P2R2C2

Overall Advice & Summary

Report 11

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Report 11 – Overall Advice & Summary

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Executive summary

Anticipated climate change in Europe, north of the Alps, over a 110 year period from the mean climate in 1960-1990 to the mean climate in 2070-2100 was estimated using two emissions scenarios and two computational approaches. The likely impact of the resulting changes in climate was then estimated for a range of pavements and pavement-related infrastructure in order to determine the consequences for road owners.

The predictions of climate change showed that there is considerable local variation, as described in one of the supporting reports. Nevertheless, it is possible to summarise the predicted principal manifestations of climate change in the study region as:

- Temperature rise. In the southern edge of the study area the greatest deleterious impact of this will be hotter summers. In the far north the greatest impact will be on the reduction of the length of the winter. In most of the Nordic countries and northern Poland the principal deleterious effect will be the reduced number of zero degree transitions meaning pavements will spend significant lengths of time non-frozen at the surface during the winter season.
- Little change in total rainfall (or snowfall) except in northern Poland, the Baltic and Nordic states and Scotland. Greatest increases are expected in the Atlantic coastal areas of Norway and Scotland but, proportionately to current rainfall levels, the increase there will be similar as in other parts of northern Europe – 20-30%. The Alps will also experience an increased precipitation.
- Increased rainfall intensity in most areas.

At the time of writing the political will to ameliorate change seems relatively small, so the estimated climate changes computed, and on which this report is based, may be an <u>under</u>estimate of those that will be experienced.

It is noted that the life cycle of the pavement is much less than the time span over which climate change will have a statistically dependable influence on pavement performance. Only for the pavements with longest life, or for the lower layers that may not be touched during future rehabilitation and reconstruction, does the current designer need to change his or her practice at present. However, if current practice were not to be progressively changed at times of major pavement rehabilitation during the next 110 years, then the effects of these changes on pavements constructed, managed and trafficked as at present might be as follows.

- In areas where rainfall is unchanged then subgrades and aggregate layers should be dryer than as at present, on average, because warmer temperatures should generate greater evaporation. Even in wetter areas, the increased rainfall intensity is likely to result, for a road in moderate or better condition, in greater run-off. Then increased net infiltration to the subgrade and aggregate should be small or even negative. A neutral effect or even a small improvement in pavement support is therefore anticipated in most locations.
- Temperature and rainfall increase will be a challenge for asphalts. Softer materials more prone to rutting and stripping can be expected.
- In those countries that rely a lot on having frozen roads during winter, the length of the frozen period will reduce in the far north with a reduced length of spring thaw – a mixed problem and benefit. To the south, in much of the Nordic countries, frozen winter road structures may disappear altogether, in some years. In other years, periods during the winter season when the pavement surfaces are thawed will

become the norm. For this reason, many thin and unsealed pavements will need upgrading to provide reliable high bearing capacity all winter long. Those thaw problems concentrated in the spring will be likely to become less problematic,

- In coastal and low lying areas raised water tables may be experienced due to points at which flood waters collect or due to raised sea levels. Road raising or special reinforcement techniques will be needed locally to address this problem.

The appropriate responses to these changes in pavement performance:

a) will be achievable, in most cases, by routine material formulations that can be employed at the next reconstruction/rehabilitation event,

b) will need new design criteria regarding temperature and return period of storm flows to be developed (regionally specific),

c) will need more attention paid to drainage systems, particularly to make them self-cleaning and easily inspectible,

d) may necessitate more rut-resistant and stripping-resistant resurfacings on 'perpetual pavements' than originally planned. Such materials are readily available at a minimal cost differential, and

e) are likely to include, in the mid and southern parts of the Nordic countries, stabilisation of unsealed pavements, or overlaying by bound layers.

However, concentrating on these technical issues is unlikely to be a significant problem, nor a great economic challenge when compared to the necessary response from highway engineers to the wider social, economic, technical and political impacts on pavements that can be guessed at over the next 110 years. Demographic change, transportation method, funding models, journey patterns, vehicle type, demands of users and demands of funders are expected to be far more of an influence on future pavement engineering. Some of these influences will likely be driven by climate change itself.

Detailed information is available in a series of 9 earlier reports, listed at the end of this report.

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1 Introduction

"ERA-NET ROAD – Coordination and Implementation of Road Research in Europe" was a Coordination Action funded by the 6th Framework Programme of the EC. The partners in ERA-NET ROAD (ENR) were United Kingdom, Finland, Netherlands, Sweden, Germany, Norway, Switzerland, Austria, Poland, Slovenia and Denmark (www.road-era.net). Within the framework of ENR this joint research project was initiated. The funding National Road Administrations (NRA) in this joint research project are United Kingdom, Finland, Netherlands, Sweden, Germany, Norway, Austria, Poland, Spain, Ireland and Denmark.

The P2R2C2 project (Pavement Performance and Remediation Requirements following Climate Change) was an 18 month project led by the University of Nottingham with the collaboration of SINTEF (Norway), VTT (Finland) and ZAG (Slovenia).

This report provides a summary of the findings and overall advice.

2 Aims of Project

The aims of the project, as originally identified, were to

- study the likely differences in moisture (water) condition in the pavements of roads in Europe, from the Alps and northwards1, as a consequence of climate change;
- estimate 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;
- perform this study for a range of representative pavement types (asphaltic, unsealed, inter-city, county, low-volume) and representative climatic zones;
- assess uncertainties to permit risk / vulnerability to be evaluated;
- define options for responding to the changes, identifying key selection criteria;
- perform exemplar cost-benefit analyses to allow road owners to determine best options for their own situations;
- formulate findings into a wide range of formats (published, brochure, web, educational, email) and disseminate them accordingly.

