Transport
Volume 167 Issue TR5

The impact of climate change on the European road network
Fifer Bizjak, Dawson, Hoff *et al.*

ice | proceedings

Proceedings of the Institution of Civil Engineers
Transport 167 October 2014 Issue TR5
Pages 281–295 http://dx.doi.org/10.1680/tran.11.00072
Paper 1100072
Received 29/11/2011 Accepted 08/11/2013
Published online 19/03/2014
Keywords: environment/mathematical modelling/roads and highways

ice
Institution of Civil Engineers
publishing

The impact of climate change on the European road network

1 **Karmen Fifer Bizjak** PhD
Head of Geotechnics & Traffic Infrastructure Department, ZAG Ljubljana, Ljubljana, Slovenia

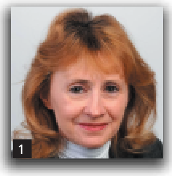
2 **Andrew Dawson** BA, MSc, DIC, CEng, MICE, FGS
Associate Professor, University of Nottingham, Nottingham, UK

3 **Inge Hoff** BA, PhD
Professor, Norwegian University of Science and Technology, Trondheim, Norway

4 **Lasse Makkonen** BA, PhD
Adjunct Professor, Principal Assistant, VTT Technical Research Centre of Finland, Helsinki, Finland

5 **Jussi S. Ylhäisi** BA
PhD student, University of Helsinki, Finland

6 **Alessandra Carrera** PhD
Researcher, ETH Zurich, Zurich, Switzerland






Anticipated climate changes in Europe over the next 100 years were estimated using two different scenarios of carbon dioxide emissions and two computational approaches. The principal manifestations of climate change within the European region are predicted to be a rise in temperature, an increase in rainfall intensity in most areas and a decrease in freeze–thaw cycling. The impacts of such possible climate changes were then estimated for pavements and the pavement-related infrastructure. It should be noted that the life cycle of pavements is much shorter than the time span over which climate change might have a statistically significant influence on pavement performance. Several analytical and numerical analyses were performed in order to simulate the effect of future climate change, taking into account the fact that the effect of these changes on pavements structures will depend on local conditions. In particular, temperature and rainfall increase will be a challenge for asphalts, as both rutting and stripping of asphalt layers can be expected. In countries where roads are presently frequently frozen in winter, the length of this period of freezing will be reduced. For this reason, many thin and unsealed pavements will need to be upgraded if high bearing capacity is to be maintained. In coastal and low-lying areas raised water tables may occur due to areas where flood waters may collect, or due to raised sea levels. For most applications, appropriate responses to these changes in pavement performance will be achievable through the use of new design criteria with regard to temperature and the return period of storm flows. More attention needs to be paid to drainage systems, which should be self-cleaning and easy to inspect.

1. Introduction

Future climate change and its possible influence on the performance of the road network is an issue which concerns more and more countries. Global climate change will affect all infrastructures, including road networks. Different effects are expected across the world due to expected differences in climate change, as well as in the structure and properties of roads.

A great deal of investigation has been performed in order to try to predict future changes in climate (and their consequences) on the Earth over the next decades, extending to periods of hundreds of years.

The most likely climate changes which may occur in the future have been investigated by the Intergovernmental Panel on Climate Change (IPCC) project. They are listed in the AR4 report (Pachauri and Reisinger, 2004). Such climate change predictions are based on the changes in carbon dioxide concentration in the atmosphere that will probably be observed in the case of different economic, industrial and ecological behaviours. A range of possible scenarios (from optimistic to almost catastrophic) has been developed based on many, more or less complex climate models. From the IPCC's AR4 report some general conclusions, independent of geographical zone or selected scenario, can be drawn. An increase in temperature is expected everywhere, which will cause the melting of terrestrial ice, and thus an increase in sea levels. Spring thawing in cold regions is likely to occur earlier. In addition, storms and surges are likely to be more frequent in future decades, whereas the amount of precipitation in Europe seems likely to increase, at least during winter. Some further issues of relevance to roads are: (*a*) increasing coastal erosion and (*b*) relocation of the population due to climate change. There are some recommendations about how local authorities might act with respect to climate change (Wilford and Fraser, 2011), but these do not apply to the whole of Europe.

Some experimental studies regarding the effect of climatic factors on the properties of roads have been performed in the past, but the results are not always in agreement, and the few equations that try to describe them can usually be applied only on a local scale or to particular materials. Part of the difficulty lies in quantifying the different factors individually. However, some general findings have been made (Doré *et al.*, 2005; Watson and Rajapakse, 2000) which indicate that at least 50% of road deterioration is due to environmental factors, provided the pavement has been designed adequately.

Temperature, solar radiation, rainfall and groundwater level rise are the climate change-related issues which will most affect roads. The predicted rise in temperature and in solar radiation will cause rutting and ageing of the asphalt, resulting in the development of cracking (Zuo *et al.*, 2007). The temperature of asphalt layers follows the same daily and seasonal changes as the solar radiation, although these temperature variations are less and less marked with depth. Air temperature is of lesser importance than solar radiation. The temperature of a road surface is always higher than that of the air above it; on average this difference is about 7°C. Some simple equations that link air temperature with asphalt temperature do exist (Lavin, 2003) but they do not take into account all the relevant factors.

Rainfall has an influence on the asphalt and lower layers of road structures. An increase in rainfall will lead to asphalt ravelling problems (Kringos and Scarpas, 2005) and even the formation of cracks. According to Chen *et al.* (2004), for an air voids value higher than 12%, the voids start to be 'effective', which means the voids start to interconnect to each other, letting water pass through the entire layer.

The relationship between rainfall and subgrade moisture content is much less clear. The amount of rainfall does influence the moisture content, but, although some data have shown a strong influence (Dawson, 2009), other studies have indicated an almost negligible effect (e.g. Erlingsson *et al.*, 2002). Furthermore, the time delay between the precipitation event and the consequent subgrade moisture content increase is not always the same, but can vary from an almost immediate effect to a delay of up to a month. This is because the soil, the road surface, the drainage and the surrounding conditions can all strongly affect the response of the road to rainfall.

When rainfall water reaches the unbound subgrade, destabilisation can take place if the drainage system is not able to remove it quickly, especially in cohesive soil. Drainage can be inadequate and, hence, ineffective during high intensity rainfall (whose frequency is expected to increase). The presence of cracks in the asphalt means that water is able to reach the subgrade even if the asphalt is almost impermeable. As an example of the consequences that can occur, reference is made to Heck *et al.* (1998) who modelled the response of a typical pavement at different water contents, and found that an increase of moisture content from 2·3 to 4·8% led to an increase of the critical strains in the pavement by about 60%.

A rise in mean sea level and a probable increase of rainfall might change the groundwater level (Hall and Rao, 1999) and, if this is too shallow, it could also reduce the strength of the soil beneath the road. The effect of the change in groundwater level is not very clear even from the available field data (Lenart, 2008; Simonsen *et al.*, 1997) concerning the subgrade's lower layers.

