P2R2C2

Analysis of pavement structural performance for future climate

Report No. 7

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Project Coordinator
University of Nottingham, UK

ZAG, Slovenia

VTT, Finland

SINTEF, Norway

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Analysis of pavement structural performance

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Author(s) this deliverable:

Inge Hoff, SINTEF, Norway

Anne Lalagüe, SINTEF, Norway

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Executive summary

Pavement performance is related to the climate. The most direct influence is resistance to rutting in bituminous materials depending on the temperature. For the unbound materials the decrease in resilient stiffness (load distribution capability) and resistance to permanent deformations for increasing water content is most important.

However to predict how this is transferred to reduction in pavement life is not straightforward to do. A few models have been proposed with emphasis on different parts of the problem. The ME-PDG (Mechanistic-Empirical Pavement Design Guide) developed in USA have included the climatic influence in the analyses in a quite thorough way. This tool was selected for use in this project. The program has been developed and calibrated for US conditions but is still considered to be useful for the comparative study performed in this project.

The analyses show a moderate decline in pavement lifetime for rutting and cracking due to increased temperature. For increase in precipitation the analyses does not show significant decrease in pavement lifetime.

According to the analyses the negative effect of increased temperature could be mitigated with minor adjustments to the mix design i.e. stiffer binders in areas with increased summer temperatures. Since it is likely that some winters will be cold, even if the average temperature increase, the low temperature properties of the bitumen should be conserved. This means that modified binders will be required for more roads. This will cause the cost both for construction and resurfacing to increase.

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1 Background

If climate change follows the scenarios that have been developed, it is possible that some existing roads today will face climatic scenarios somewhat different from those they were designed for. Therefore, prudent planners and policymakers need to know what possibilities are available to them for rehabilitation and new construction.

The climatic scenarios predict increased temperatures in varying degree for most of Europe. The amount of rainfall is also predicted to change with some areas getting less rain and some areas more. Both these factors are included in the performance prediction tool M-EPDG that has been developed in the USA (NCHRP 2010).

In this report the results of analyses of three different types of structures exposed to current and future climate for five different areas are presented. This is obviously not an attempt to test all types of structures for all types of climate and climate change, but rather an example of the type of calculations that could be performed for a real case.

2 Analysis

The purpose with these analyses is to calculate the effect of climatic change. The main idea is to design a structure that performs reasonably well under current conditions but with some predicted damage and to study the effect of predicted climatic change.

The three different structures were kept constant for all types of climate except for the binder stiffness of the top layer. The binder stiffness was adjusted to get reasonable damages for the current climate at each location.

2.1 How to use M-EPDG for analyses of performance due to climate change

The M-EPDG is not directly a design method. The guide will predict the performance of a given structure and based on this you can adjust your structure until you find a design that gives you satisfactory performance for an acceptable price.

The program has three levels of analysing the structure depending on how much information you have available for the structure that you want to analyse. In this project we did not want to analyse a specific road section but rather wanted to assess the influence of climate change in general. For this purpose the level 3 (lowest degree of details) have been used. The analyses method has followed the following steps:

- Establish a representative climatic file (.icm) for the location that is to be studied. This could be done from recorded climatic data at the location or by finding a US location with similar climate. Both these methods were used in these analyses.
- Define one or several typical structures for the region.
- Perform test analyses using the current climate file.
- Adjust the structure so it will give a reasonable amount of damages. The level of damaged are not so important. However, to see some differences the calculations should show some damages but not excessive.
- Import the climatic file (.icm) to a spreadsheet e.g. MS Excel and change the temperature (and other climate parameters) according to predicted future climate. (sorting and re-sorting of the data is necessary to do the changes)
- Analyse the structure again using the modified climatic file
- Compare the results – the change in percentage have been presented rather than the actual predicted damage

2.2 Traffic

The traffic is the primary cause for damages in the ME-PDG. The traffic volumes shown in Table 1 have been used:

The high volume road have AADT=15 000 and is a two lane road. The traffic is not extremely high but higher volumes will normally require more lanes to distribute the traffic so the actual number of vehicles per lane will normally not increase very much.