The project was performed by a combination of literature review, laboratory evaluation of materials, computational studies of pavement structural and hydrological performance and by the development of recommendations suitable for implementation by national road owners into their specifications and design guides.

[1] Excluding states of the former USSR

3 Reporting

The project was performed as several tasks and these are reported separately, or sometimes two together, in separate reports. A list of the reports is presented at the end of this Summary Report.

4 Climate Changes

Climate change is a presumption of the project and is not argued or defended here. The question of relevance to the project is not whether climate change exists but, rather, to what extent, and in what respects, it is changing. The predictions of climate change undertaken by VTT and the University of Helsinki especially for this project are described in detail in Report No. 6. In making predictions there were three main issues to address – timeframe, variables to determine and prediction scenarios / models.

4.1 Timeframe

It was quickly decided that climate change over a 100 year + timescale was the preferred subject to address. This was because, over a much shorter timescale, year-to-year weather variations will tend to mask the underlying climate changes. Over a much longer timescale projections of climate change become very uncertain so that the reliability of estimated impacts seriously declines. So a 100 year, or so, period of study seems appropriate between these two limiting factors.

To overcome the year-to-year variability problem, changes in variables were defined in terms of the change in the 30-year average value from the period 1960-1990 to the period 2070-2100 [as is commonly done in IPCC modelling[2]]. So the actual timeframe is 110 years of which 20 years have already passed. The rate of acceleration (or de-acceleration) of climate change across 20 years is expected to be small compared with other uncertainties in the prediction, so most of the results of the project could be assumed to apply to changes over the next 110 years without much loss of accuracy

4.2 Variables Determined

The next issue was to select, on the basis of the degree to which they influence a road's health, those measures of climate change that should be quantified. The study team needed information on changes to inputs to pavement performance prediction models and to paving material behavioural models. After a review of desiderata, the ability to abstract information (and bearing in mind the funds available to make the study), the changes in the values, averaged over thirty years, of the following parameters were computed:

- Annual maximum temperature – an indication of extreme summer weather conditions.
- Annual number of times the temperature changes more than 15°C in a 6 hour period – in cold climates this is expected to give an indirect indication of change in 0°C transitions.
- Annual numbers of 0°C transitions – an indication of freeze-thaw cycling potential

[2] IPCC = Intergovernmental Panel on Climate Change

which, with the next two variables, can help study the spring-thaw issue.

- Number of 0°C transitions in December to February inclusive – an indication of freeze-thaw cycling potential in winter
- Number of 0°C transitions in March to May inclusive – an indication of freeze-thaw cycling potential in spring
- Annual number of degree-hours when the temperature is beneath freezing multiplied by the number of degrees below freezing – thus this is an indication of the change in severity of winter weather.
- Annual number of degree-hours when the temperature is above 25°C multiplied by the number of degrees above 25°C – thus this is an indication of the change in severity of summer weather in those parts of Europe where temperatures above 25°C are not the norm. For this reason, this property is not so useful for studying summer climate change in parts of southern Europe.
- Annual precipitation – an indication of the change in ground moisture (although this needs to be read alongside temperature that drives evaporation).

For all the temperature-related variables, it is emphasized that they relate to air temperature, not pavement temperature .... but the sophistication of the climate modelling has its limitations!

4.3 Climate Prediction Models & Scenarios

There are an enormous number of climate prediction scenarios and models (see Report 1). By 'models' is meant the computational assumptions and technique adopted by the climatologist. The climatologist has to adopt certain rules governing the interrelationships between a host of factors such as sea temperature, aerial carbon, solar radiation, etc. Different centres of research into climate change have made different assumptions about how the many factors act to change each other and hence, even from the same starting point and assuming the same external influences, they make different predictions. In the work of the team, two climate simulation models have been used – the Hadley Centre model (which has an atmospheric emphasis) and the Max Planck Institute model (which stresses the importance of the influence of the ocean). The same computer code was used with each model implemented in it, covering only Europe in approximately 50×50km squares (i.e. each variable is deemed to apply equally over this area). Details are available in Report No. 6. These are the most commonly used models for estimating climate change..

In addition, the climatologist has to make assumptions about anthropogenic inputs to climate change prediction models – of which CO_2 emission is the most politically sensitive. However CO_2 is only one such factor, there are several others, too. The climatologist has no ability to predict the future magnitude of these. Instead he/she must rely on the political forecaster and the social scientist's predictions. In the 2007 report of the IPCC, 6 families of emissions scenarios were used. In the work reported here the team has used two of these – A2 and B1 (refer to Report 6 for details). To give an idea of the reasonableness of these two models it may be noted that the IPCC placed a 'best estimate' of global temperature rise over the 110 year study period at 2.4°C with model B2, and 3.4°C with model A1 in a range of 1.8 to 4°C for the 6 models. Thus the team doesn't expect that its predictions of change to be the largest or smallest that is credible, but expects that they will bracket the most likely outcomes – where "most likely" means "excluding the biggest and smallest predictions".

With two models and two emissions scenarios there are, therefore, a total of 4 predictions for each variable assessed.