Continuous subzero temperatures during winter deliver strong, frozen, roads whereas in locations where the temperature hovers daily around 0°C during the winter, daily or multi-daily thawing can take place, with a consequent temporary loss of strength of the road, and the need for traffic and axle weight limits (Bullock *et al.*, 1998). It is generally recognised that moisture content-related problems in cold regions, including thawing problems, are the main cause of pavement failure. St-Laurent *et al.* (1995) evaluated the relative damage caused by a given load when a seasonally frozen road thawed during springtime. They reported a damage factor of 1·5 to three times relative to the average annual damage.

Two assessments of the impact of climate change on roads and the development of plans to address the possible problems that will arise on a national scale have been performed in Australia (Austroads, 2004; Kinsella and McGuire, 2005).

Transit New Zealand (Kinsella and McGuire, 2005) identified the most vulnerable assets and analysed them in terms of the necessity to act during the present in order to manage future potential related problems. Austroads' analysis (Austroads, 2004) of climate change impact stressed the importance of population and settlement patterns (especially with regard to the highest concentration of population in relation to climate changes) and the consequent change in road transport demand.

2. Climate change projections for variables affecting road networks in Europe

Climate change projections are presented herein for those climate variables which are considered the most likely to affect the long-term performance of road networks in Europe.

2.1 Global models

Data from two global climate simulation models, the Hadley Centre HadAM3H – HAD (Gordon *et al.*, 2000) and Max-Planck Institute ECHAM4/OPYC3-MPI, were used to drive the numerical regional climate model RCAO (Rockner *et al.*, 1999).

The global climate models were first run from 1860 to 1990 using observed or estimated changes in atmospheric composition. From

1990 on, the calculations were continued until 2100 as two separate simulations, using the A2 scenario (higher greenhouse gas emission) and B2 scenario (lower greenhouse gas emission) as defined by the IPCC (Nakićenović *et al.*, 2000; Solomon *et al.*, 2007).

In order to drive the regional climate model, 30-year periods from both the HadAM3H and MPI/ECHAM4/OPYC3 simulations, namely the 'control run' (January 1961 to December 1990), and the 'scenario run' (January 2071 to December 2100) were used. The inherent variability in weather from year to year masks climate change-induced effects over any period much shorter than 30 years.

Daily values were used for maximum and minimum temperatures, whereas in the case of precipitation and instantaneous temperature the data used had a 6 h resolution.

2.2 Results of the global change projection

A map of the simulated changes was produced at the Department of Physics/University of Helsinki (Makkonen *et al.*, 2010). The greatest expected rise in the annual maximum temperature (Figure 1) is observed in Central Europe; France, the southern parts of Germany, northern Italy and the Balkan region, being 5 to 10°C. In western Europe the change is greater than in eastern Europe. In the Mediterranean region and the southern parts of the UK the change is not so extreme: 4 to 8°C. In northern Europe, in the northern parts of the UK and Ireland the change is limited to 1 to 6°C.

A change in the annual number of cases when the temperature crosses the freezing point of zero degrees is evident for the whole of Europe. This variable is calculated from the 6 h temperature data. The relative change in this variable is therefore quite significant in the way that it leads to an increase or decrease in the number of freeze–thaw cycles.

The change in annual precipitation is different for northern and southern Europe (Figure 2). The projected changes represent a very significant relative change, up to 50% increase in north-eastern Europe and as much as 30% less in the south.

The 30-year annual global mean warming predicted by HadAM3H from 1961–1990 to 2071–2100 is 3·2°C for the A2 scenario of higher greenhouse gas emission and 2·3°C for the B2 scenario of lower greenhouse gas emission. The corresponding warming predicted by ECHAM4/OPYC3-MPI is 3·4°C in the scenario of higher greenhouse gas emission and 2·6°C for lower greenhouse gas emission. These values are in the mid-range of the uncertainty interval reported by Meehl *et al.* (2007). Taking into account a wider range of emission scenarios, model-specific climate sensitivities and uncertainties in the carbon cycle, they projected a global warming of 1·1 to 6·4°C from 1990 to 2095.

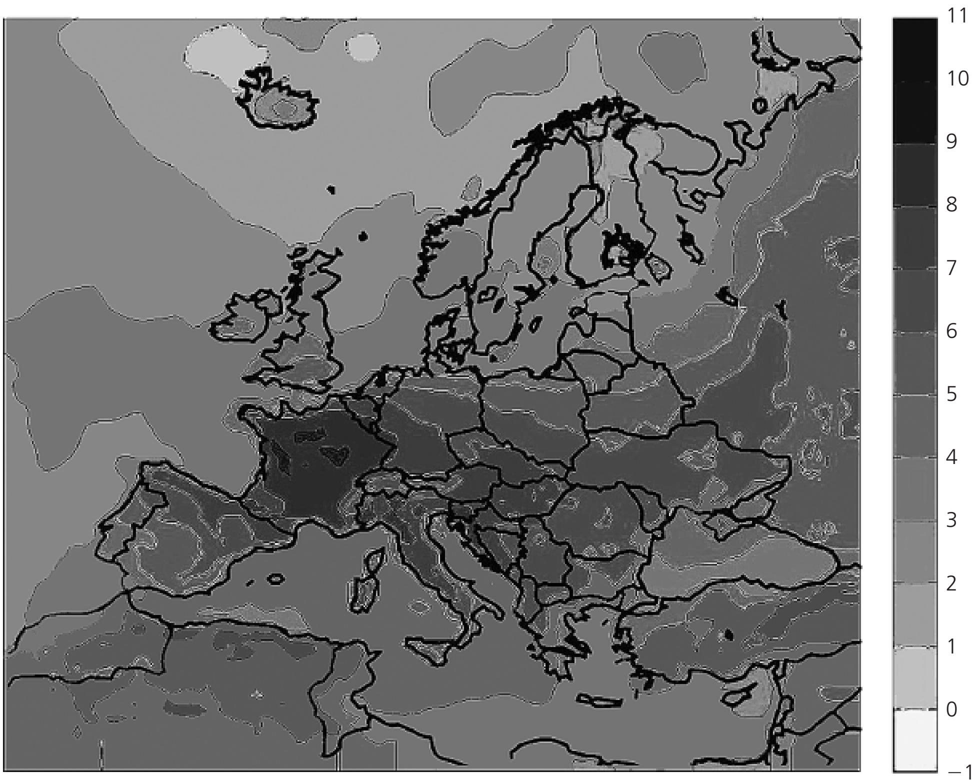


Figure 1. Expected change in the annual maximum air temperature (°C)

