing Beijing's transport nightmare, chinadialogue (Creutzig, 2009)

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

No response

8.2.5. Colombia

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The major potential impacts on Colombian infrastructure identified in the International Panel on Climate Change (IPCC) 2007 Fourth Assessment Report (AR4) for Central America and the West Indies, which are quite relevant to Northern Colombia, are a greater likelihood of extreme rainfall and more powerful hurricanes and some inundation from sea level rise (IPCC, 2007; ECE, 2010).

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

There is considerable Colombian (government and university), World Bank, Inter-America Development Bank (IDB), and US Geological Survey (USGS) adaptation to climate change activities, often collaborative, in progress. The major Colombian climate change activity is the application of Earth Simulator (ES) data at the Instituto de Estudios Ambientales y Meteorologia de Colombia (IDEAM) (WBLAC, 2007). It should be noted that the applied road and airport pavement technology in Colombia is generally based on current American Association of State Highway and Transportation Officials (AASHTO) and U.S. Federal Aviation Administration (FAA), with very good pavement materials design and construction engineering and testing available. It should also be noted that Colombia has a developing asphalt binder production capability and considerable applied research on asphalt binders is conducted by Ecopetrol, for instance.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Reports on the Colombian World Bank, Inter-America Development Bank, Pew Center on Global Climate Change and US Geological Survey, are generally available on-line. These reports include:

- Responding to Climate Change, an Action Plan for the World Bank in Latin America and the Caribbean (Vergara, 2006)
- Adapting to Climate Change, activities, lessons learned and recommendations for further work in Latin America (WBLAC, 2006)
- Visualising Future Climate in Latin America: Results from the Application of the Earth Simulator (WBLAC, 2007)
- Mapping Vulnerability to Disasters in Latin America and the Caribbean, 1900-2007 (Maynard-Ford et al, 2008)

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

No response

8.2.6. Denmark

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

Main concern – drainage: The climatic changes which are predicted by models, point towards more precipitation seen on average throughout the year, as well as stronger and more intense shower activity in summer in Denmark. This means that the drainage systems of the road net-work must be prepared to drain larger amounts of water and in extreme cases in relatively short periods of time. The existing drainage systems are designed and constructed on the basis of previous precipitation events (statistics). More net precipitation leads to larger water stream flows, possibly causing problems with present culverts that are designed based on outdated statistics of high flow events.

Secondary concerns: Increasing wind-speed, and the effect on road furniture; Rising ground-water level, and the effect on road stability and pavement; Rising sea level, and the effect on near-shore roads.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

In general: Strategy for climate adaptation in the Danish Road Directorate (ongoing). New roads has to be build for future challenges. Research is done to know, how to update guidelines for planning, building and running future roads. For now, all new drainage constructions are build with a climate factor, thereby made 30% larger than before, to ensure enough capacity for future rain intensity.
Research and development – Danish Road Institute: Defined strategy for research and development on climate change and environmental issues. Current research projects: (1) Era-net Road SWAMP project (Storm Water prevention - Methods to Predict damage from the water stream in and near road pavements in lowland areas); (2) Existing detention basins along motorways – functionality and environmental issues due to climate change risk factors; (3) Mapping of vulnerable areas and risk assessment on the Danish motorway system. Blue spot identification (areas in risk of flooding) using GIS modelling and interviews with road personnel; (4) Life cycle analysis on road construction, amongst others CO_2 emission in every life cycle phase. This project is completed.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Ph.D thesis by Thomas Ruby Bentzen: Accumulation of pollutants in highway detention ponds. Aalborg University, Department of Civil Engineering 2008.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

At the moment we focus on rain and flooding issues, but rising groundwater level is also a concern. The wind factor on road furniture and roads situated near the coast will also require more work, but not in the near future. There is a project coming up on rolling resistance and the influence on the CO_2 emission from vehicles.

8.2.7. Estonia

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

Estonia is located in the Atlantic climate zone. The year-round amplitude of temperature is from –25°C in winter to +25°C in summer. It makes pavement friable in wintertime and mild in summertime.
There are plenty of changes in temperature around the zero degree – the so-called zero-cycle.
There is a lot of precipitation rain and snow. That makes worse adhesion between the stone aggregate and the binder worse. The humidity hastens the wearing of pavement.
A lot of salt is used against freezing, but salt solution causes even more zero-cycles than we naturally have.
Before the arrival of cold, humidity level is rather high.
Our local stone aggregate (limestone) is not very frost-resistant.
The frostboil caused by capillary rise will damage the pavement.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

All of the factors listed in Question 1 are taken into account in designing the road pavements, which takes into account five indicators:

a the resistance of the entire design of a flexible deflection;
b the balance of shear stress in soil;
c drainage or frost-resistant layer;
d frost-resistance of the whole design, and
e the tensile strength of monolithic layers.

QUESTION 3: If nothing is being done, why not?

We do not have to replace limestone with volcanic rocks, which have better frost resistance and strength, because volcanic rocks are more expensive (about 3 times).