The ME-PDG has the possibility to adjust the distribution of vehicles of different types and also when the vehicles traffic the road (over the day and year). For this purpose the standard settings for the traffic were used even if the vehicles types popular in US could be a little different compared to European types.

Table 1 Analysed traffic volumes

Traffic group	Description	AADT	AADT (Heavy)
A	Low volume road	2 000	200
B	High volume road	15 000	1 500

2.3 Structures

The idea behind these analyses was to select structures that are reasonable well adapted to the current climatic conditions at the selected sites. An informal inquiry was performed to some selected contact persons in Europe to have an idea of what are the typical structures in their respective countries. In the ME-PDG the structures were adjusted to show some damage for the selected traffic volume. In most cases this was done by reducing the thickness of the asphalt layers.

The reason for this “weakening” of the roads was to better see the influence of the climatic change. If the road does not show any damage after 20 years for the current climate it is not possible to know if the climate change influence on the pavement performance.

The analysed structures are shown in Table 2

Table 2 Analysed structures

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

Binders in use today are selected to fit current climate at the place they are used. Table 3 shows selected binder types used in the analyses to give reasonable damages for current climate. The binders are characterised by the SHRP Performance Grade system (PG-grade) with highest and lowest functional temperature. e.g. 64 – 32 means a binder that will work well between +64°C and – 32°C. Some of the PG-grades used in the analyses could require modification to be able to perform in the given temperature interval.

Table 3 Asphalt binder properties

Structure	Sibenic	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

3 Base climate

The ME-PDG uses climatic files from weather stations throughout the US. We have a few climatic files for Norway that were used in the analyses. For the rest of Europe we have not been able to find already prepared files. It is possible to generate the files from available climatic data but for the purpose of these analyses it was not considered worthwhile to put the necessary effort into this. Instead we searched the US database for locations with similar climatic conditions to the selected European sites. For all the sites it was possible to find a location with reasonable similar conditions (Canty & Associates 2010). Figures 1 to 6 show temperature and precipitation if available for European locations compared to US locations.

Table 4 Climatic regions used in the analysis

Location	Mean annual temperature	Mean annual precipitation	Similar US location
Sibenic, Croatia	15.8 °C	806 mm	Seattle, Washington
Madrid, Spain	14 °C	438 mm	Sacramento, California
Warsaw, Poland	8 °C	495 mm	Bozeman, Montana
Trondheim, Norway	5.3 °C	892 mm	N/A
Lyon, France	18.6 °C	732 mm	Lewiston, California
Rovaniemi, Finland	0 °C	534 mm	Anchorage, Alaska

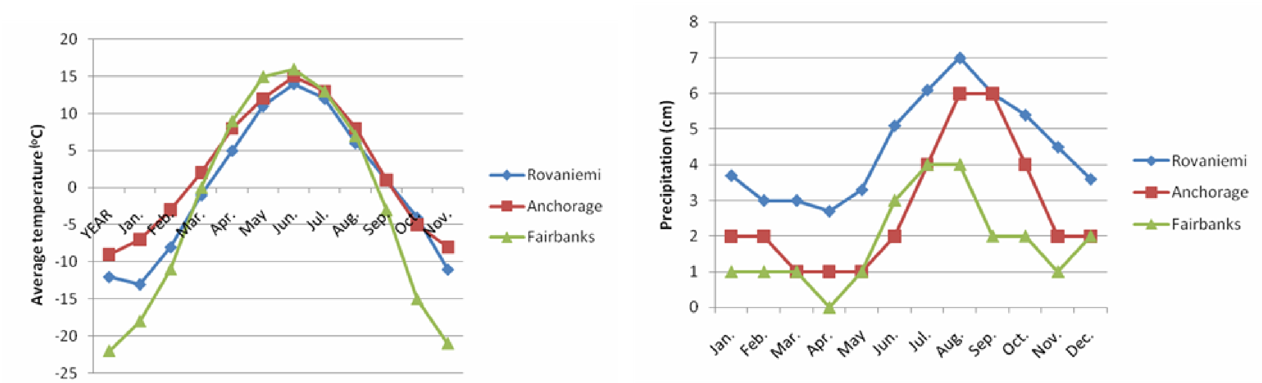

Figure 1 Comparison between climate in Rovaniemi and Anchorage (and Fairbanks)