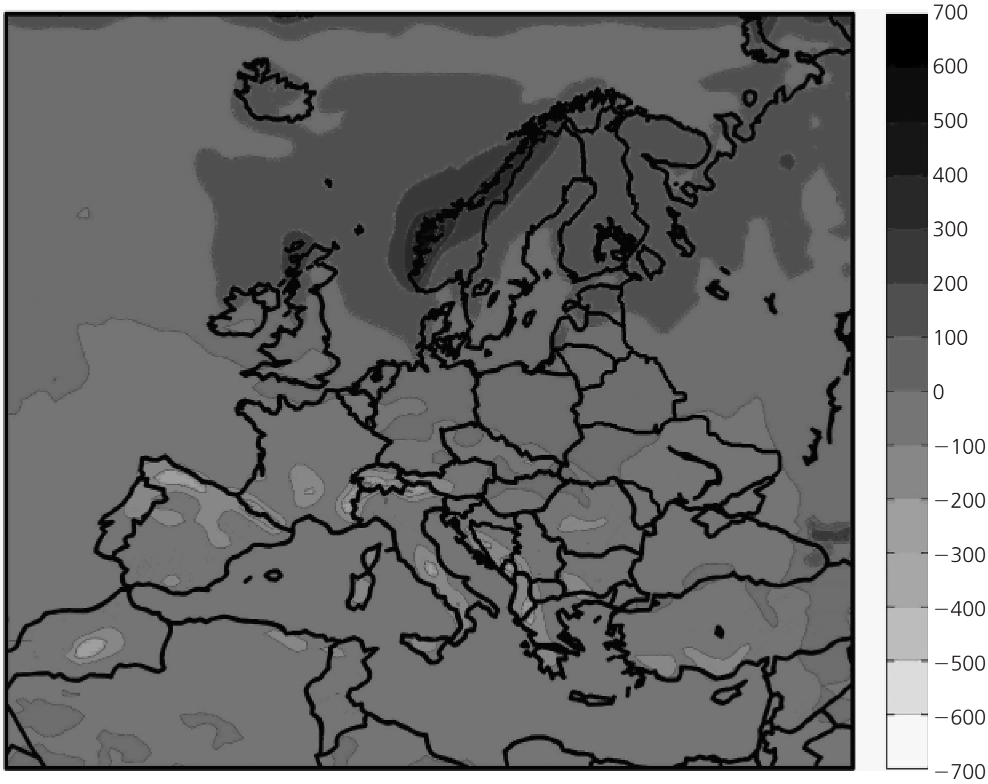


Figure 2. Expected change in the annual precipitation (mm/year)

3. Analysis of pavement structural performance for the future climate

Pavement performance is related to climate. The most direct influence occurs in the case of the resistance to rutting of bituminous materials or being dependent on temperature. In the case of unbound materials the decrease in resilient stiffness (from which it derives load distribution capability) and resistance to permanent deformations due to increasing water content is the most important (Bandyopadhyay and Frantzen, 1983).

However, it is not easy to predict how such effects can be transferred to the reduction in pavement life. A few models have been proposed, each with emphasis on different parts of the problem. In the case of the analyses considered herein a mechanical-empirical model was used. Three different pavement structures were kept constant for all types of climate except for the binder stiffness of the top layer. The binder stiffness was adjusted on the basis of temperature in order to determine the damage effects under the current climate at each location. The ME-PDG software was used for the analyses (AASHTO, 2008). Subsequently, the pavement structure was re-analysed for the new climate.

3.1 Structure and data of the model

The assumed traffic volumes are shown in Table 1. The high-volume road was assumed to have an annual average daily traffic flow (AADT) equal to 15 000, including 10% heavy vehicles (AADT heavy), and is a two-lane road. This traffic load is not very high but higher volumes would normally require more lanes in order to distribute the traffic, so that the actual number of vehicles per lane would usually not increase very much.

Traffic group	Description	AADT	AADT (heavy)
A	Low-volume road	2000	200
B	High-volume road	15 000	1500

AADT, annual average daily traffic.

Table 1. Analysed traffic volumes

The analysed structures are shown in Table 2. Binders which are in normal use today were selected to fit the current climate at the place where they are in use. Table 3 shows the selected binder types used in the analyses. The binders are characterised by the SHRP Performance Grade system, with the highest and lowest functional temperature. For example, 64–32 means a binder that will work well between +64°C and +32°C.

For the calculations climatic data relating to at least two years have been used. A few climatic files for Norway were used in the analyses. For the rest of Europe it was not possible to find already

Structure	Traffic group	Asphalt thickness: cm	Granular base layer thickness: cm	Base/soil stiffness (E measured in MPa)
1	A	5	25 (strong)	Sand, E = 168
2	A	15	25 (weak)	Silty, E = 63
3	B	36	25 (moderate)	Sand, E = 168

Table 2. Analysed structures

Structure	Šibenik	Madrid	Warsaw	Trondheim	Lyon	Rovaniemi
1	64–28	64–28	58–34	58–34	64–28	58–34
2	58–10	58–10	52–34	52–28	58–10	52–28
3	58–10	58–10	52–28	52–28	58–22	52–28

Table 3. Asphalt binder properties

prepared files. It is possible to generate the files from available climatic data, but for the purpose of these analyses the US database (Table 4) was used for locations with similar climatic conditions to the selected European sites (Table 5). It was possible to find a location with reasonably similar conditions for all of the sites (see www.weatherbase.com/weather).

3.2 Temperature increase and change in precipitation

As expected, temperature increase results in an increase in rutting and cracking. The different types of predicted damage did not change dramatically, and the largest increase in damage (31·5%) was found in the case of the highest increase in temperature of 9% (Table 6). The numbers in the tables represent the percentage

Location	Mean annual temperature: °C	Mean annual precipitation: mm	Similar US location
Šibenik, Croatia	15·8	806	Seattle, Washington
Madrid, Spain	14	438	Sacramento, California
Warsaw, Poland	8	495	Bozeman, Montana
Trondheim, Norway	5·3	892	N/A
Lyon, France	18·6	732	Lewiston, California
Rovaniemi, Finland	0	534	Anchorage, Alaska

Table 4. Climatic regions used in the analyses

Location	Mean annual temperature: °C	Mean annual precipitation	Precipitation relative to today: %
Šibenik, Croatia	+7	−200	−25
Madrid, Spain	+5	−100	−23
Warsaw, Poland	+5	+100	+20
Trondheim, Norway	+2	+200	+22
Lyon, France	+9	−100	−14
Rovaniemi, Finland	+2	+100	+19

Table 5. Climatic change used in the analyses

Location	Šibenik	Madrid	Warsaw	Trondheim	Paris/Lyon	Rovaniemi
Temperature increase: °C	+7	+5	+5	+2	+9	+2
Terminal IRI (longitudinal roughness index)	+0·5	+1·6	−2·7	+0·2	+2·6	−1·5
Asphalt top down cracking (long. cracking)	+243	+52·4	+51·4	+43·9	+86·6	+45·1
Asphalt bottom up cracking (alligator cracking)	+100	+33·3	+33·3	+20·0	+66·7	+14·3
Asphalt thermal fracture (transverse cracking)	0	0	−99·3	0	0	−87·6
Permanent deformation (asphalt)	+100	+43·8	+42·9	+20·0	+82·4	+16·7
Permanent deformation (total pavement)	+20·5	+17·3	+16·0	+2·7	+31·5	+5·1

Table 6. Summary of road distress as predicted from change in temperature for structure type 3 (% increase)

changes in the amount of distress due to the predicted change in climate.