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Studies of the heat and humidity of embankment have been made in our region since 1930. The summary of the studies can be found in the Estonian Flexible Pavement Design Guide 2001-52. In addition to Estonian theoretical studies, and the Russian guidelines for the calculation of pavements VSN 46-83 have been taken into account.

Wear resistance is tested by the Nordic test – such as the Los Angeles experiment, but water is added.
Frost resistance was previously tested by the GOST (Russian) method (the direct determination of the freezing-melting cycles).
To determine the frost resistance we have the national standard AL ST 1-97.
The indirect test to the determining the frost resistance is the following: stone material is impregnated with sodium sulphate (Na2S04) solution, which expands and creates the freezing effect.
Determine the weight loss of rocks by freezing them (25 and 100 cycles).
Better stone material can be imported from Russia or Finland.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

A better use of local materials; using oil shale ash as building material; additives of asphalt concrete to improve the quality of the mix; testing local limestone and crushed gravel in both distilled water and sodium chloride (research will be finished by 01 May 2009).

8.2.8. Finland

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

Main concern is the performance of road pavements. The deterioration speed of road pavements (asphalt surfacing) will increase because pavement surfacing is wet and unfrozen in winter due to the warming of climate. In Finland studded tires are used in the winter time. If road surfacing is wet the rutting due to studded tires will increase 2-3 times more quickly than in normal winter conditions. To conclude, climate change (warmer climate in winter) will speed up deterioration of road pavements.
In addition, there will be other distresses as a consequence of having moist surfaces (i.e. water on pavement surface) longer than in usual winter. More cracks and potholes appear on wet pavement surface than normally.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Updated guidelines for material selection of asphalt pavements have been published which take wet conditions more into account.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Referring to the answer in item 2.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

Material selection of asphalt pavements and updated deterioration models of asphalt pavements (deterioration may be faster than expected).

8.2.9. France

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

Potential identified impacts are mostly drainage issues related to more intense rainfall, standing water and changes in soil moisture affecting the structural integrity of the pavement, increase in heat waves and freeze/thaw cycles and related impacts (e.g. softening, traffic-related rutting, embrittlement (cracking), migration of liquid asphalt).

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

The LCPC research institute and Egis engineering company are both developing methodologies and tools to assess and address the consequences of climate change on road pavement (e.g. GERICI tool developed by Egis in 2006).

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

- Guerard, H. and Ray, M. (Egis), 2006. GERICI project: Risk management related to climate change for infrastructures. European roads review 9, Fall 2006, RGRA.
- Pierre Hornych (LCPC), 2010. Research Programme 11P063: Advanced techniques for the structural design of pavements (taking into consideration the effects of temperature on the structural design of pavements). (in French)

- Yves Brosseaud (LCPC) and David Mathon (LRPC Blois), 2010. The effects of high temperatures and drought conditions on pavements (consequences of the summer of 2003, based on case studies evaluated by LRPC de Blois). (in French)
- Caroline Mauduit and Stéphane Ollier (LRPC Clermont-Ferrand), 2010. The effects of low and moderate temperatures (freeze-thaw and the movement/action of water). (in French)

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

Following two hard winters, the northern part of the French road network has been affected by severe problems of cracks and potholes on the road surface, showing also some lack of maintenance. As this situation is mostly related to unusual succession of freeze-thaw cycles, research should focus on specifying new pavement types that are less sensitive to such climatic conditions and on improving climate change knowledge on freeze-thaw cycles.

8.2.10. Hungary

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The main concerns in Hungary about the potential impact of climate change on road pavements are:

- higher air temperature → deformation of asphalt pavements,
- intensive, durable precipitation → flooding of roads with drastic bearing capacity loss.

As a recent example for the future new challenges of climate change, it can be mentioned that spring and summer weather in Hungary in 2010 had 3 to 4 times extreme weather events (hurricanes, deluge type precipitation) that the same period in preceding year. As a consequence, flooding resulted in road damages at an unprecedented level.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Several Hungarian research studies have been carried out in the topic during the past 5 years, among others:

- assessing the possible consequences of climate change on road pavements (changing in pavement type selection, modification in asphalt mixture design, updated slope protection, further development of winter road operation etc),

- reviewing road-related Hungarian standards and technical specifications to assess whether further developments were needed to account for the more frequent extreme weather events resulting from climate change; the critical issues were identified and the direction of changes to the criteria was proposed in broad terms,
- road-related consequences of climate change of the continental climate in Hungary with hot summers and cold winters.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Not aware of any other studies, apart from those mentioned in the answer to question 2, currently being undertaken in Hungary. KTI Non-profit Institute Ltd, has recently proposed a new research theme entitled *"Road-related consequences of climate change"* to the ministry responsible also for transport issues, but the study has not yet been initiated.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

The following pavement-specific issues would require more work:

- analysing LTPP-data to identify the role of various climate (weather) elements which (actually) had a significant impact to the deterioration of pavements;
- updating road pavement design to account for the increased resistance of pavements to the detrimental effect of extremely high level of soil water or even flooding;
- extension of the world-wide research study on the development/design of long-life (or perpetual) pavement structures to include the new challenges coming from the harmful effects of climate change; the original research concentrated on limiting strain levels at the bottom of an asphalt structure for durable protection against fatigue damage. Climate change can accelerate other damage types (such as pavement deformation, layer disintegration etc.) which could cause pavement failures other than fatigue;
- multidisciplinary research with the participation of road, hydraulic and agricultural experts to reduce the harmful effect of a strong wind-storm with intensive precipitation on road pavement structures;
- long-term cost/benefit analysis of climate change adaptation measures on road pavements.