Readers should be aware that the local climate predictions made, and the implications for pavements that are deduced on the basis of these predictions could, very easily, be a long way from what will be experienced. The mid-range IPCC models tacitly assume that the World will, to some extent, address the drivers of climate change, but this is not an assumption that has gone unchallenged. Clark (2010) encapsulated the counter-view when he wrote “Can western eco-critics comfortably inhabit a stance from which to engage the environmental degradation latent in the hopes of millions of people in the Far East planning to buy a first car?” Certainly, eastern governments have shown no appetite to embrace emissions reduction. India’s Environmental Minister recently stated “I don’t expect any agreement at Cancun this December [2010] as the developed nations have so far failed to keep their promises of funds releases made last year at Copenhagen to the developing countries” (Ramesh, 2010), effectively stating that developing nations have no desire to address climate change unilaterally and that the developed nations aren’t intervening outside their own boundaries

5 Summary of Project Outcomes

5.1 Climate Change

The first, and rather significant part of the project, was to determine the changes in climate that could be expected to affect pavement performance. These are reported in detail in Report 6. In summary, taking into account all 4 project predictions, the project observed that, for the study period and area (Europe north of the Alps):

1) The annual maximum temperature might rise between 1 and 12°C with greatest rise in the West (particularly France) and less in Eastern and Northern Europe.
2) For the vast majority of areas studied, the frequency of rapid air temperature changes will remain the same or reduce.
3) In the Nordic and Baltic countries (Norway, Mid-Northern Sweden, Finland, Estonia, Latvia, Lithuania) the annual cold sum (number of hours when air temperature is less than 0°C multiplied by the number of degrees below freezing) will decrease significantly. In Southern Sweden and Poland there will also be marked reductions though not as great as in the countries previously listed.
4) The change in number of hour-degrees per year higher than 25°C will be less than 1000 for the UK, Ireland, the Nordic countries, most of the three Baltic States and in the Alps. The change will be greater (as much as 4000 hour-degrees) in Germany, particularly in the south, parts of the Czech republic, Slovakia and France.
5) In all areas, except the very north of Norway, Sweden and Finland (“Lapland”), the number of freeze-thaw cycles is expected to reduce.
6) For most of mainland Europe and the British Isles total rainfall will change little. Only Scotland, northern Poland, the Baltic and Nordic states will see increased rainfall (or snowfall). Greatest increases are expected in the Atlantic coastal areas of Norway and Scotland but, proportionately to current rainfall levels, the increase there will be similar as in other parts of northern Europe – 20-30%. The Alps will also experience an increased precipitation.
7) Rainfall intensity will increase in most areas.

Taking into account points 3 and 5 together implies that (contrary to some popular suggestions) the frequency and length of period over which “Spring-thaw” problems occur will not be worse than at present in the Nordic countries. Overall, the length of time over which partially thawed conditions occur should reduce – both because the number of freeze-thaw cycles reduces and because the seasonal freezing doesn't go so deep due to a shorter period constantly less than 0°C. Thus, thawing will complete in a shorter period with the benefit that trafficking limitations at this period will be relaxable, to some extent. However, these findings also mean that the stable, frozen winter period will reduce with thaw conditions occurring earlier in the spring and freezing occurring later in the autumn, so reliance on the high load carrying capacity of frozen winter road construction will be less and less available.

Taking into account points 6 and 7 together implies that, in non-northern Europe, rainfall events will be less frequent but heavier when they occur.

This summary has, necessarily, been rather generic and readers are pointed to Report 6 for further details and more particular interpretations / features of future climate changes.

5.2 Anticipated Effects on Pavements

In the "do nothing" case – i.e. keeping to the same construction and maintenance régimes and using materials of the same formulations – what are the anticipated impacts of the changes in climate just mentioned?

Report 1 gives a review of the likely impacts on current road construction in more detail, drawing on previous studies of relevance. Linkages between climate factors and pavement response are made in that report and have been incorporated into Table 1. It is noted that, for rutting of asphalt, solar radiation is more important than air temperature as it is the former that controls the pavement surface temperature to a greater degree. Climatic modelling of cloud cover wasn't possible in this project. However, it is surmised that greater mean temperatures will give rise to greater oceanic evaporation producing moister atmospheres with greater cloud cover. Thus, it is possible that the effects of temperature rise as far as rutting and asphalt embrittlement is concerned may be offset, somewhat.

5.3 Pavement Design, Rehabilitation & Operational Strategies

Pavements are repaired and rehabilitated on a short time-scale compared with the time period over which climate changes are observable. This study has provided 30-year mean values "before" and "after" climate change (or, at least, over a 110 year 'window') because year-to-year weather variability would mask such changes if the mean value had been calculated for a much shorter sampling length. Thus, if a pavement is being significantly rehabilitated on a 20-year timescale, the impact of long-term climate change may be less than the influence of the variation in weather conditions experienced in that 20-year period. Accordingly, the few road authorities that have considered climate change appear to have come to the conclusion that, for the most part, it can be largely ignored as far as the pavement is concerned. Responding to actual weather condition variability by the regular updating of temperature and rainfall levels in design guides will, over the next cycle of the life of the road, automatically provide a response to the small, underlying climate change.

A further concern is that climate change is likely to indirectly affect pavements to a greater degree than it will affect them directly. For example, demographic changes due to people's desire to move away from low-lying flood-prone areas will change the sections of the pavement that are most trafficked. Responding to these induced changes in traffic pattern is likely to have a much greater impact on pavement maintenance and rehabilitation strategies than will the small temperature or moisture change over the study period.