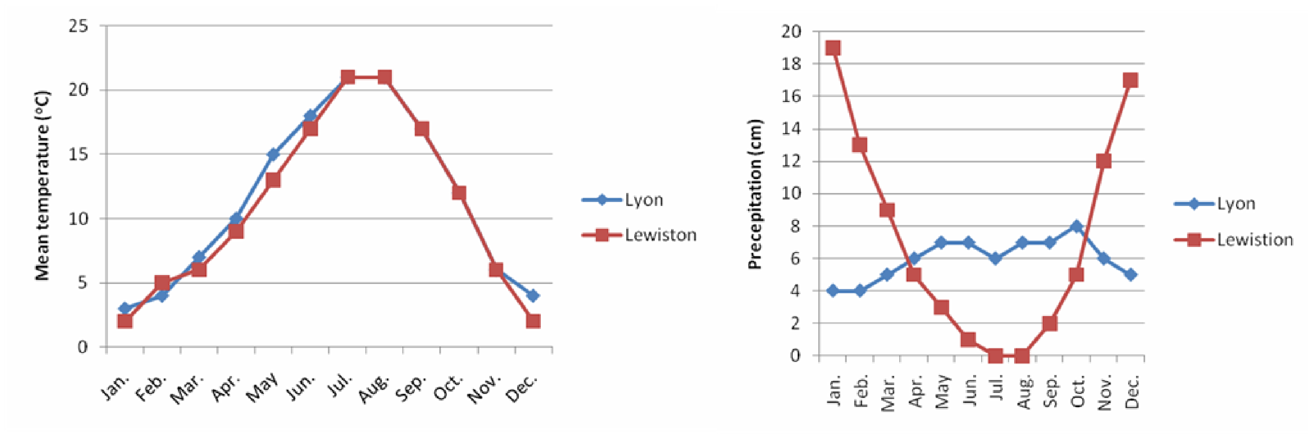

Figure 2 Comparison between climate in Lyon and Lewiston

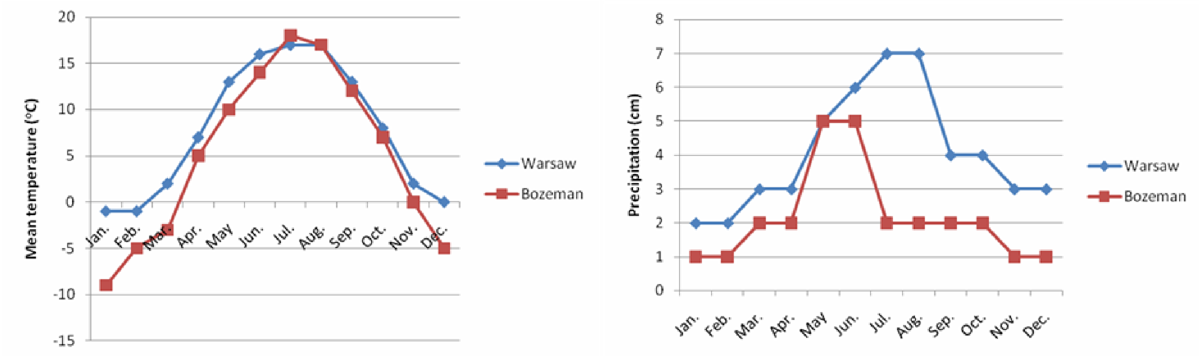

Figure 3 Comparison between climate in Warsaw and Bozeman

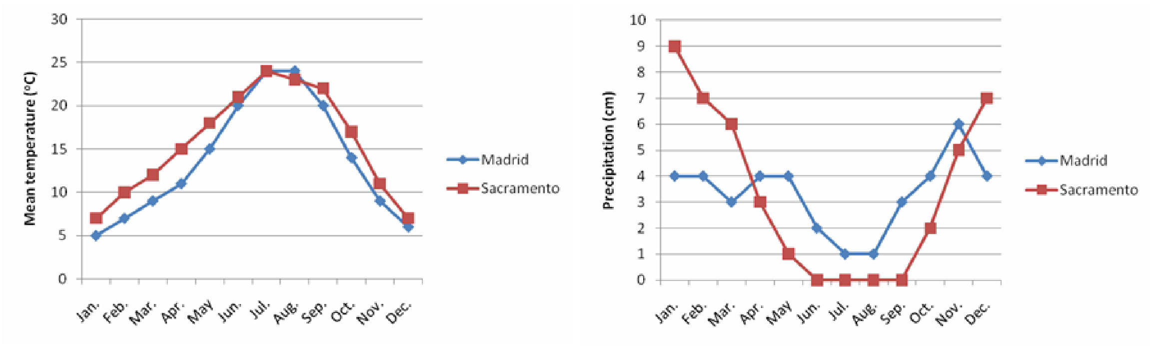

Figure 4 Comparison between climate in Madrid and Sacremento

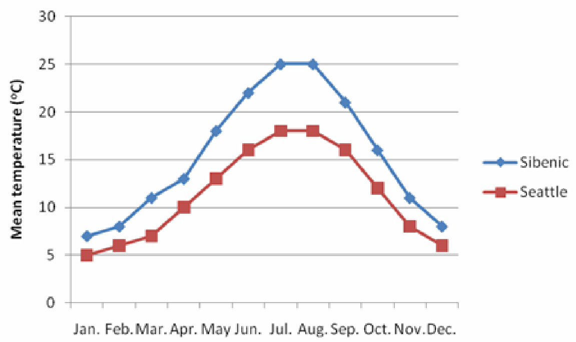

Figure 5 Comparison between temperatures in Sibenic and Seattle (precipitation was not available in the database)

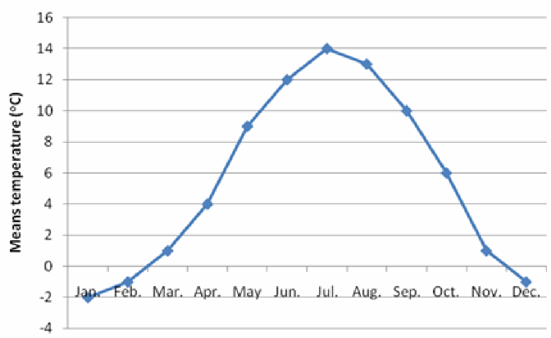

Figure 6 Temperature curve for Trondheim (data from Norwegian climate data used directly)

As can be seen from the figures above the climate is not a perfect match between the European location and the US weather stations. It was easier to find a match between temperature profiles than precipitation. If the M-EPDG is to be used for more detailed studies for an exact location one should take the effort to establish a climatic file based on local historic weather records.

4 Climate change

Several scenarios for climate change have been estimated for Europe. Since climate is very complicated to predict for future beyond a few days these scenarios are uncertain and we can not even be sure that the scenario that predicts the most severe changes is “worst case”. There are several factors that potentially could influence the performance of pavements like frost-thaw cycles. However, since the ME-PDG is most focused on temperature and moisture we have only studied these two effects in this report.