8.2.11. Japan

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The main concern is an increase of rutting caused by higher temperature. However, it is not regarded severe and difficult. We are expecting the development of modified asphalt to decrease rutting problems.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Nothing special. However, road surface characteristics such as rutting depth, cracking ratio and longitudinal roughness are monitored every 3 years in national highways.

QUESTION 3: If nothing is being done, why not?

While climate change will not progress so rapidly, it may be possible to develop proper countermeasures after something has been changed. We regard it more important to develop pavement technologies which can contribute to restrain climate change rather than its counter-measures.

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

In Japan, like no other countries, permeable pavement technology is under consideration as a countermeasure for severe floods in urban areas. Heat shield pavement and water retention pavement are also under consideration as a countermeasure for heat island effects.

References:

Kazuyuki Kubo: Study on pavement technologies to mitigate the heat island effect and their effectiveness, Proceedings of the 10th International Conference on Asphalt Pavements, Quebec, Canada, 2006

Atsushi Kawakami, Kazuyuki Kubo: Development of a cool pavement for mitigating the urban heat island effect in Japan, Proceedings of the International ISAP Symposium, Zurich, Switzerland, 2008

Kazuyuki Kubo, Masahide Ito, Takayuki Ayabe: A study on application of permeable pavement in traffic roads, Proceedings of the 6th International Conference on Road and Airfield Pavement Technology, Sapporo, Japan, 2008

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

As was answered in Q1 and Q3, it is regarded important to develop new pavement technologies to restrain climate change. For example, Warm mix asphalt to reduce CO_2 emissions, recycling technologies to reduce life-cycle CO_2 emissions and cool pavement (heat shield pavement and water retention pavement).

8.2.12. Lithuania

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The main concerns about the potential impact of climate change on road pavements are:

- Higher temperatures during summer (problem of rutting);
- Heavier precipitation (insufficient capacity for surface water disposal capacities);
- Due to milder winters, longer wet seasons influencing bearing capacity.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Currently, the problem of rutting is being addressed. New studies have been proposed for improving surface drainage (especially where kerbs are present) and drainage within the road structure.

QUESTION 3: If nothing is being done, why not?

As indicated in the answer to question 2, not much is being done at present, but this is because the impact of climate change is still very small. In fact, in some cases, climate change could have some small benefits (e.g. reduced winter maintenance costs & longer construction periods).

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

No studies on the potential impact of climate change on road pavements are being undertaken at present.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

Better understanding of changes in the regime of road structure condition:
from short wet autumn period, frost penetration in winter, short flow period, to long wet period from autumn to spring.

8.2.13. Mexico

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

It is a fact that the world climate change, due to a higher air contamination produced by industry and transportation modes, has produced everywhere and in Mexico, more *"extreme"* seasons along the year, that is, summer more extreme hot and winter more cooler; all of this definitively leads to highway pavements life reduction, poor behaviour or performance and of course more often maintenance (major/minor) action and costs increasing. Climate change is affecting specially network highways supporting traffic with heavy vehicles and high percentage of them circulating on asphalt pavements with temperatures inside the asphalt overlay around 50-60°C. We really consider this effort of new standards or normative from IMT/AMAAC, as a very important step to deal with some of the risks and effects of world climate change.

The main concern is that more intense rain showers can cause flooding of the road, due to inadequate drainage capacity in the road substructure or next to the road. The effect of climate change on the water ground level is another concern; too high levels may weaken the substructure whereas too low levels can cause setting of the peat land resulting in cracks in the asphalt. Also a concern is that higher temperatures and longer sunshine duration may cause rutting on the dense asphalt concrete roads. More of a safety concern is a rising sea level and more extreme river discharges due to climate change, which of course will affect road infrastructure in case of a calamity (dike breach).

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

There are various Mexican initiatives dealing with climate change mitigation and adaptation:

1. Since 6 years approximately, all the projects for new federal highways and toll roads (responsibility of S.C.T., Ministry of Communications and Transports) in Mexico, must comply with SEMARNAT standards and environmental requirements

(Ministry of Environmental Protection and Natural Resources). Those regulations for maintenance and construction have helped Mexico to protect environment and natural resources on specific land areas, in order to minimise the negative impacts of climate change. The norms, amongst others, control emissions during highway construction.