Table 1. Conclusions of the effects in a changing climate

Implication	Where significant	Effects
Change in the annual maximum temperature	Western Central Europe	Increased rutting deformation Expansion of joints in concrete pavements & at bridge decks
Change in the annual cold sum	Nordic Countries, Baltic states	Reduced frost penetration, a positive effect Bearing capacity reduction in winter-time affecting truck transport
Change in the annual heat sum	Mountains, France, S. Germany, Slovakia	Deformations on bitumen-paved roads, increased vegetative growth and indirect erosion risk
Change in number of freeze-thaw cycles	Northern Europe	Lapland: an increase in these cycles will be negative with regards to length of fully frozen period, but positive with respect to length of spring thaw and length of fully-thawed period; other regions positive effect
Change in the annual precipitation	North-western Atlantic coastal areas and Nordic / Baltic states	A largely neutral effect for water tables because increased rainfall will be offset by increased proportion running-off, except in locales prone to flooding
	All areas	Stripping of asphalt may increase following storm events and in the presence of traffic loading More rapid decay, by base and subgrade destabilization) of cracked pavements due to greater water availability during storm events, with washouts due to temporarily overcharged drainage systems. Otherwise, somewhat positive effect as water tables drop due to greater evaporation (due to higher average temperatures), greater run-off and less infiltration (because precipitation occurs in more intense, but less frequent, events)
	Local low spots	Accumulated run-off in intense rainfall events could lead to more flooding and locally raised water tables
Sea level rise	Roads at low level by sea	Greater risk of flooding and salt intrusion

On top of these changes will be changes of use due to economic, development, migration and other changes that are even more difficult to predict than climate change (!). If we imagine, for a moment, ourselves as pavement engineers in the year 1900, the changes in materials, structures, alignments, maintenance strategies, etc., etc. that have occurred between 1900 and 2010 would be seen as the consequence of many factors, but climate change wouldn't be one of them! Thus, although climate change between 1990 and 2100 will likely be much greater than between 1900 and 2010, nevertheless its impact on pavement design, maintenance and operation may be hidden by the impact of other factors, whose importance is even more uncertain than is climate change.

This is not to say that climate change should be ignored. There is a need to consider particular issues as follows:

- Changes to design parameters,
- Changes to design options, and
- Changes to pavement material formulation.

5.4 Material Response to Climate Change

Subgrade

Report 4 deals with the sensitivity of subgrades to moisture change. Parts of Report 2 also cover subgrade wetting issues, but cover water in the other pavement layers, as well. About 80% of road distresses are associated with water, directly or indirectly. In thin pavement structures these distresses are heavily influenced by the condition of the subgrade. Thus keeping the subgrade relatively dry is important for maintaining pavement life. As mentioned above, on average, except near the Atlantic coasts of Europe and in the Nordic/Baltic region, precipitation is not expected to increase much. So, with less, but more intense rain storms, the ratio of run-off to ingress should increase. Coupled with higher mean temperature which will increase evaporation, this should lead to dryer subgrades and better performing roads. Where rainfall does increase the greater run-off in higher intensity rainfalls will compensate somewhat for the increased volume, so subgrades aren't expected to be in much worse condition that at present, as long as the road is in good conditions and properly designed. Exceptions are low spots, where flood waters are likely to collect, and unpaved roads or heavily cracked roads, into which large amounts of rainfall can quickly infiltrate and greatly reduce the strength, even if only for a short time.

Aggregate

Capping, subbase and granular base layers (all usually formed of aggregate of some kind) are also sensitive to moisture condition, although less so than many subgrade soils. Provided water tables do not rise (discussed a little below in Section 5.6), then aggregate performance should be largely unchanged or even slightly improved, due to evaporative drying. The aggregate layers are those most affected by freezing and thawing issues. These are discussed in Section 5.5.

Asphalt

Report 5 particularly addresses issue associated with Asphalt and climate change. Standard good practice with asphalt mix design will continue to ensure low intact permeability of asphalts, a prerequisite of encouraging run-off. With more water on a road surface during rainstorms, because of their intensity, erosion and de-bonding ("stripping") of aggregate particles from the bituminous matrix are of increasing concern. This is expected to be of particular concern in the Atlantic fringe where the biggest rainfall increases are expected (see Report 6) and also in France and central Europe where more intense rainfall will often be associated with higher temperatures in the summer – the most damaging combination. This has implications for thickness of bitumen film, polymer modification to resist de-bonding and void reduction to reduce water entry and stripping action. Increasing the angularity of aggregates may also increase bitumen-aggregate bonding.

On the basis of pavement analyses (Report 7), rutting is expected to increase, for materials of the same formulation, due to the increased temperatures, particularly in summer in France and just north of the Alps where the greatest temperature increases are expected. However, for the cases analysed the increase is relatively small and was still within permissible limits. Doubtless there would be some locations where current pavement and mix designs are at the limit of permissibility where climate change will result in excessive rutting if mix formulations are not changed.

Porous Asphalt

Porous asphalt is not very durable compared to conventional asphalt and therefore, even more than other materials, it will need replacing at a life that is much less than the period over which climate change is observable. Successful use of porous asphalt will not be changed much by climate change, although its use may become a little easier due to a range of locations in which frost damage is experienced. Offsetting this, the heavier rainfall intensity will lead to a greater tendency to stripping / de-bonding with the concomitant formulation needs already mentioned in the immediately previous paragraphs. Conversely, the use of porous asphalt has an important role in limiting flooding of the road and thus in maintaining traffic flows and road safety. A part of Report 5 is dedicated to this material.