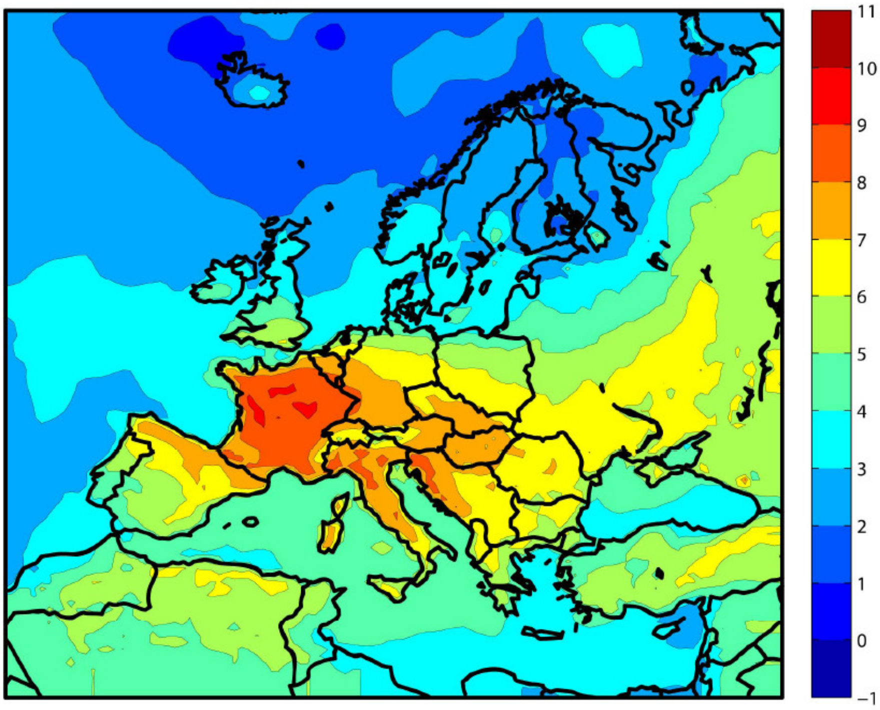

Figure 7 Change in maximum summer temperature (Makkonen, Törnqvist et al. 2010)

From the maps in Figures 7 and 8 the following climate change parameters have been determined.

Table 5 Climatic change used in the analyses

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

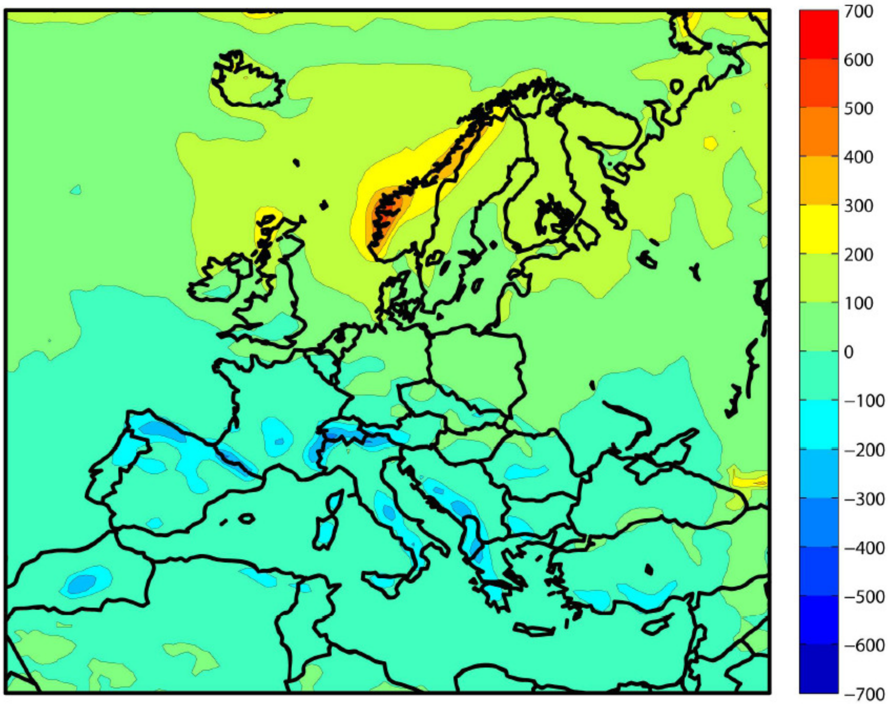

Figure 8 Change in annual precipitation (Makkonen, Törnqvist et al. 2010)

5 Results for temperature increase

Numbers in the table represent *change from current climate to predicted future in percentage*.

Table 6 Summary of Distress Predicted from change in climate for structure type 1 (% increase)

Location	Sibenic	Madrid	Warsaw	Trondheim	Paris/Lyon	Rovaniemi
Temperature increase (°C)	+7	+5	+5	+2	+9	+2
Terminal IRI	0	+1	+1,4	+0,3	+0,9	+0,4
AC Top Down Cracking (Long. Cracking)	+86,0	+43,6	+50,0	+14,9	+88,9	+20,3
AC Bottom Up Cracking (Alligator Cracking)	+50*	+20*	+25*	+33*	+40*	0
AC Thermal Fracture (Transverse Cracking)	0	0	-100	0	0	-76,7
Permanent Deformation (AC Only)	+66,7	+35,0	+32,5	+14,3	+60,0	+11,1
Permanent Deformation (Total Pavement)	+18,2	+12,1	+12,5	+2,4	+21,3	+4,5