2. Over the last 10 years, the Mexican Transportation Institute, depending from the SCT Ministry, has been running a research group dealing with the environment. They have been involved in more than 20 projects dealing with environmental impacts related to highway construction, maintenance and operation, including the effects on tunnels, hydraulics, forest protection, land-soil changes, and natural resources exploitation of materials used in construction and maintenance of highways. The detail of those research projects can be obtained from www.imt.mx
3. Mexico has appointed several delegates in PIARC Technical Committees dealing with environmental impacts, sustainable development and climate change. They are: Paul Garnica (TC D.4 - pgarnica@imt.mx), J. Fernando Mendoza (TC A.1 - jmendoza@imt.mx) and Rodolfo Téllez (TC D.2a) who directly or indirectly deal with Mexican experiences on Adaptation to Climate Change.
4. Another important action taken in Mexico for adaptation to climate change is produced by the Mexican Transportation Institute and AMAAC (Mexican Asphalt Association), working together in 7 new protocols and new Standard for Asphalt mixtures and materials with better quality, designed for resisting high temperatures due to climate change (40°C or more) or low temperatures in some high land areas (0°C or less).

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

At the Mexican Transportation Institute (IMT), the Unit of Geospatial Information Systems is completing a research project which involves the production of a map providing an inventory of all highways in México (including bridges, airports, ports and rail way network) addressing the *"potential risks"* due to a climate change (i.e. hurricanes, heavy rains, floods, bridge failures, slope failures, earth fill or embankment failures, etc. When this project is finalised, Federal, State and Municipal governments, will have detailed information on potential risks. They will then be able to respond through the locals Civil Protection Units to save lives, protect infrastructure investments and also to have in the future better engineering buildings/ highways to support extreme climate conditions such as the ones mentioned above.

Other projects/initiatives (on climate change mitigation) include:

1. Toll Road *"ARCO NORTE"* (north arch), almost 200 km length, concrete pavement, intelligent highway. México city metropolitan area, with almost 20 million people population has very serious problems with air pollution. The new highway, almost complete, will serve to avoid crossing the area by more than 3 million vehicles/year (10,000 every day); long itinerary heavy trucks, passenger buses and private light cars. With this highway engineering work, the city and users will reduce costs of operation, time trips, and mainly, everyone will save tons of greenhouse gas emissions which contribute to global warming, and result in climate change.
2. J. Fernando Mendoza leader of Environmental Area at the IMT, member of committee A.1 PIARC, is working at this time on a research job for emissions inventory from vehicle operation and the air contamination all over Querétaro State in México, in order to see the transport contribution to the local air pollution and global warming. It is considered to have results and mitigation aspects at the end of 2009 year.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

No response

8.2.14. Netherlands

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The main concern is that more intense rain showers can cause flooding of the road, due to inadequate drainage capacity in the road substructure or next to the road. The effect of climate change on the water ground level is another concern; too high levels may weaken the substructure whereas too low levels can cause setting of the peat land resulting in cracks in the asphalt. Also a concern is that higher temperatures and longer sunshine duration may cause rutting on the dense asphalt concrete roads. More of a safety concern is a rising sea level and more extreme river discharges due to climate change, which of course will affect road infrastructure in case of a calamity (dike breach).

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Rijkswaterstaat has carried out a couple of studies; first to investigate the magnitude of the problem and consequently to determine the actions that needs to be taken by Rijkswaterstaat. These actions to be taken are especially in relation to the abovementioned impacts, and are currently investigated by Rijkswaterstaat in more detail.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4 :If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

The investigative study carried out by Rijkswaterstaat has an English translation (title *"Climate change and infrastructure, an exploratory study"*), and can be obtained on request. The other Rijkswaterstaat studies are in Dutch and are really internal documents of Rijkswaterstaat.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

The issues mentioned earlier, more heat-resistant pavements and better drainage, need to be worked out further and actions are being taken to address this at Rijkswaterstaat. Also, the European project SWAMP will investigate so-called *"blue spots"*, areas where roads in Europe are likely to become inundated, and identify preventive actions to be undertaken.

8.2.15. New Zealand

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The road network is vulnerable to weather conditions and the Transit NZ 2005/06 annual report stated that the state highway lanes closed on over 150 occasions due to weather related incidents that year.

Bridges: There are 15,000 bridges in NZ, 4,000 of which are part of the state highway network. Increased water temperatures and sea level rise may lead to saline incursion at coastal bridges and therefore advanced material deterioration.

Culverts, drainage and flood protection: Around NZ roads that have been built in flood prone areas may be susceptible to flooding.

Pavement surface: Hot weather can cause the surface to bleed, freezing conditions can quickly lead to cracking and water ingress, causing further damage.

Land stabilisation: because many roads follow old alignments they tend to run alongside rivers or around hills, meaning that a large number of roads are cut to embankments. These locations are much more prone to slips, either uphill, with the risk of road closure while debris is cleared, or downhill, with the risk that part of the road collapses.

High priority climate change risks to roads identified included:

- Increased rainfall intensity and duration causing slips and flooding
- Coastal roads at risk from coastal flooding and erosion
- High wind effects - damage to signs and infrastructures, vehicles blown off the road, temporary road closure and imposition of bridge restrictions.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Bridges: NZTA calculated a rough estimate of possible design changes to adapt to increased waterway depth anticipated as a result of climate change. Design changes would result in an estimated additional 10% increase in cost due to the extended foundation heights.