In the next calculations increased precipitation was taken into account. It is well known that an increase in moisture content for an unbound granular material in a base or sub-base layer will decrease the resilient modulus and the strength against permanent deformation (Dawson, 1999). How important this effect is will vary greatly between different materials and conditions. Generally a material containing a lot of fines will be more susceptible to increased water content. If the road is built with materials that are relatively open graded, without too many fines (⩽ 8 %), the performance is not so badly affected. However, for cases in which the asphalt is already cracked, or the ditches and drainage system are not working as they should be or if the base and sub-base materials are full of fines and very water-susceptible, then an increase (or decrease) in precipitation could make a big difference.

Thus, for thick structures that are well built and well maintained, the effects of rainfall change may be relatively small, whereas it will not be easy to predict the behaviour of other types of roads. Many of them are low-traffic roads and resources for investigations of condition, structure and material moisture sensitivity are not usually available. However, in a future climate with increased rainfall new maintenance strategies should be considered for this type of road. The more rain, the more profitable it will be to keep a good watertight ‘roof’ and efficiently working drainage.

The few calculations that were performed for Warsaw, Trondheim and Rovaniemi (Table 7) showed the highest predicted increase in rainfall. The increase in precipitation was about 20%. This will lead to an increase in moisture content in the unbound granular layers and subgrade, thus reducing the resilient modulus and resistance against permanent deformation.

In the case of locations with a predicted decrease in precipitation, drying out of the unbound layers and of the subsoil could be expected to some extent, and thus increased stiffness and a reduction in permanent deformation can be anticipated. However, this effect has not been calculated as it fell outside the scope of this project.

Longitudinal roughness (IRI) is very little affected by global warming (Tables 6 and 7). The modelling shows changes of only a few percent (from −2·7 to +2·6%), with improvements in some cases. It is likely that increased rainfall could increase roughness even if the results of these analyses do not show a significant change in IRI. Local differences in drainage conditions or water susceptibility in materials could lead to damage that would increase roughness.

Bottom-up cracking is affected very little by increase of precipitation. Even if the percentage change is very large (19–22%), the change in bottom-up cracking is small (14–33%) when compared with the changes due to temperature (Table 6).

Performance criteria	Warsaw	Trondheim	Rovaniemi
Precipitation increase: %	+20	+22	+19
Terminal IRI	+2·4	+2·5	+2·1
Asphalt top down cracking (long. cracking)	+38·4	+3·6	+8·9
Asphalt bottom up cracking (alligator cracking)	+33·3	+20	+14·3
Asphalt thermal fracture (transverse cracking)	0	0	0
Permanent deformation (asphalt only)	−7·1	0	0
Permanent deformation (total pavement)	+14·0	+16·2	+12·8

Table 7. Summary of road distress predicted from change in precipitation for structure type 3 (% increase)

Thermal fracture occurs at low temperatures when the temperature drops rapidly. It is closely associated with binder stiffness. If the chosen binder is not flexible enough the characteristic cracks will develop. The cracks are seen across the width of the road and are often evenly spaced (10–20 m). For the calculations performed in the present study, the increase in temperature would eliminate this problem for the locations that have low temperatures.

Permanent deformation in asphalt is very dependent on temperature. Thus, as expected, the largest increase in permanent deformation is found in the case of the highest increase in temperature. Deformation is closely connected to binder stiffness. If the stiffness is increased by one temperature class the calculated deformation decreases quite significantly.

In the case of increased temperature, practically all the increase in total pavement deformations comes from the asphalt layers. This is as expected since there is very little temperature dependency in unbound granular materials. The small increase that is found in these layers results from the reduced stiffness in the asphalt causing an increase in the stress in the unbound layers.

In the case of increased water content the permanent deformation comes from the unbound layers. This is reasonable as experience and the results of many laboratory experiments have shown that resistance to permanent deformation decreases as more water is added (Dawson, 2009). The calculations that have been performed here are very simple, thus the calculated values could only be used as an indication about what can be expected under future climates.

4. Pavement response to rainfall changes using numerical models

The climate change projections described earlier have shown that, whereas in southern Europe there will be a decrease in rainfall of up to 30%, on average central Europe will not experience any considerable change in the annual precipitation compared to 2014 levels, whereas northern Europe will see an increase of between 100 and 200 mm/year on average, with peaks of 400 mm/year on the coast of Norway (Figure 2).

Projections made by the IPCC have shown that the increase in rainfall will be higher in winter than in summer. Northern Europe will most likely witness an increase in rainfall of about 20% during the winter, but only 10% during summer; in central Europe, about 10% during winter and no change in rainfall in comparison with the present situation during summer. IPCC also predicts an increase in heavy precipitation events, especially 'extreme events' such as storms and surges, with a consequent increase in the risk of flooding.

The pavement subsurface hydrology was simulated for present and predicted future conditions using a simplified model. In addition, different ways of dealing with the presence of water in the sub-base and practical ways to reduce water infiltration into the sub-base were simulated.

4.1 Description of the models

The simulation was performed using Modflow-Surfact, a three-dimensional (3D) finite-difference groundwater flow and contaminant transport program. This program was chosen because it allows, among other things, the simulation of water movement in an unsaturated soil, as well as de-saturation and re-saturation processes. Groundwater Vistas, a software package for 3D groundwater flow modelling, calibration and optimisation using the Modflow codes, was used as a graphical interface. The simulated period was equal to one year, which is considered to be enough to observe a steady situation. It should be noticed that evapo-transpiration was not considered, so that even after dry periods the simulations show that water can still be found close to the surface.

4.1.1 Modelling of the materials

The structure of the road was simplified for the simulations, as climate change predictions include some uncertainties which have been described in Section 2.2, a very precise model is not needed in this case. The aim of the model is to predict the global behaviour of road structures as influenced by climate change. The subgrade and the surrounding soil were considered to be either clay or sand, which are the most typical materials of the subgrade. The base was chosen to be an unbound material, with a relatively low permeability relative to a clean, freshly crushed aggregate, in order to simulate an unbound sub-base aggregate which, after a few years, gets mixed with fine debris, as is usually the case.

The asphalt surface and the asphaltic base were considered to be just one material. Finally, a drainage aggregate was considered for use at the side of the roads as a lateral drain, or as a substitute for the unbound sub-base aggregate to create a subdrainage layer. Each material in the simulation was described by the parameters presented in Table 8.

The values of hydraulic conductivity were taken from Dawson (2009). The values for porosity were found mostly in Boothroyd (2008). The storage coefficient was considered equal to the specific yield as the simulated aquifer was always unconfined. The Van Genuchten parameter values for the clay, the sandy material and the draining aggregate were taken from Carsel and Parrish (1988), whereas the values of specific yield were taken from Johnson (1967).