5.5 Freezing and Thawing

In cold climates the behaviour of these aggregate layers can be severely affected by freezing and thawing action. In the most northern parts of Europe where these layers currently experience seasonal freezing for several months, warming winters will reduce the depth that is frozen and thus thawing of the pavement will take place over a briefer period, earlier in the year. The length of period when the pavement is constantly frozen will be shorter, while summer will be longer. The length of the frozen period can be estimated from the data in Report 6. The pavement response will then be rather similar to that currently experienced by pavements some hundreds of kilometres to the south (as road construction practice is largely unchanged over this distance in each Nordic state).

Further south, in the more southerly parts of the Nordic countries, equivalency of future response with current behaviour some hundreds of kilometres (e.g. current practice in the northern parts of Poland & Germany) to the south is less feasible for two reasons:

1) Road construction practice changes. It would, of course, be possible to commence building roads in the manner that they are currently built several hundreds of kilometres to the south (see point 2), but that might not be sensible because each country tends to adopt a rather consistent construction practice within its own boundaries and it might be difficult to operate two approaches without a clear demarcation boundary between the zones of their applicability.
2) Winter climate becomes frost marginal – i.e. seasonal freezing is not certain. Unsealed roads experience surface thaw problems intermittently over the course of the winter and not just at a period of ‘spring thaw’. The typical response has been to provide bound materials of some kind (thicker asphalt surfacing, stabilised base, etc.) that deliver the resistance to frost damage and/or to provide a more usable surface, year-round. Whereas these strategies are usually untenable in very cold climates they become usable in cold, but not very cold, climates. However, to deeply reconstruct pavements with stabilised bases would be very expensive, probably prohibitively so. However, new roads could consider this approach. For existing pavements facing occasional thaw problems, monitoring systems (see Report 2) offer a possible operational management method to minimise the problem.

In the northern parts of mainland Europe, milder winters will mean less frost penetration so that thick coverage of frost-susceptible materials becomes less necessary.

5.6 Drainage Requirements

The ‘Subgrade’ part of Section 5.4, above, suggested that subgrades should improve due to a greater proportion of rainfall running off and due to higher evaporation. Whilst this appears to be the case for pavements with well-maintained surfaces, where a pavement is distressed and already cracked, run-off could be relatively small. In that case, water entering through the cracks needs to be conveyed out of the pavement rapidly – and this will normally require operational drains. This is particularly the case on moisture-sensitive clay soils (see Report 4). There is considerable hearsay evidence, and some written reports, showing that sub-surface drainage systems are frequently compromised due to poor construction and poor or no maintenance (Dawson, 2009; Fleckenstein & Allen, 1996; Dunnam & Daleiden, 1999). With rainfall events becoming more intense, there is greater need for these drains to work otherwise they will provide a sump from which the road can draw water and, hence deteriorate. Additionally, the expected increase in peak flow, yet lower frequency of storms, is likely to give rise to greater erosion of surface soil and vegetation leading to greater potential of drain blockages.

Report 9 covers the efficiency of drainage systems in detail, using mathematical modelling techniques to predict sensitivity of performance to the drainage provision. The simulations performed show that, in general, small changes in rainfall pattern (i.e. average intensity and duration) not accompanied by increase in yearly amount of rainfall water, do not sensibly affect the saturation level of the road structure. On the other hand, extreme intensity events and/or large changes in rainfall quantity can be an issue, because then subbase saturation can increase.

In summary it was observed that:

- Changes in rainfall patterns will, generally, have little effect on roads in good condition, while increased temperatures should aid drying of subgrades and improve pavement performance, somewhat. However the most extreme rainfall events are the key challenge and drainage provision will often require a change of approach in order to address these events appropriately.
- Un-cracked pavement surfaces can handle rather well changes in rainfall intensity and quantity.
- Porous asphalt surfaces are suitable to convey greater peak flows away from the road surface. Their capacity to detain a significant volume of water for a short period will, if anything, be beneficial during heavier rain storms. Layer thickness and, in particular, the outfall arrangements from the porous layers may require re-design to handle greater assumed water flows.
- The more intense rainfall events anticipated will require run-off water to be collected and more effectively conveyed away from the road structure. If water stays at the road margins it is likely to generate localised flooding, backing-up of drains and, consequently, saturating subgrades with consequent rapid pavement deterioration.
- Such decreased performance would be likely to be sporadic at points where water collects (i.e. particularly at fault spots in the surface or sub-surface drainage systems).
- There is a need for improved provision of:
    - Sub-surface drainage systems, particularly so that they are easy to monitor and repair, and
    - Surface run-off systems capable of handling increased peak flows (perhaps of the order of 50% higher design flows – the exact amount depending on location).
- There is also a need for improved maintenance by:
    - Promptly sealing surface damage,
    - Maintaining efficient surface drainage systems, and
    - Checking function of sub-surface drainage systems and maintaining as needed.
- In a few locations, where roads are built close to the sea at low elevations, sea level rise may be an issue, raising the local water table. Low spots in an undulating topography may become more flood-prone so, locally, water tables could rise in

such locations. In these cases an improved drainage may not be a possible solution, due to insufficient falls, and raised construction of the pavement may be necessary.