Culverts, drainage and flood protection: State highway drainage systems are designed for local conditions. NZTA assesses its current practice as sufficient and believes improvement works will be able to cope when exacerbated rainfall and flooding conditions apply. It is also considered that the current Culvert Manual is still valid methodology and should be able to cope with climate change conditions.

Pavement surface: The NZ-dTMS pavement deterioration model has been practised in NZ for the last 10 years to provide a robust method of predicting the maintenance requirements of roading networks. Mean temperature and total rainfall are monitored along with traffic demand as part of pavement performance monitoring.

Land stabilisation: Know slip sites on the state highway network are identified and monitored as part of network maintenance contracts. Preventive maintenance works are carried out on slopes and batters sensitive, slip prone areas to ensure that the road remains open.

QUESTION 3: If nothing is being done, why not?

As discussed above climate change issues are being addressed and the research carried out has identified further gaps in our knowledge which will have to be addressed.

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

As noted above NZTA commissioned MWH to carry out research on *"Climate change effects on the land transport network - Stage One and Stage Two"*. To obtain a copy of the report please contact Patricia McAloon.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

The climate change report identified certain areas. In brief these were:

- better understanding of the vulnerability of the transport network to extreme weather (more data collection of extreme events).
- more robust systems are needed to assist evaluation.
- better understanding and more robust systems are need to assist evaluation of the significance of extreme weather events and weather variability in the design, cost, mobility and safety of the existing network.
- better linkage of climate change to asset management.
- development of risk analysis tools

8.2.16. Norway

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The road network is influenced by climate conditions. Higher groundwater levels will yield higher probability of floods and erosion. More rain will give a higher risk of slides, occurring at new locations and new types, such as slush avalanches, debris slides and mud flows. This is already documented. Our methods for the choice of structural solutions and dimensioning of physical protection need review. Areas exposed to stable winter conditions may experience higher exposure to freezing and thawing. One should also count on reduced accessibility and regularity. All this requires improved emergency plans.
1991-2008 as compared to the reference period 1961-1990 has seen:

- an increase in annual mean temperature in mainland Norway of 0,5-0,6°C (most in winter months, least in summer months)
- an increase in annual precipitation: 5% (at most 17% in winter)

The following weather effects have been observed:

- Temperature changes (daily and yearly variation)
  Rock fall registered on days with high day temperature and low night temperature.
- Rainfall/flooding
  More often occurrence of heavy rainfall of short duration, causing local flooding, especially in urban areas. Mudslides have carried away road sections and bridges, but this has not been scientifically proven to be caused by climate change. Some bridges also experience problems with erosion and damages to foundations due to scouring. Again, it has not been scientifically proven that these are caused by climate change.
- Wind/tornados
  Hurricanes are not uncommon in Norway, especially along the west coast and in northern Norway. It is difficult to say if they increased in frequency.
- Snow/ice
  The past several years we experienced several episodes of extremely heavy intense snow fall causing trouble on the roads. Some places known for snow avalanches seem not to be a problem any more. There has generally been less snow in lowlands, more in the mountains.
- Sea level rise
  Higher sea level, due to local storm surges, causes problems with sub-sea tunnels if tunnel openings are exposed. Some places, waves splash over the road, meaning that the road has to be closed for traffic.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

The government has started the work on identifying vulnerable areas of work and economy. A report should be due November 2010. No strategy for adaptation to climate change has been defined yet. The road authorities have an ongoing R&D program on adaptation to climate change.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Road design manuals will be updated concerning design criteria (e.g. for bridge design). No action concerning design loads has been done, apart from a suggestion of taking into account a longer return period for floods and sea /water level.
At this stage, no additional expenditure is being spent on inspections and design changes as a result of a concern/affect of climate change.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

No response

8.2.17. Philippines

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

There is a major concern for higher precipitation levels leading to floods, highlighting the need for disaster mitigation measures.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Indirectly, yes. The Department of Public Works and Highways will integrate climate change strategies into its policies, plans, programs and institutionalise climate considerations in DPWH's business processes. An existing Department Order No. 15 of 2002 and DO 30 of 2006, established tree planting as a standard component in road construction and improvement projects. Planting of trees along highways, roadsides and other vacant portions of land are implemented as mitigation measures for environmental sustainability.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

At present, there is a National Framework for Climate Change creating the Climate Change Commission proposed under Senate Bill No. 1890. The Executive Order No. 774, Reorganising the Presidential Task Force on Climate Change, formed tasked groups in every agency of the Government towards the vision and goals of sustainable development. Another initiative by the Philippines to address climate change in 1991, is the establishment of the Inter-Agency Committee on Climate Change (IACC), Its main task is to coordinate various activities and provide technical support on climate change issues. Although no specific measures on the impact of climate change on road pavement exists, disaster mitigation measures on infrastructure are in place such as flood control and drainage facilities, rehabilitation/improvement of existing facilities, maintenance of conveyance capacities of canals, floodways, etc

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

In future conditions where there will be more frequent and severe flooding of underground tunnels and low-lying coastal infrastructure. Adaptation in the design deemed appropriate for future protection of bridges, tunnels, transit entrances and critical evacuation routes.