4.1.2 Modelling of the different types of roads

Pavements are 3D structures. However, on level ground, there is a large degree of symmetry in the longitudinal direction, so that two-dimensional (2D) cross-sections of the pavement can provide a reasonably reliable geometrical description of the whole pavement. For this reason, 2D numerical simulations were performed

Material	Hydraulic conductivity: mm/s	Storage / porosity		Van Genuchten values		
		Storage coefficient and specific yield	Porosity θ_s	α (1/mm)	β	θ_r
Clay (subgrade)	0·0001	0·04	0·5	0·0008	1·2	0·068
Sandy mat (subgrade)	0·008	0·21	0·43	0·0147	2·68	0·045
Sub-base	0·01	0·25	0·33	0·0063	1·3	0·06
Draining aggregate	1	0·22	0·4	0·0058	1·27	0·005
Asphalt	—	—	—	—	—	—
Porous asphalt	1	0·2	0·2	0·01	2	0·1

α, inverse characteristic length of the soil pores; β, degree if pore-size uniformity; θ_r, residual saturation.

Table 8. Values used to describe the parameters of the materials used in the model

using cross-sections of typical pavement substructures. As the pavement cross-section is symmetric, only half of the structure was modelled.

Three models of roads were simulated: a typical European highly trafficked road (Figure 3), a road surfaced with porous asphalt (Figure 4) and a highly cracked road (Figure 5). The design of the roads was based mostly on answers given by the transport departments of the European countries to a questionnaire sent out by the members of project (Dawson, 2009).

The initial design is described in the following paragraphs, although some modifications of the models and of the subsoil were implemented in order to study different cases. The

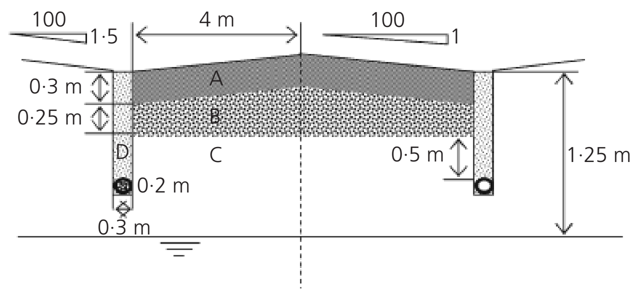


Figure 3. Structure of the high-volume traffic road

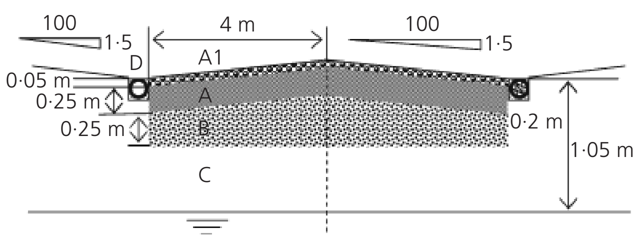


Figure 4. Structure of the porous asphalt road

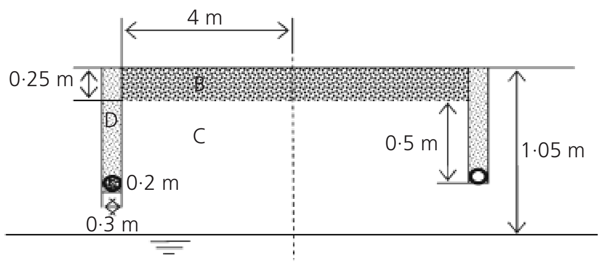


Figure 5. Structure of the heavily cracked road

surrounding soil was considered in almost all cases to be clayey, in order to obtain conservative results. A sandy soil drains quickly, and thus represents a much smaller challenge to the pavement drainage system. The technical characteristics are presented in Table 9.

4.1.3 Modelling of the rainfall patterns

Typical rainfall patterns in Europe were first studied; a mean yearly rainfall of 800 mm/year was adopted as typical.

In order to calculate its distribution, the average number of days per year with more than 0·1 mm of rainfall was taken for each country (see http://www.climatetemp.info/), and a mean European value of 170·8 d of rain per year was found. This corresponded to 46·8% of the year, meaning that it rained every 2·13 d. Taking into account a rainfall of 800 mm/year meant that, on average 4·68 mm of rain fell every time it rained.

The aim of the first simulations was to see how the designed roads responded to different rainfall intensities. The models were therefore run simulating a rainfall of 4·68 mm each 2·13 d, in the first case falling within 1 h, and in the second case falling within 6 h (Table 10).

Rainfall intensity was classified as (Met Office, 2007)

Characteristics	Model 1 Highly traffic motorway	Model 2 Porous asphalt road	Model 3 Heavily cracked road
Thickness of asphalt (surface + base): mm	300	300	
Thickness of unbound base: mm	250–300	250–310	250
Thickness surface porous asphalt: mm		50	
Thickness asphaltic base: mm		250	
Drainage pipe	At 1150 mm depth (500 mm from the bottom of the sub-base)	On the surface	At 1150 mm depth (500 mm from the bottom of the sub-base)
Road surface slope: %	1	1·5	None
Subsoil	Clay	Clay	Clay

Table 9. Characteristics of the road structures

	Rainfall intensity: mm/h	Frequency: d	Duration: h
Case 1	4·68	2·13	1
Case 2	4·68	2·13	6
Case 3	9·36	4·30	1
Case 4	50·00	15·00	1

Table 10. Rainfall patterns

- light rain, when the precipitation rate is < 2·5 mm/h
- moderate rain, when the precipitation rate is between 2·5 and 10 mm/h
- heavy rain, when the precipitation rate is between 10 and 50 mm/h
- violent rain, when the precipitation rate is > 50 mm/h.

Therefore, the first case can be considered a moderate rain, and the second case is a light rain.

An extreme case was also studied, simulating rainfall events that were double the above amounts of rain. The pattern was thus of 9·36 mm/h rainfalls for the duration of 1 h, but every 4·3 d (case 3). A final rainfall pattern (case 4) was characterised as violent rain (50 mm in 1 h) following a long period of dry weather (15 d).

For these pavements, the initial ground water table was at a depth of 1·05–1·25 m below the pavement edge level; that is, between 0·2 and 0·5 m below the bottom of the drains (Figures 3–5). Finally, a high water table analysis was simulated with the water table just below the drainage system, as it may be more probable in the future as the risk of floods increases, a problem that will likely become more and more common, especially in coastal roads.

4.2 Results of modelling for rainfall changes

4.2.1 Model 1: high-volume traffic road

The subgrade was considered to be clay and, as the asphalt was considered to be impermeable, the asphaltic surface and base were defined as no-flow areas. The rainfall that could not infiltrate into this area, namely the runoff water, was simulated as extra rainfall falling above the lateral drain.

In the case of rainfall patterns 1 and 2 not much difference can be seen for the sub-base (Figure 6). In both cases it performed well, as the saturation never increases excessively, not even when the surrounding clay is completely saturated and there is a rather high flow of water from the clay into the lateral drain, which then infiltrates into the sub-base. Also, the simulation of violent rainfall pattern no. 4 showed a sub-base that kept an acceptable level of saturation.