Once again, these effects are likely to be mostly masked by year-to-year weather variability in any shorter (<20 year) window.

5.7 Overall Pavement Performance

Using modern analytical pavement design procedures, the more general issues of rutting development, roughness generation and cracking were studied (see Report 7). It was concluded that the effects of climate change are, from most deleterious to most beneficial, likely to be:

- A sharp increase in top-down cracking,
- Some increase in rutting,
- Slight increase in rate of asphalt aging due to higher mean temperatures,
- Negligible effect on roughness development and on bottom-up cracking, and
- Decreased thermal cracking.

Each result is based on the assumption of no-change in pavement or asphalt mix design. In fact, small changes could readily address the undesirable impacts identified (see Section 6, below). If no change is made the implication is that increased maintenance expenditure will be required to address cracking (and a lot less, but still some increase, to address increased rutting).

6 Suggested Changes in Practice

As the life cycle of a pavement surface is relatively short, weather changes due to climate change are very unlikely to increase or decrease the pavement deterioration process in a non-negligible way during that cycle. Instead, as the climate evolves, newly-built roads should be designed and constructed taking into account *up-to-date* climate-related factors as well as traffic factors. Where the deleterious impact of climate change on the pavement is such that change in engineering practice is warranted, there are several response options available to combat or ameliorate those impacts. Broadly these can be divided into design/ constructional, material and operational/maintenance responses. Reports 3 and 10 deal, in particular, with changes that might beneficially be made in response to climate changes.

6.1 Design & Construction

Increased temperature has, overall, the impact of making the pavement softer (warmer asphalt and less frozen ground), a softening that may be offset, or even over-compensated, by unbound and subgrade layers that are dryer due to greater evapo-transpiration. However, such stiffening of the lower layers cannot be relied upon, so conservative pavement structural design may need to assume that these foundation materials are getting wetter (softer) due to more infrequent, but heavier, rain storms. The resulting, softer, pavement will need greater thickness of layers of the same materials to achieve the same load spreading which may not be an efficient solution. Instead stiffening of one or more of the pavement layers could be a more appropriate solution – this option is covered in the next section on

Alternative Materials.

Given the relatively short reconstruction cycle of many pavements, design using the then-current climate will usually be acceptable. The exceptions are "perpetual" pavements. These pavements are expected to function, with only small maintenance interventions at their service, for more than 50 years. Such pavements will need to be designed (using available design approaches) with a warmer-than-current design temperature.

Softer near-surface materials will give rise to increased rutting if no changes are made. The obvious solutions are, again, material based and covered in the next section. Reinforcement of asphalts using polymeric grids is feasible, though probably not cost effective. Indirect structural solutions that reduce the pavement temperature are, however, more attractive. If water is stored in the pavement surface then warm weather will cause evaporation thereby lowering the pavement temperature compared to what it would otherwise have been, due to the consumption of latent heat energy. Some initial research into such a concept has been undertaken (e.g. in Japan) but is at its early stages. Another technique is to encourage greater reflection of solar gain by special surfacings. Both concepts are driven by the so called "Heat Island Effect" and not by pavement performance concerns. If pavements can be kept cooler so will the air around them. Thus urban populations, where there is a lot of paving, should experience less extreme summer temperatures. More details on both techniques are given in Report 3.

The use of pervious asphalt as the uppermost layer has already been discussed in some detail. A pavement exploiting this material's ability to take water out of the pavement must be equipped with an impervious layer directly beneath it, and that layer must not be susceptible to cracking. With greater water management issues, geosynthetics are expected to play an increased role as well – details are again found in Report 3. The use of sealing barriers in, or adjacent to, pavements can be expected to be of increased benefits in areas experiencing rainfall increase.

Perhaps the most critical change required in pavement design and construction should be the drainage system. With increased intensity storms, larger volumetric flow rates need to be adopted as design criteria[3]. Self-flushing and easily inspectible drain runs need to be constructed, too so that maintenance becomes much more practicable than at present (see Operation / Maintenance, below).

In specific locations, raised water tables may be experienced (areas where flood waters collect and very near coasts). Design will need to predict such changes and make adjustments to the construction (higher pavement levels, highly permeable underdrains, etc.). More generally, the need for better functioning drains and the possibility of raised water levels at outlets could cause local problems of inadequate falls along drainage runs. Therefore higher construction of pavements in low-lying areas is preferred.

As already discussed in Section 5.5, the change in climate in the central Nordic region brings particular difficulties. There will, likely, be a loss of guaranteed frozen pavements during winter associated with a single, problematic spring thaw. This will be replaced with on-going near-surface freeze thaw cycles of several weeks. Unsealed roads have functioned well in the past, except during the thaw period. In the longer-term future they seem likely to perform less well over most of the winter, to suffer little or no traumatic spring thaw event and to exhibit their summer behaviour for longer (with associated dust problems). Countries to the south (northern Poland /Germany) which currently experience the type of weather which may be experienced in south/central Nordic countries in future rely on binding of the upper pavement layers (and associated post-winter maintenance) to see them through this type of

[3] The development of new (more frequent) 'return periods' for design might be adopted using historic data or, better, the water flow associated with specific return periods might be adjusted upwards. Highway authorities should consider commissioning hydrologists to re-evaluate, in the light of anticipated climate change, the flows associated with the design periods that they use.

climate. Therefore stabilisation of the upper, currently unsealed, pavement layers seems likely to be needed in future. This could be costly. As a some recompense, major highways in the Nordic region have usually been built on large thicknesses of crushed granular material so that the frost penetration never reaches deep enough to cause heave (and hence allow later thaw) of the subgrade. This thickness can be progressively reduced in future.