* Change from a very small value

Table 7 Summary of Distress Predicted from change in climate for structure type 2 (% increase)

Location	Sibenic	Madrid	Warsaw	Trondheim	Paris/Lyon	Rovaniemi
Temperature increase (oC)	+7	+5	+5	+2	+9	+2
Terminal IRI	-1,3	+0,5	+0,8	-0,2	-0,2	+8,3
AC Top Down Cracking (Long. Cracking)	0	+300	+450	0	+2300	0
AC Bottom Up Cracking (Alligator Cracking)	0	0	0	0	0	0
AC Thermal Fracture (Transverse Cracking)	0	0	-99,6	-100	0	0
Permanent Deformation (AC Only)	+80	46,2	+41,7	0	+84,6	+50,0
Permanent Deformation (Total Pavement)	+28	21,4	+18,5	+5,9	+40,7	+17,6

Table 8 Summary of Distress Predicted from change in climate for structure type 3 (% increase)

Location	Sibenic	Madrid	Warsaw	Trondheim	Paris/Lyon	Rovaniemi
Temperature increase (oC)	+7	+5	+5	+2	+9	+2
Terminal IRI (in/mi)	+0,5	+1,6	-2,7	+0,2	+2,6	-1,5
AC Top Down Cracking (Long. Cracking)	+243	+52,4	+51,4	+43,9	+86,6	+45,1
AC Bottom Up Cracking (Alligator Cracking)	+100	+33,3	+33,3	+20,0	+66,7	+14,3
AC Thermal Fracture (Transverse Cracking)	0	0	-99,3	0	0	-87,6
Permanent Deformation (AC Only)	+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

6 Results for change in precipitation

It is well known that 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 much between different materials and conditions. Generally a material containing a lot of fines will be more susceptible to increased water content.

A 20 % increase or decrease in precipitation gave practically no difference in damages with the M-EPDG. Even if the increase in precipitation was increased by 100 % almost no extra damage was predicted. The problem in the M-EPDG is that there is no connection between rainfall and moisture content in the base and sub-base layers.

This is maybe not so surprising for a new road with a well functioning drainage system. It does not matter that much if it rains more if the water flows nicely into clean ditches and is led away by a working drainage system.

Also if the road is built with materials that are relatively open graded without too much fines the performance is not that affected if some water should be able to enter the structure through cracks in the pavement or by infiltration from the side.

However, for some roads this will not be the case. The asphalt is already cracked, ditches and drainage system are not working as they should and base and sub-base materials are full of fines and very water susceptible. For these cases increase (or decrease) in precipitation could make a big difference.

It is not easy to predict the behaviour of these roads. Most of them are low-traffic roads and resources for thorough investigations are in most cases not 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 will it be to keep a good watertight “roof” and well working drainage.

A few calculations were performed for Trondheim that have the highest predicted increase in rainfall. The increase in precipitation is 22 %. This will lead to an increase in moisture content in the unbound granular layers and sub-ground (Bizjak 2010) and this again will reduce the resilient modulus and resistance against permanent deformation.

In Tables 9 to 11 the results from analyses with reduced resilient moduli for base and underground with the same percentage as the increase in perecipitation. In the M-EPDG this will also reduce the resistance against permanent deformation since this is calculated using the vertical elastic strain as input to the model.

For the locations with a predicted decrease in precipitation it could be expected to dry out the unbound layers and subsoil to some extent and by this increase stiffness and reduce permanent deformation. This effect has not been calculated in this project.