4.2.2 Model 2: porous asphalt road

As in the case of high-volume traffic roads, porous asphalt performs well with different rainfall patterns. Water does not seem to accumulate on top of the road surface, and it maintains itself below saturation level.

A more intense rainfall pattern (case 3) shows only a slight increase in the saturation level in the porous asphaltic layer on the sides of the road, but saturation does not reach the surface, whereas the sub-base does not show any remarkable increase in the saturation level (Figure 7).

It should be noted that, in the case of porous asphalt, the presence

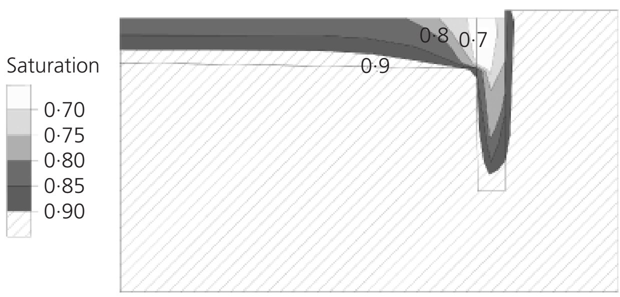


Figure 6. Saturation levels after rainfall, rainfall pattern 1

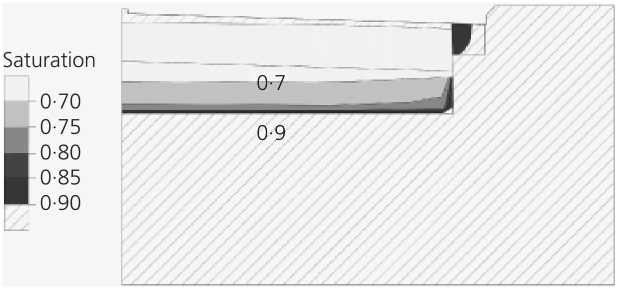


Figure 7. Saturation levels after rainfall and a dry period, rainfall pattern 3

of a subsurface drainage system below the level of the sub-base does not seem to be necessary, although its presence would help keep the aggregate drier.

The problem of a high level of saturation in the sub-base appears in the presence of a high water table (even though this water table level is, initially, just beneath the drain level). In this case, independently of the amount of rain falling, the saturation of the sub-base becomes rather high. However, the sub-base works as a barrier, not allowing water to reach the asphaltic layers.

4.2.3 Model 4: Heavily cracked road

Due to difficulties in simulating a heavily fractured asphalt surface properly, all the rainfall was assumed to penetrate directly into the pavement structure. This simplification, however, allows a conservative estimate of the real situation. In this case, no surface drain is present as the simulation involves subsurface layers only. Furthermore, in this case the presence of a low permeability soil surrounding the structure can be considerably more harmful than a high permeability soil as it prevents lateral drainage.

The situation deteriorates even more in the case of heavy rainfall periods (Figure 8). The simulation of such events shows that the sub-base is almost always above 80% saturation, and again, it is likely to be even higher due to the large amount of runoff water that cannot be simulated properly. The high saturation of the sub-base has been confirmed by moisture measurements in several different test installations (Dawson, 2009; Fifer Bizjak, 2010). It should be noted that the model shows that the high saturation level does not decrease appreciably even after a dry period of 15 d, probably due to the runoff water infiltrating only slowly into the surrounding soil.

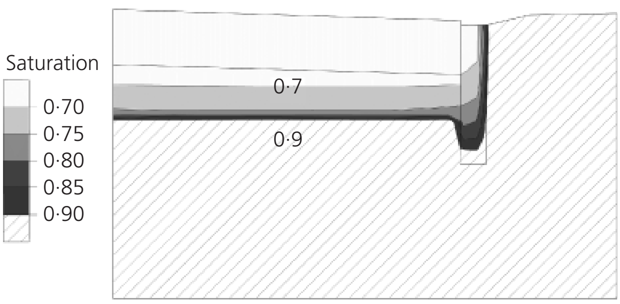


Figure 8. Saturation levels after rainfall, rainfall pattern 4

The level of saturation increases with increased or more intense, precipitation (Figure 9). From a comparison of the results it can be seen that a cracked surface becomes an issue for the stability of the sub-base, as the latter's water content increases to dangerous levels.

4.3 Predicted response of roads to rainfall changes

The simulations performed, although probably conservative in assumption, show that a well-constructed, high-volume traffic road, with a surface that does not show cracks, can handle changes in rainfall intensity and quantity quite well. This stresses the importance of taking action promptly as soon as damage appears on the surface, or even earlier. The simulations show that the presence of a surface lateral drain is, however, going to be more and more important as rainfall events are likely to be more extreme, so that a greater amount of run-off water needs to be conveyed and removed from the road surface in order to avoid flooding and/or high sub-base saturation levels.

Porous asphalt also seems to perform well even in the case of intense rainfall patterns: only a slight increase in the saturation level in the porous asphaltic layer at the sides of the road can be observed, but saturation does not reach the surface, whereas the sub-base does not show any significant increase in the saturation level. It thus seems to be a better option to try to prevent road flooding. In the case of porous asphalt, the presence of a subsurface drainage system below the level of the sub-base does not seem to be very important, although the presence of such a system does help keep the aggregate slightly drier.

An issue that is likely to become more important in the future is the presence of a high water-table below the road structure. In this case the saturation of the sub-base can reach levels that can decrease the strength of the aggregate considerably. When the

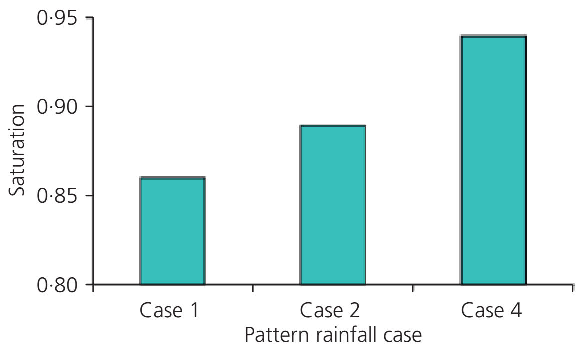


Figure 9. Saturation levels in the sub-base for rainfall pattern cases 1 to 4

water table is shallow, the saturation of the sub-base is rather high, independently of the amount of rain falling. In these cases, an impermeable geotextile placed between the sub-base and the subgrade, together with a drainage layer underneath the geotextile whose purpose is to let water flow from the subgrade into the drainage pipe, seems to give very good results. The presence of a drainage layer alone, on an incline, between the sub-base and the subgrade also helps, although the benefits are less significant.

A cracked pavement surface is an issue for the stability of the sub-base, independently of the rainfall intensity, as its water content can increase to dangerous levels, and the situation obviously deteriorates in extreme cases such as heavy rainfalls. An inclined sub-base aimed at helping the outflow of water towards the lateral drainage channel brings a slight improvement, but, as the saturation is still too high, it cannot be considered as the only precaution to be taken. A thicker layer also seems to bring some benefit, but again the difference is not very significant. Thus, a combination of a thick sub-base with an inclined bed might be more effective.

