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State of the art of likely effect of climate on current roads

Report Nr 1

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Report Nr 1 – State of the art of likely effect of climate on current roads

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1 Introduction

The future climate change and its influence on the performance of the road network is an issue that is concerning more and more countries. It will be shown in this report that the predicted changes will affect highways performance, most likely in a negative way. If temperatures rise and precipitation increases, it looks as though present design theory and construction techniques must be amended to accommodate for these differences of climates. Some governments and organisations have already started facing the problem by financing studies and projects with the aim of finding possible ways to precaution.

2 Summary of the most likely climate changes

A lot of work has been done so far trying to predict the future changes in temperature (and their consequences) on the earth in the next decades, up to hundreds of years. Clearly, the longer timescale over which the climate is tried to be predicted, the less accurate the prediction is.

One of the most complete and up-to-date studies on climate change made on a global scale is presented in the IPCC's 4th assessment report (AR4). The IPCC (intergovernmental panel on climate change) is a scientific intergovernmental body, established by the United Nations, whose aim is to evaluate the risk of climate change caused by human activity, the current observations of climate change and its likely evolution. The AR4 is a collection of all the latest studies related to climate change, as the organisation is not directly involved in the research. The observations of how the climate has changed in the last decades have highlighted an evident increase in temperature, widespread over the globe, but greater at higher northern latitudes. A decrease in snow and ice extent, as a consequence, has been observed, and also an increasing ground instability in permafrost region. The main reason of the global warming has been identified in the increase of concentration of CO_2 (the most important anthropogenic GHG) in the atmosphere, primarily due to fossil fuel use. Obviously, many other factors influence the global average radiative forcing. The anthropogenic emissions (which are mainly greenhouse gases and aerosols) are caused by:

- global population growth,
- economic expansion,
- continuation of the present trend of energy use
- industrial and agricultural production.

However, also some natural variability must be taken into account: the planet climate has always passed through cycles, due to variations in solar activity and other "external" sources of radiation. Although the solar cycles are nowadays known with a certain degree of precision, especially the shortest ones, there are many other factors that are still unknown, and that make the prevision of the natural forcing unreliable.

The future predictions are now analysed; IPCC created a range of possible future scenarios. The creation of different scenarios is compulsory because of the uncertainty in the future previsions, that is, the uncertainty in weighing correctly the influence of each of these factors and to the limited knowledge of all the physic-chemical processes that are involved (see Fig. 1). The majority of the present studies, however, agree with indicating these as the main reasons of the future climate change.

The IPCC panel developed a range of possible future scenarios of CO_2 emissions (see Fig. 2), covering a wide range of demographic, economic and technological driving forces, in order to assess projections of likely future changes in climate. The future climate change results are based on many models, ranging from Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth System Models of Intermediate Complexity (EMICs) to Simple Climate Models (SCMs); multi-model means have been used often. Among these models are:

- AIM - Asian Pacific Integrated Model, from the National Institute of Environmental Studies in Japan;
- ASF - Atmospheric Stabilization Framework Model, from ICF Consulting in the USA;

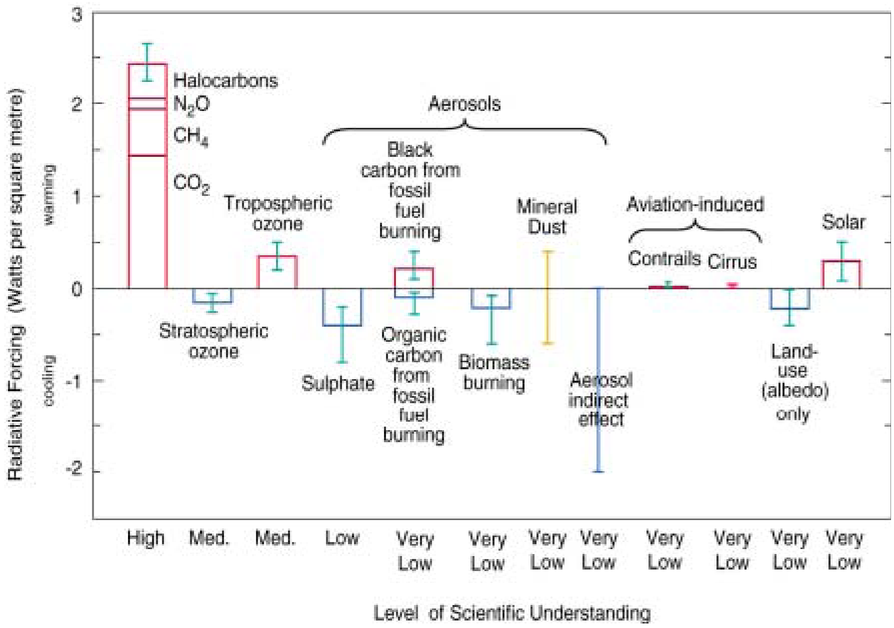

Fig. 1: Global mean radiative forcing in 2000.