Table 9 Summary of Distress Predicted from change in climate for structure type 1 (% increase)

Location	Warsaw	Trondheim	Rovaniemi
Precipitation increase (%)	**+20**	**+22**	**+19**
Terminal IRI	+2,4	+2,6	+2,3
AC Top Down Cracking (Long. Cracking)	+63	+85,1	+49,3
AC Bottom Up Cracking (Alligator Cracking)	+75	+133	+100
AC Thermal Fracture (Transverse Cracking)	0	0	-76,7
Permanent Deformation (AC Only)	+12,5	-12,5	0
Permanent Deformation (Total Pavement)	+11,6	+14,3	+11,4

* Change from a very small value

Table 10 Summary of Distress Predicted from change in climate for structure type 2 (% increase)

Location	Warsaw	Trondheim	Rovaniemi
Precipitation increase (%)	+20	+22	+19
Terminal IRI	+0,9	+1,1	+1,0
AC Top Down Cracking (Long. Cracking)	0	0	0
AC Bottom Up Cracking (Alligator Cracking)	0	0	0
AC Thermal Fracture (Transverse Cracking)	0	0	0
Permanent Deformation (AC Only)	0	0	0
Permanent Deformation (Total Pavement)	+9,1	+17,6	+10,0

Table 11 Summary of Distress Predicted from change in climate for structure type 3 (% increase)

Performance criteria	Warsaw	Trondheim	Rovaniemi
Precipitation increase (%)	+20	+22	+19
Terminal IRI (in/mi)	+2,4	+2,5	+2,1
AC Top Down Cracking (Long. Cracking)	+38,4	+3,6	+8,9
AC Bottom Up Cracking (Alligator Cracking)	+33,3	+20	+14,3
AC Thermal Fracture (Transverse Cracking)	0	0	0
Permanent Deformation (AC Only)	-7,1	0	0
Permanent Deformation (Total Pavement)	+14,0	+16,2	+12,8

7 Discussion

The calculated results from increase in temperature seem reasonable. A slight increase in rutting and cracking is predicted as expected. The predicted damages are not dramatically changed and the most increase in damages is found for the highest increase in temperature.

The accuracy of the calculation could obviously be questioned. Some of the factors that contribute to inaccuracy are:

- Different traffic loads
- The method for introducing climate change
- Material models developed and calibrated for US conditions and building tradition
- Generalisation from a few locations

This means that the predicted changes in behaviour should be considered as indications of what could happen in the future if no adaption strategies were applied. With small changes to the asphalt mix (e.g. binder with better resistance against permanent deformation) most of the extra predicted damage could be avoided.

7.1 Roughness prediction

Longitudinal roughness (IRI) is very little affected by the global warming (Tables 6 to 11). The modelling shows only a few percentage changes and also show improvement for some cases.

In Appendix OO-1 (NCHRP 2010) the Design Guide identifies the design features that affect the smoothness, according to different studies. From these data, it appears that IRI is closely related to initial smoothness, traffic data and the pavement age. Climate data, such as maximum temperature, are marked as important factors by only one study.

Others studies (NCHRP 2010) have found that flexible pavement smoothness is significantly affected by rutting and thermal cracking.

It is likely that increased rainfall could increase roughness even if these analyses do not show significant change in IRI. Local differences in drainage condition or water susceptibility in materials would lead to damages that would increase the roughness.

7.2 Top-down (longitudinal) cracking prediction

The sharp increase in top-down cracking for all types of structures was surprising. Such a tendency is not expected on a thin asphalt layer under warm climate. The Design Guide gives some answers.

The top-down longitudinal cracking is a distress that starts at the surface of the pavement and then propagates in the asphalt layer. The mechanism hypothesized for this distress is due to excessive tensile strains at, or near, the pavement surface (NCHRP 2010). Because the longitudinal cracking mechanism is not very well understood, an analysis of measured top-down cracking was performed by the NCHRP. The effects of the mean annual air temperature (MAAT) and the AC thickness upon the longitudinal cracking were investigated:

Contrary to expectations, the investigation showed that longitudinal cracking is high for thin asphalt layers and considerably decreases for thick layers.

The Design Guide itself admits: "Quite candidly, the trends showing a decrease in longitudinal cracking, as the AC thickness increased, was opposite to initial views of the research team for longitudinal cracking. It was thought that more longitudinal cracking would occur with thick asphalt sections and less with thin sections. Obviously this was an erroneous initial impression".

7.3 Bottom-up cracking prediction

The bottom-up cracking is very little affected by the global warming. Even if the percentage change could be very large, the change in absolute numbers is small (Table 6 - 11).