6.2 Alternative Materials

Modification of asphalt has already been covered in Section 5.4 with respect to the problem of stripping, so this section deals with other, material-based solutions. Cement-based stiffening of lower pavement layers (or stiffening by other binders, such as fly ash and lime) is likely to be one solution although its propensity to crack militates against its use. The use of bitumen filled pre-cracking is one solution available to address this difficulty; a conventional asphalt layer on top of the cemented layer but separated from it by a stress absorbing membrane interface ('SAMI') is another; fibre reinforcement a third. Of course, carbon concerns may cause both cement and fly ash to become premium products over the next 100 or so years, in which case other solutions will be needed. Chief amongst these might be more viscous (lower penetration) bitumen and asphalts with denser graded aggregate. They will be more resistant to rutting and stiffer – therefore spreading load effectively even at higher temperatures than currently experienced.

Where soils are particularly sensitive to water, or where periodic flooding is anticipatable, then stiffening of subgrades may be required. Fibre reinforcement is a possible non-stabilisation technique (see Report 3 for details). For unsealed, or thinly surfaced, roads the use of foamed bitumen stabilisation of the current surface layers will be likely to be one of the more economic solutions (see Report 3).

Polymeric and other non-conventional aggregate treatments – especially dry powdered polymers (DPP) – are promising although, as yet, their applicability to a particular aggregate remains a little uncertain. The understanding of the capability and limitations of these materials will, doubtless, increase. As greater understanding of these treatments is developed, selection of treatment agents tuned to the properties of the material being treated is likely to become possible. Again, details are available in Report 3.

Other materials have also been considered in the study. Bitumen emulsions, for example, may not be better than hot-mix asphalts, so may not provide solutions to the problems of climate change, but with increasing temperatures their limited use in northern Europe is expected to rise. Ultra-thin, fibre-reinforced concrete overlays and specialist micro-surfacings are also expected to become more popular. By combining surface stiffness and greater solar reflectivity, they are likely to be an attractive solution to reducing heat-induced pavement deterioration. Rubber additions to asphalt, apart from giving a useful second life to what would otherwise be a waste, can increase the asphalt's resistance to cracking. Therefore there may be a role for such treatment where solar gain is expected to increase a lot (leading to top down cracking) or as a material modification for a layer deeper in the pavement that is designed to act as an impermeable barrier to water.

6.3 Operation / Maintenance

Although road construction design approaches may need to change (as just described), nevertheless if pavements were to be built according to existing standards and approaches, success could, mostly, still be assured provided that maintenance and rehabilitation changes were made in line with the change in climate. It would be likely that these operations would need to be planned more often if materials and processes remain the same. Table 1 in Report 10 describes in detail how the future climate might interfere with the different types of distress that are the main reasons for maintenance actions.

Regionally imposed load restrictions on the secondary and tertiary road network have been a common strategy to limit pavement damage in many Nordic countries during the spring thaw. Quite apart from the impact on businesses, the limited ability to predict spring thaw in the pavement makes such a policy of questionable value. Local sensing of conditions, whatever the weather pattern may be, seems by far the most preferable manner of managing the limited load capacity of thawing roads. Local sensing is able to cope with climate change and year-to-year variation without difficulty and is, therefore, recommended for the future.

A common change that will be required in most jurisdictions is greater attention to drain maintenance. With rain appearing in more intense rainfalls, and in greater amounts in Atlantic fringe and the Nordic/Baltic areas; with evidence that many existing drains malfunction, and with the need for better functioning in future, it will be more important than ever before that run-off and subsurface drains function. More intense storms at greater spaced intervals will tend to mean greater wash-off of soil and vegetation leading, making drain blockage more likely. Greater temperatures can be expected to result in greater growth potential, so penetration of drains by vegetation, particularly roots, can be anticipated. For these reasons, a more frequent inspection regime and specialist drain clearing equipment is likely to become *de rigueur*, and post-storm checks should become routine.

Unsealed roads can be expected to suffer more aggregate loss by water erosion if rain storms become heavier. This implies a greater repair and remediation budget would be required for such pavements. The inter-storm periods will be dryer and warmer giving rise to increased dust problems for these pavements. With more restrictive pm_{10}[4] regulations now in force, and the probability, based on past experience, that future restrictions will be tighter and not more generous, then the rationale for the stabilisation of the upper levels of unsealed pavements becomes stronger and the material treatments discussed in the previous sub-section become more and more necessary.

7 Economics

A study of the cost effects of climate change on pavements was performed, but with some difficulty! Because the costs of materials in the long-term future cannot be estimated with any useful accuracy, present costs were taken as a guide. This overcomes the problem of predicting the economic situation in the future, but doesn't overcome the limitation that the relative costs of one material to another, and one activity to another, could change considerably over the notional 110 year window in view. Furthermore, transport costs of the bulky materials needed usually dominate particular projects, meaning that local availability of materials heavily influences any design or maintenance decision. Thus any economic study needs to be made at the local level and will not be readily translatable to other places.