Owing to large differences in different scenarios of climate change effects, especially for temperature and precipitation, conservative input data for calculation were used.

Verification of the more detailed results of the numerical calculations would require test installations that allow measurements over long durations, under different climatic conditions.

5. Discussion

Anticipated climate change in Europe over a 110 year period from the mean climate in 1960–1990 to the mean climate in 2070–2100 was estimated using two different emission scenarios and two computational approaches. The likely impact of the resulting changes in climate was then estimated for a range of pavements and road drainage infrastructures.

The links between climate factors and pavement response have been incorporated into Table 11. It is noted that, in the case of the cracking and rutting of asphalt, solar radiation is more important than air temperature, as the former controls the pavement surface temperature to a greater degree. Climatic modelling of cloud cover was not possible within the scope of this project. However, it is surmised that higher mean temperatures will give rise to greater oceanic evaporation producing more moisture-filled atmospheres with greater cloud cover. Thus, it is possible that the effects of temperature rise, as far as asphalt embitterment are concerned, may be somewhat offset.

Implication	Where significant	Effects
Change in the annual maximum temperature	Western Central Europe	Increased rutting deformation. Expansion of joints in concrete pavements and 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, South 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 regard to the length of the fully frozen period, but positive with respect to the length of the spring thaw and the length of the 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 an increased proportion of run-off, except in localities 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, destabilisation 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 the sea	Greater risk of flooding and salt intrusion.

Table 11. Conclusions of the effects of climate change

Pavements are repaired and rehabilitated on a short time-scale in comparison with the time period over which climate changes are observable. This study has provided 30 year mean values 'before' and 'after' climate change over a 110 year span during which temperatures increase by a few degrees. Thus, if a pavement is significantly rehabilitated on a 20 year cycle with an allowance for temperature change in the next 20 years, the impact of long-term climate change should be less than the influence of the variation in weather conditions experienced in that 20 year period. Responding to the variability of actual weather conditions by the regular updating of temperature and rainfall levels in design guides will, over the next life cycle 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 carry the most traffic. Responding to these induced changes in the traffic pattern is likely to have a much greater impact on pavement maintenance and rehabilitation strategies than any small temperature or moisture change over a typical 20 year maintenance cycle.

Based on climate change there is a need to consider the following particular issues

- changes to the design parameters
- changes to the design options
- changes to the pavement material formulation.

5.1 Material response to climate change

5.1.1 Subgrade

About 80% of road distress is associated with water, directly or indirectly. In thin pavement structures different types of distress are heavily influenced by the condition of the subgrade. Thus keeping the subgrade relatively dry is important for the maintenance of pavement life (Huntington, 2007). As mentioned above, on average, except near the Atlantic coasts of Europe and in the Nordic/Baltic region, total 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 temperatures which will increase evaporation, this should lead to drier 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 are not expected to be in much worse condition that at present, as long as the road is in good condition and properly designed. The 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 strength, even if only for a short time – a likely result during the heavier rainstorms anticipated.

5.1.2 Aggregate

Capping, sub-base 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, 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, especially in cold climates.

In the most northerly parts of Europe where these layers currently experience seasonal freezing for several months, warmer 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, whereas summers will be longer. The pavement response will then be rather similar to that currently experienced by pavements some hundreds of kilometres to the south. Sound pavement design and maintenance is already available for this change as road construction practice is largely unchanged over this distance in each Nordic state. Furthermore, because these milder winters will mean less frost penetration, the need for thick coverage of subgrades with non-frost-susceptible materials will be reduced.

To the south, in many of the Nordic countries, frozen winter road structures may disappear altogether, over a period of some years. Repeated periods during the winter season when the pavement surfaces are thawing will become the norm. Spring thaw problems will likely become less problematic, but many thin and unsealed pavements will need upgrading if reliable high bearing capacity is to be provided throughout the winter as the current expectation of seasonally frozen pavement structures will not be achieved.

5.1.3 Asphalt

Standard good practice with asphalt mix design will continue to ensure low intact permeability of asphalts, which is a prerequisite for satisfactory run-off. With more water on a road surface during rainstorms, particles from the bituminous matrix are of increasing concern owing to their intensity, erosion and de-bonding ('stripping') of aggregate. This is expected to be of particular concern for countries near the Atlantic Ocean where the biggest rainfall increases are expected, as well as in central Europe, where more intense rainfall will often be associated with higher temperatures in the summer – the most damaging combination. This has implications for the thickness of bitumen film, and for polymer modification to resist de-bonding and void reduction and to reduce water entry and stripping action. Increasing the angularity of aggregates may also increase bitumen-aggregate bonding.

On the basis of the pavement analyses 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 appears to be within permissible limits. Doubtless there will be some locations where current pavement and mix designs are at the limit of permissibility, where climate change will result in excessive rutting if the mix formulations are not changed.

5.1.4 Porous asphalt

Porous asphalt is not very durable compared to conventional asphalt. Research has shown that modified binders tend to perform better than conventional binders with respect to permanent deformation for asphalt mixes with higher void contents (Kandhal and Mallick, 1999). It will therefore need replacing after a life-span which is much shorter 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 the range of locations where frost damage is experienced. Offsetting this, heavier rainfall intensity will lead to a greater tendency to stripping/de-bonding, with the concomitant formulation needs already mentioned earlier. Conversely, porous asphalt has an important role in the limiting of road flooding, and thus in maintaining traffic flows and road safety.

5.2 Drainage requirements

The simulations with numerical modelling performed show that, in general, small changes in the rainfall pattern (i.e. average intensity and duration) which are not accompanied by increases in the yearly amount of rainfall water do not significantly 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, as the sub-base saturation can increase.

In summary the following observations are presented.

- Changes in rainfall patterns will, in general, have little effect on roads in good condition, whereas increased temperatures should aid the drying of subgrades and somewhat improve pavement performance. However, extreme rainfall events are the key challenge and drainage provision will often require a change of approach in order to address these events appropriately.
- Uncracked pavement surfaces can handle changes in rainfall intensity and quantity fairly well.
- Porous asphalt surfaces are suitable for the conveyance of 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 redesign in order to handle the greater water flows that are anticipated.
- The more intense rainfall events anticipated will require that the run-off water be collected and more effectively conveyed away from the road structure. If water stays at the road edges, it is likely to generate local flooding and the backing-up of drains, causing saturation of the subgrades with consequent rapid pavement deterioration.
- At a few locations, where roads are built close to the sea at low elevations, a rise in mean sea level may be an issue, with a rise in the local water table. Low spots in an undulating topography could become more flood-prone so that, locally, water tables could rise at these locations. In such cases improved drainage may not be a possible solution, since the falls are insufficient, and raised construction of the pavement may be necessary.

6. Conclusion

The effects of climate change on pavement construction in Europe will vary, depending on the local climate conditions in each part of Europe.