8.2.18. Slovakia

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

Climate change has impacted on the temperature regime of road pavements (asphalt and cement-concrete), their serviceability and service life. More permanent deformation and surface rutting are being observed. Intensive rain has affected the condition of pavements and embankment, and has impacted on slope stability.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Not yet addressed in standards, nor in technical recommendations and guidelines.

QUESTION 3: If nothing is being done, why not?

Absence of organised (managed) research, as well as financial support.

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

More information is available in the following reports and proceedings:

a National Climate Change Programme of the Slovak Republic – NKP 12/08, Climate change impact and adaptation measures (by Milan Lapin and Pavol Nejedlík, Bratislava 2008);
b the influence of climate conditions on road construction. XIIIth Seminar of Ivan Poliaček, November 20-21, 2008, Bratislava.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

More work is required on the measurement of road pavement temperature regimes (continually), and the evaluation of data and characteristics for pavement design. Important is better cooperation between climatologists and civil engineers.

8.2.19. South Africa

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

- Physical effects of extreme temperature changes
- Weather effects – increases in storm frequency could lead to higher flood line designs
- Extremes in weather patterns could occur more often – impact on design, construction, maintenance and traffic management.
- Western Cape may become dryer, impacting on pavement roughness, whilst the eastern parts of the country are getting wetter, impacting on the bearing capacity of pavements
- Various slope failures have occurred in recent years, attributed to rainfall of longer duration and/or greater intensity
- Road surface temperatures in the Highveld could reach 70°C, resulting in not only greater instances of rutting and bleeding, but also cracking as a result of more rapid ageing of bituminous binders

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

Whilst there are mitigating efforts in design, manufacture & construction practices, with the intent to minimise any environmental impact, consequences are being dealt with (high-modulus asphalt as an example) on a more ad hoc basis.

QUESTION 3: If nothing is being done, why not?

Insufficient studies have been conducted to assess possible consequences.

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

Only mitigation studies:

- The development of estimation tools to assist industry in the management of its carbon footprint and energy consumption during the asphalt manufacturing phase.
- Research to develop protocols for recycling distressed granular pavements using bitumen emulsion and foamed bitumen.
- Development of best practice guidelines for using reclaimed asphalt pavements in the manufacture of new hot mix asphalt.
- Development of guidelines for warm-mix asphalt

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

- Any initiative that would lead to less natural resource & energy consumption.
- Promotion of public awareness of *"green roads"* and adequate recognition to the parties that produced such a road.
- With the advent of vehicles powered by alternative fuels, are there any design considerations to be made that can assist this trend?
- Studies to determine the potential impact of extreme weather patterns on road design

8.2.20. Sweden

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

- Loss of frost in the soil during the winter will create problems. The winter in the northern parts of Sweden may be permanent thawed instead of frozen soil.
- Increasing problems concerning land slides.
- Floods
- Rising sea level

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

- Sweden facing climate change - threats and opportunities; Final report from the Swedish commission on climate and vulnerability. Appendix number 1 contents facts about road pavements.
- Swedish Road Administration (SRA) has developed a risk analysis model for road pavements called *"Vald Vägsträcka"* (Chosen distance) which is being implemented.
- In long-term planning 2010-2021, the SRA has proposed additional resources for climate change adaption.

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

- Sweden facing climate change - threats and opportunities; Final report from the Swedish commission on climate and vulnerability: (see PIARC website)
- Risk based functionality specifications – contact person: SRA Ebbe Rosell phone: +46 243 75674 e-mail: ebbe.rosell@vv.se
- Hydraulic dimensioning – contact person: SRA Lovisa Moritz phone: +46 13 189034 e-mail: lovisa.moritz@vv.se
- Report *"Storm Floods"* – contact person: SRA Pontus Gruhs phone: +46 243 75482 e-mail: pontus.gruhs@vv.se
- ERA NET ROAD project *"Road owners getting to grips with climate change":* (a) RIMAROCC; (b) IRWIN; (c) P2R2C2 and (d) SWAMP

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

- Methods for calculating storm floods in small watercourses;
- Exchange of experience and development of practical solutions concerning protection of culverts and small bridges due to storm floods.

8.2.21. United States of America

QUESTION 1: What are the main concerns your country has about the potential impact of climate change on road pavements?