Figure 9, extracted from the Design Guide, shows that the amount of alligator cracking is very close for all the regions, and independent of the MAAT. The MAAT appears to have little influence; the pavement structure and material properties are probably more influent.

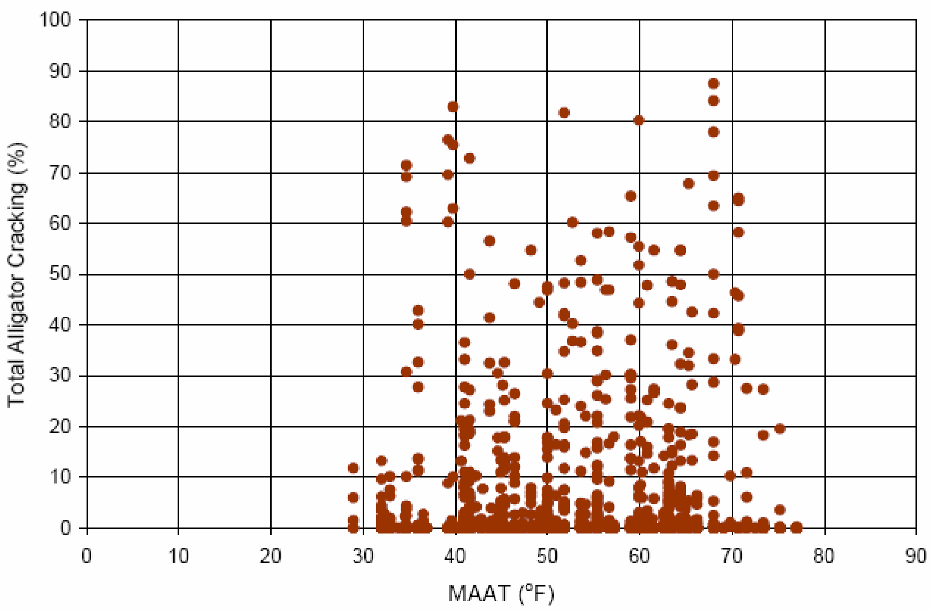

Figure 9 Alligator Cracking versus Mean Annual Air Temperature (MAAT) (NCHRP 2010)

7.4 AC thermal fracture

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 these characteristic cracks develop. The cracks are seen across the width of the road and is often evenly spaced (10 – 20 m). For these calculations the increase in temperature would eliminate this problem for the locations that have low temperatures.

This is maybe too optimistic as one can not be sure that the extreme low temperatures changes as much as the mean temperature.

7.5 Permanent deformation - Asphalt

Permanent deformation in asphalt is very dependent on the temperature. This is well known from earlier experience and laboratory testing. The results seem to be consistent and the largest increase in permanent deformation is found for the highest increase in temperature.

The deformation is closely connected to the binder stiffness. If the stiffness is increased by one temperature class the calculated deformation decreases quite a lot.

7.6 Permanent deformation - Total pavement

For increased temperature practically all the increase in total pavement deformations comes from the asphalt layers. This is as expected because there is very little temperature dependency in unbound granular materials. The little increase that is found comes from the fact that the reduced stiffness in the asphalt increases the stress in the unbound layers.

For increased water content the permanent deformation comes from unbound layers. This is reasonable as experience and many laboratory experiments show that the resistance against permanent deformation decreases as more water is added. The calculations done here are very simple and the calculated numbers could only be used as an indication on what to expect for future climate.

8 Conclusions and recommendation

Effects on pavement distresses are easily observed and are directly related to the temperature increase.

- We do not observe any significant change in Bottom-up cracking and IRI. We can say that the impact of climate change in negligible for these damages.
- The thermal cracking, as expected, is decreasing. This is due to the MAAT which raises the pavement temperature.
- As expected too, the permanent deformation is increasing with temperature
- The top-down cracking is the distress that undoubtedly will cause the most problems in the future for this type of road. It is sharply increasing

Costs of pavement maintenance and construction may increase, especially because of top-down cracking. This may be prevented by using a higher Performance Grade asphalt binder. The life of bituminous surface is, as a general rule, slightly affected by ambient temperature. Effects of temperature rising over the next 100 years are expected to be quite small.

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