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

In those countries that rely a lot on having frozen roads during winter, the length of the frozen period will be reduced, especially in the far north. To the south, in much of the Nordic countries, frozen winter road structures may disappear altogether, over a period of some years. Periods during the winter season when the pavement surfaces are thawed will become the norm. In this case many thin and unsealed pavements will need upgrading in order to be able to provide reliable high bearing capacity throughout the winter.

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

Acknowledgement

The results presented in this paper were obtained with the support of Road ERA-NET, within the scope of the project P2R2C2: Pavement Performance of Remediation Requirements following Climate Change.

REFERENCES

AASHTO (American Association of State Highway and Transportation Officials) (2008) Mechanistic-empirical pavement design guide, interim edition: a manual of practice. AASHTO, Washington, DC, USA.

Austroads (2004) *Impact of Climate Change on Road Infrastructure, Austroads Incorporated*. See https://www.onlinepublications.austroads.com.au/items/AP-R234-04 (accessed 13/02/2014).

Bandyopadhyay SS and Frantzen JA (1983) Investigation of moisture-induced variation in subgrade modulus by cross-correlation method. *Transportation Research Record* **945**: 10–15.

Boothroyd P (2008) *Groundwater Contamination in the Underground Environment*. PhD thesis, The University of Nottingham, UK.

Bullock D, Schrader C, Van Deusen D *et al.* (1998) Recent research on springtime thaw weakening and load restrictions in the state of Minnesota. *Proceedings of the 77th Annual Meeting of the Transportation Research Board, Washington, DC, USA*, Paper No. 980621.

Carsel RF and Parrish RS (1988) Developing joint probability distributions of soil water retention characteristics. *Water Resources Research* **24(5)**: 755–769.

Chen J, Lin K and Young S (2004) Effects of crack width and permeability on moistureinduced damage of pavements. *Journal of Materials in Civil Engineering* **16(3)**: 276–282.

Dawson A (2009) *Water in Road Structures – Movement, Drainage and Effects*. Geotechnical, Geological and Earthquake Engineering Series, vol. 5. Springer, Dordrecht, the Netherlands.

Dawson AR (1999) Implications of granular material characteristics on the response of different pavement constructions. *Proceedings of the Symposium on Modelling and Advanced Testing for Unbound Granular Materials*. Balkema, Rotterdam, the Netherlands, pp. 221–226.

Doré G, Droiun P, Pierre P and Desrochers P (2005) *Estimation of the Relationships of Road Deterioration to Traffic and Weather in Canada*. University Laval, Quebec, Canada, Final report, BPR reference: M61–04–07 (60ET).

Erlingsson S, Bjarnason G and Thorisson V (2002) Seasonal variation of moisture and bearing capacity in roads with a thin surface dressing wearing course. *Proceedings of the 9th International Conference on Asphalt Pavements, Copenhagen, Denmark*. ISAP, Copenhagen, Denmark, CD disc.

Fifer Bizjak K (2010) Soil wetting-drying study. Book title. Era Net, ZAG, Ljubljana, Slovenia, Report Nr 4. Project P2R2C2.

Gordon C, Cooper C, Senior CA *et al.* (2000) The simulation of SST, sea ice extent and ocean heat transport in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics* **16(2–3)**: 147–166.

Hall DK and Rao S (1999) Predicting subgrade moisture content for low-volume pavement design using in-situ moisture content data. *Transportation Research Record* **1652**: 98–107.

Heck JV, Piau JM, Gramsammer JC, Kerzreho JP and Odéon H (1998) Thermovisco-elastic modelling of pavements behaviour and comparison with experimental data from the LCPC test track. *Proceedings of the 5th Conference on Bearing Capacity of Roads and Airfields, Trondheim, Norway.*

Huntington G (2007) Gravel roads surface performance modelling. *Transportation Research Board, 86th Annual Meeting, Washington, DC, USA*.

Johnson AI (1967) *Specific Yield — Compilation of Specific Yields for Various Materials*. US GPO Washington, DC, USA, US Geological Survey Water Supply Paper: 1662-D.

Kandhal PS and Mallick RB (1999) *Design of New-Generation Open-Graded Friction Course*. National Center for Asphalt Technology of Auburn University, Auburn, AL, USA.

Kinsella Y and McGuire F (2005) *Climate Change Uncertainty and the State Highway Network: a Moving Target*. Transit New Zealand, Auckland, New Zealand.

Kringos N and Scarpas A (2005) Raveling of asphaltic mixes due to water damage: computational identification of controlling parameters. *Transportation Research Record* **1929**: 79–87.

Lavin P (2003) *Asphalt Pavements: A Practical Guide to Design, Production, and Maintenance for Engineers and Architects*. Spon, London, UK.

Lenart S (2008) Odziv zasičenih zemljin na dinamično obremenitev. [The response of saturated soils to a dynamic load.] *Acta Geotechnica Slovenica* **5(1)**: 36–49 (in Slovenian).

Makkonen L, Törnqvist J, Ylhäisi J and Jouni R (2010) *Report No. 6 –Climate Change Projectors for Variables Affecting Road Networks in Europe*. Era-Net, Helsinki, Finland. Internal report P2R2C2.

Meehl GA, Stocker TF, Collins WD *et al.* (2007) Global climate projections. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, pp. 747–845.

Met Office (2007) *Fact Sheet No. 3: Water in the Atmosphere*. Met Office, London, UK. See http://www.metoffice.gov.uk/media/pdf/f/c/Fact_sheet_No.3.pdf (accessed 13/02/2014).

Nakićenović N, Alcamo J, Davis G *et al.* (2000) *Emission Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, IPCC*. Cambridge University Press. See http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm (accessed 13/02/2014).

Pachauri RK and Reisinger A (2004) *Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Geneva, Switzerland.

Rockner E, Bengtsson L, Feichter J, Lelieved J and Rodhe H (1999) Transient climate change simulations with a coupled atmosphere-ocean GCM including the tropospheric sulfur cycle. *Journal of Climatology* **12(12)**: 3004–3032.

Simonsen E, Janoo VC and Isacsson U (1997) Prediction of temperature and moisture changes in pavement structures. *Journal of Cold Regions Engineering* **11(4)**: 291–307.

Solomon S, Qin D, Manning M *et al.* (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change*. IPCC, Cambridge University Press, Cambridge, UK.

St-Laurent D, Roy M and Bergeron G (1995) Variations saisonnières de la portance des chaussées: une étude au FWD. *Proceeding of the 30th Annual Conference of AQTR, Hull, Quebec, Canada*, pp. 52–73 (in French).

Watson DK and Rajapakse RKND (2000) Seasonal variation in material properties of a flexible pavement. *Canadian Journal of Civil Engineering* **27(1)**: 44–54.

Wilford F and Fraser S (2011) Local and regional climate change research. *Proceedings of the Institution of Civil Engineers – Transport* **164(3)**: 199–206.

Zuo G, Drumm EC and Meier RW (2007) Environmental effects on the predicted service life of flexible pavements. *Journal of Transportation Engineering, ASCE* **133(1)**: 47–56.