Although Report 10 investigates costs associated with particular options to resist the impacts of climate change, the investigation showed that indirect effects are likely to have the most impact on costs. For example, an analysis of the costs and benefits of several techniques aimed at improving asphalt design and maintenance showed that savings during the life cycle that are greater than higher initial costs. For subbase treatment, cement is shown to be the cheapest binder, but the drawbacks are non-negligible. Foamed bitumen, although slightly more expensive than cement, gives better results, and the higher costs are easily absorbed thanks to lower design restrictions and lower anticipated expenses during the lifecycle. Specialist treatments (e.g. by enzymes or polymeric-based additives) are relatively expensive at the outset. Some could yield a real pay-back during the project life, but greater

[4] pm_{10} indicates those airborne particles less than 10microns in size

experience in the long-term is necessary before this can be assured. But these materials might be expected to show the greatest price change with time as current novelty becomes the norm of the future.

8 Conclusions

The overall conclusion of this study is centred on three observations:

1) The life cycle of the pavement is much less than the time span over which climate change will have a statistically dependable influence on pavement performance. Only for the pavements with longest life, or for the lower layers that may not be touched during future rehabilitation and reconstruction, does the current designer need to change his or her practice at present.
2) The direction of climate changes is evident, but the degree of change in any one location is very uncertain. At the time of writing the political will to ameliorate change seems relatively small, so the estimated climate changes which are used in this report (which are biased towards mean climate change predictions) may be an <u>under</u>estimate of those that will be experienced.
3) The social, technical and political impacts on pavements – in terms of demographic change, transportation method, funding models, journey patterns and vehicle type – will be far more of an influence on future pavement performance. And some of these impacts will likely be driven by climate change itself.

As far as the direct effects of climate change itself are concerned, these can be grouped as follows:

- Most areas will experience temperature rises. In the southern edge of the study area the greatest deleterious impact of this will be hotter summers. In the far north the greatest impact will be on the reduction of the length of the winter. In most of the Nordic countries and northern Poland the principal deleterious effect will be the reduced number of zero degree transitions meaning pavements will spend significant lengths of time non-frozen at the surface during the winter season.
- For most of the region studied the total rainfall will change little. Only northern Poland, the Baltic and Nordic states and Scotland will see increased rainfall (or snowfall). Greatest increases are expected in the Atlantic coastal areas of Norway and Scotland but, proportionately to current rainfall levels, the increase there will be similar as in other parts of northern Europe – 20-30%. The Alps will also experience an increased precipitation.
- Rainfall intensity will increase in most areas.

The effects of these changes on pavements constructed, managed and trafficked as at present would be mixed:

- In areas where rainfall is unchanged then subgrades and aggregate layers should be dryer on average, especially because warmer temperatures should generate greater evaporation. Even in wetter areas, the increased rainfall intensity is likely to result in greater run-off so increased net infiltration to the subgrade and aggregate should be small or even negative.
- Temperature and rainfall increase will be a challenge for asphalts. Softer materials more prone to rutting and stripping can be expected.

- In those countries that rely a lot on having frozen roads during winter, the length of the frozen period will reduce in the far north with a reduced length of spring thaw – a mixed problem and benefit. To the south, in much of the Nordic countries, frozen winter road structures may disappear altogether, in some years. Periods, during the winter season, when the pavement surfaces are thawed will become the norm. Spring thaw problems will be likely to become less problematic, but many thin and unsealed pavements would need upgrading to provide reliable high bearing capacity all winter long. Major pavements in these areas will be more economic to construct as less protection against frost penetration will be necessary.
- In coastal and low lying areas raised water tables may be experienced due to points at which flood waters collect or due to raised sea levels. Road raising or special reinforcement techniques will be needed locally to address this problem.

The appropriate responses to these changes in pavement performance:

a) will be highly dependent on those social and political constraints mentioned above,

b) will be fairly dependent on the climate change model & scenarios used,

c) will be relatively easy to handle given the rapidity with which pavements are renovated relative to the timescale over which climate is expected to change,

d) will be achievable, in most cases, by routine material formulations that can be employed at the next reconstruction/rehabilitation event,

e) will need new design criteria regarding temperature and return period of storm flows to be developed (regionally specific),

f) will need more attention paid to drainage systems, particularly to make them self-cleaning and easily inspectible,

g) may necessitate different resurfacings on 'perpetual pavements' than originally planned,

h) are likely to include, in the mid and southern parts of the Nordic countries, stabilisation of unsealed pavements, overlaying by bound layers or operational management solutions based on continuously monitored condition, and

i) are likely to be over-ruled by the responses needed to satisfy user and funder demands and to deal with changes in use consequent on demographic, technological and economic changes (some of which are a consequence of climate change).

Sources

Other Reports from P2R2C2

The work of the project is reported in 9 other reports, numbered and titled as follows. All can be downloaded from www.nottingham.ac.uk/~evzard/P2R2C2 .

Number	Title
1	State of the art of likely effect of climate on current roads
2	State of the art of materials' sensitivity to moisture change
3	Alternative materials and methods to enhance resistance to climate change
4	Soil wetting-drying study
5	Study of water effects on asphalt and porous asphalt
6	Climate change projections for variables affecting road networks in Europe
7	Analysis of pavement structural performance for future climate
8	*Not used*
9	Pavement response to rainfall changes
10	Future rehabilitation and maintenance & cost-benefit study of alternative solutions
11	This report

Other References

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Dawson, A.R., (2009), "*Water movements in road structures*", Springer (see Chapter 13).

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