The International Panel on Climate Change (IPCC) 2001 Third Assessment Report (TAR), and particularly the IPCC 2007 Fourth Assessment Report (AR4), have generated a comprehensive US Program to deal with transportation climate change impacts adaptation and mitigation (IPCC, 2001; IPCC, 2007). The overall US transportation sector approach is detailed in the Transportation Research Board *"TRB 2008 Special Report 290, Potential Impacts of Climate Change on US Transportation"*, and the Department of Transportation (DOT) 2008 parallel report *"Impacts of Climate Variability and Change on Transportation Systems and Infrastructure: Gulf Coast Study, Phase 1"* (DOT, 2002; TRB, 2008; CCSP, 2008; ECE, 2010). It should be noted that the United States and Canada have an interactive North American approach and the Canadian Questionnaire responses and references reflect this, and should be considered jointly. The US transportation sector climate change activities have been widely reviewed and publicised through, for instance, the United Nations - Sigma Xi Scientific Expert Group on Climate Change Report *"Confronting Climate Change, Avoiding the Unmanageable and Managing the Unavoidable"*, Roads & Bridges Special Report *"Worse by Degrees – As climate changes transportation planners will have to protect infrastructure from heat, heavier rainfall, stronger storms and higher storm surges"*, and the TR News issue on *"Climate Change: Curbing Transportation Contributions"* (UNSXi, 2007; Karr, 2008; TRN, 2010). The main US concerns with the potential impact of climate change on road pavements is summarised in *table US1* (TRB, 2008).

TABLE US1 POTENTIAL CLIMATE CHANGES AND EXAMPLES OF IMPACTS ON ROAD AND AIRPORT PAVEMENTS (a)
Increases in Very Hot Days and Heat Waves (Highly Likely, >90% Probability of Occurrence)
Examples of Impacts on Operations (b) Lift-off load limits at high-altitude and/or hot airports with insufficient runway lengths. Limits on construction activities due to health and safety concerns. **Examples of Impacts on Pavements (b)** Thermal expansion of bridge expansion joints, pavement joints and paved surfaces. Concerns regarding asphalt pavement integrity (e.g., softening), traffic-related rutting and flushing.
Increases in Arctic Temperatures (Virtually Certain, >99% Probability of Occurrence)
Examples of Impacts on Operations (b) Increased ice roads construction and maintenance costs. **Examples of Impacts on Pavements (b)** Thawing of permafrost, causing subsidence of and/or damage to embankments and pavement structures. Shorter season for ice roads.
Rising Sea Levels Combined with Storm Surges (Virtually Certain, >99% Probability of Occurrence)
Examples of Impacts on Operations (b) More frequent interruptions to coastal and low-lying roadway travel. Potential for closure or restriction of airport pavements in coastal areas. **Examples of Impacts on Pavements (b)** Inundation and/or damage of embankments, drainage structures and pavement structures. Erosion of embankments and pavement structures.
Increases in Intense Precipitation Events (Highly Likely, >90% Probability of Occurrence)
Examples of Impacts on Operations (b) Increase in weather-related delays. **Examples of Impacts on Pavements (b)** Increase in flooding and/or damage to embankments, drainage structures and pavement structures. Increase in road washouts and landslide (earth movement) damage to embankments and road pavement structures.

TABLE US1 POTENTIAL CLIMATE CHANGES AND EXAMPLES OF IMPACTS ON ROAD AND AIRPORT PAVEMENTS (a)
More Frequent Strong Hurricanes (Category 4-5) (Likely, >66% Probability of Occurrence)
Examples of Impacts on Operations (b) More debris on pavements causing traffic interruption. **Examples of Impacts on Pavements (b)** Increase in flooding and/or damage to embankments, drainage structures and pavement structures.
Notes: a. Adapted from Summary of the 2008 Transportation Research Board (TRB) Special Report 250, Potential Impacts of Climate Change on U.S. Transportation (TRB, 2008). b. IPCC Fourth Assessment Report (IPCC, 2007) c. A more detailed treatment of North American climate change impacts on road and airport pavements is given in Canada's Table C1 and particularly Table C2 *"Potential Climate Change Impacts on Pavements"*, noting the close American and Canadian interaction on climate change and transportation through TRB and AASHTO, for instance.

QUESTION 2: Is anything being done in your country to assess and/or address the consequences of climate change on road pavements?

In addition to the Transportation Research Board and Department of Transport activities outlined in the answer to Question 1 and impacts on road and airport pavements summarised in Table US1, there are a number of other Agency, Public Association, Academic and Trade Association road pavement climate change adaptation activities that have been completed and reported and/or are in active progress. A listing of the major US participants and their climate change activities is given below, noting this listing is not inclusive and should be considered along with the Canadian Question 2 response.

Federal Highway Administration (FHWA) www.fhwa.dot.gov
The Federal Highway Administration (FHWA) has a comprehensive highways and climate change program including the provision of information on the FHWA research, publications and resources related to climate change science, policies and actions. This includes the Transportation and Climate Change Monthly Newsletter and Transportation and Climate Change Clearing House. The FHWA's role in climate change involves improving transportation, mobility and safety while protecting the environment, reducing greenhouse gas emissions and preparing for climate change effects on the transportation system.

U.S. Army Corps of Engineers (USACE) www.usace.army.mil
The United States Army Corps of Engineers (USACE) is involved with civil works programs to deal with the impacts on coastal and estuarine zones caused by future sea level changes related to global warming (USACE, 2009). The USACE broad civil

engineering activities also involve ice engineering to deal with problems such as ice build up on walls, ice accumulation in navigation channels, and ice damage to shore structures and shorelines (USACE, 2002).

NASA National Snow and Ice Data Center (NSIDC) DAAC
http://nsidc.org/daac
The NSIDC DAAC provides data and information for snow and ice processes, particularly interactions among snow, ice, atmosphere, and ocean, in support of research and global change detection and model validation. NSIDC also provides general data information services to the cryospheric and polar processes research community.

National Centre for Atmospheric Research (NCAR) www.ncar.ucar.edu
The National Centre for Atmospheric Research (NCAR) is involved with the development and provision of advanced weather data and products, for instance the Road Weather Maintenance Decision Support System (MDSS). NCAR works closely with the Department of Transportation (DOT), for instance with road weather management performance monitoring. NCAR is managed by the University Corporation for Atmospheric Research (UCAR) under sponsorship by the National Science Foundation.

National Oceanic and Atmospheric Administration (NOAA) - Arctic
www.arctic.noaa.gov
The National Oceanic and Atmospheric Administration (NOAA) provides Arctic information and a set of reputable indicators that describe the present state of the Arctic ecosystem and climate. NOAA has an Arctic theme page that provides news updates and features covering the broad spectrum of the Arctic, including permafrost.

California Department of Transportation (CALTrans) www.dot.ca.gov
The California Department of Transportation (CALTrans) is very active with the broad spectrum climate change mitigation and adaptation activities through an ambitious legislative plan to address global warming (Iwasaki and Navai, 2008).

American Society of Civil Engineers (ASCE) www.asce.org
The American Society of Civil Engineers (ASCE) is very involved with the provision of quality infrastructure systems to address their adaptation requirements with respect to climate change. The ASCE has developed the 2009 *"Guiding Principals for the Nation's Critical Infrastructure"* essentially in response to the devastating consequences of levee failures in New Orleans associated with Hurricane Katrina.

Pew Centre of Global Climate Change www.pewclimate.org
The Pew Centre of Global Climate Change brings together business leaders, policy makers, scientists and other experts to bring a new approach to the complex and

often controversial issue of global climate change. The Pew Centre of Global Climate Change approach is based on sound science, straight talk, and the belief that all can work together to protect the climate whilst sustaining economic growth. The Pew Centre has also focused on China and climate change, providing a valuable resource in this regard (PC, 2010).

Lawrence Berkeley National Laboratory Urban Heat Island Group [www.lbl.gov]
The Environmental Energy Technology Division (EETD) of the Lawrence Berkeley National Laboratory (Berkeley Lab) has an Urban Heat Island Group that is studying effective ways to counter the urban heat-island effect by reflecting more of the sun's energy back into space. The focus is on reroofing and repaving with cool, solar reflective materials (Calkins 2006).

QUESTION 3: If nothing is being done, why not?

Not applicable

QUESTION 4: If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?

In addition to the research and resulting publications outlined above for Question 2 (noting also the Canadian Questions 2 and 4 responses), some of the completed United States studies with specific relevance to adaptation to the impacts of climate changes on road and airports are:

Rutting of HMA
Quantification of the Effects of Polymer-Modified Asphalt for Reducing Pavement Distress (AI, 2005).

Perpetual Asphalt Pavements
Perpetual Asphalt Pavement (Newcomb et al, 2010)

Top-Down Cracking of HMA
Top-Down Cracking of Hot-Mix Asphalt Layers (NCHRP, 2010)

Warm-Mix Asphalt
The FHWA and its technology partners continue to advance warm-mix asphalt which can cut production costs and emissions and still provide long lasting pavements, with reduced asphalt binder aging for instance (Corrigan et al, 2010).

Sustainability
The FHWA and technology partners continue to develop practices for quantifying the sustainability associated with roadway materials, design and construction (Muench and Anderson, 2009).

Geology and Climate Change
Equipping the Transportation Infrastructure for Geologic and Climate Change (Keaton et al, 2007). Please note that studies involving permafrost are covered in *section 4.1.3*. Increases in Arctic temperatures.

QUESTION 5: Can you please list road pavement-specific issues associated with climate change that in your opinion would require more work?

The Transportation Research Board (TRB) Special Taskforce on Climate Change and Energy has developed Research Needs Statements for Climate Change and Transportation (TRB, 2010). The specific research needs statements for road pavements adaptation are:

1. Explore adaptation as a defensive strategy to address climate variability impacts on critical transportation infrastructure;
2. Identify and develop climate change modelling outputs and climate scenarios to support transportation agencies in assessing climate risk and adaptation strategies; and
3. Explore the effects of aspects of climate change on transportation infrastructure.

It should be noted that the National Research Council of the National Academy of Sciences has recently released the Report Assessment of Intra-seasonal to Inter-annual Climate Prediction and Predictability (NRCNA, 2010) that addresses climate prediction components of several of the TRB research needs statements (TRB, 2010).