- IMAGE - Integrated Model to Assess the Greenhouse Effect, from the National Institute for Public Health and Environmental Hygiene (RIVM), used in connection with the Dutch Bureau for Economic Policy Analysis (CPB) WorldScan model, the Netherlands;
- HadCM3 and HadGEM1 – Hadley Centre Climate Model and Hadley Centre Global Environmental Model, developed by the MET Office Hadley Cetre for Climate Change;
- MARIA - Multiregional Approach for Resource and Industry Allocation, from the Science University of Tokyo in Japan;
- MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact, from the International Institute of Applied Systems Analysis (IIASA) in Austria;
- MiniCAM - Mini Climate Assessment Model, from the Pacific Northwest National Laboratory (PNNL) in the USA.

Each scenario has a range of possible outcomes associated with it. The most optimistic outcome assumes an aggressive campaign to reduce CO_2 emissions; the most pessimistic is a "business as usual" scenario, while other scenarios fall in between.

The main results for the next hundred years are now analysed. In the next two decades, a warming of about 0.2°C per decade is projected, even if the concentrations of all GHGs and aerosols will be kept constant. The probability of such an increase in temperature in the next years is almost certain. Afterwards, surface warming increasingly depends on specific emissions scenarios (see Fig. 3): in the 21th century, an increase of temperature between 1.1 and 6.4˚C is expected. As a consequence, sea level rise is prospected to be between 0.18 and 0.6 m. However, it should be noted that sea level projections do not include all the feedback processes due to the changes in the climate-carbon cycle because published literature is lacking.

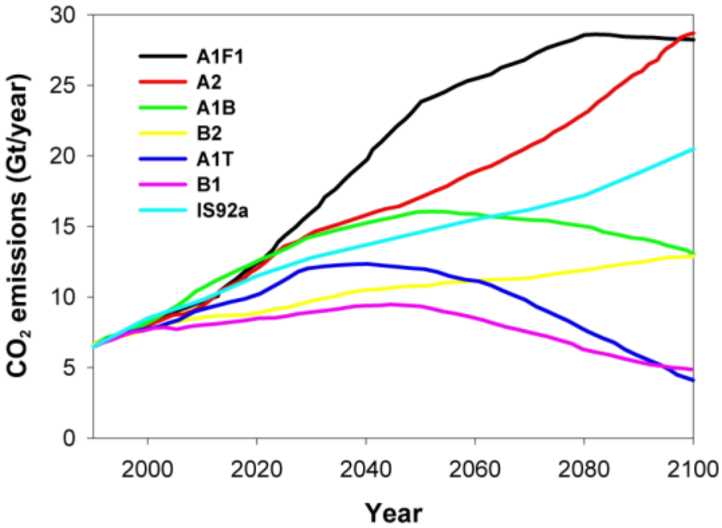

Fig. 2: The most representative emission scenarios developed by IPCC for the next 100 years (IPCC's "synthesis report").

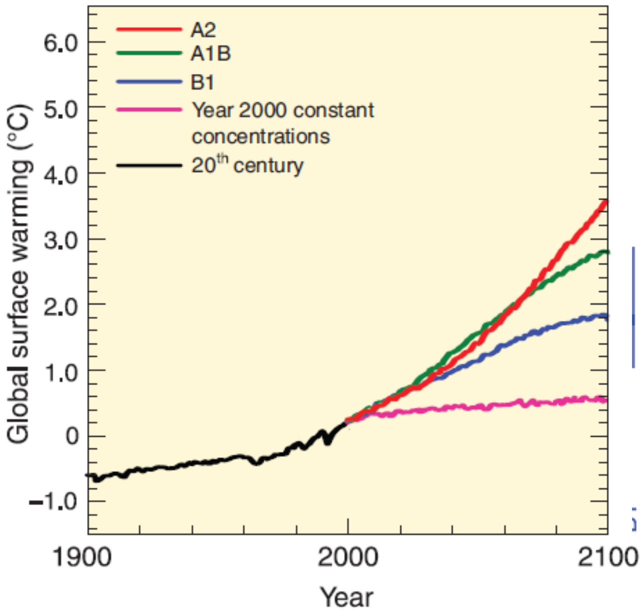

Fig. 3: Global averages of global warming for different scenarios (IPCC's "synthesis report").

It is very likely that the Atlantic Ocean Meridional Overturning Circulation (MOC) (known as "Gulf Stream") will slow down during the course of the 21st century. However, the consequent decrease in temperature in the northern Europe will be small compared to the warming caused by the much larger radiative effects of the increase in greenhouse gases (at least, until 2100).

It is also very likely that hot extreme temperatures and heavy precipitations will become more frequent, especially "extreme events" such as storms and surges. The amount of precipitation is probable to increase at high-latitudes, while decreases are likely in most subtropical regions (as can be also observed in the recent trends). In Fig. 4 are shown these precipitation changes: although the scale is too small for a more detailed description, it seems that, in the Northern hemisphere, during winter an increase in rainfall between 5 and 20% is expected in the central-northern part of Europe. During summer, Scandinavian countries will see an increase in precipitation between 5 and 10%, but the rest of Europe (including UK) will have a decrease between 5 and 20%, which counterbalances the winter increase.

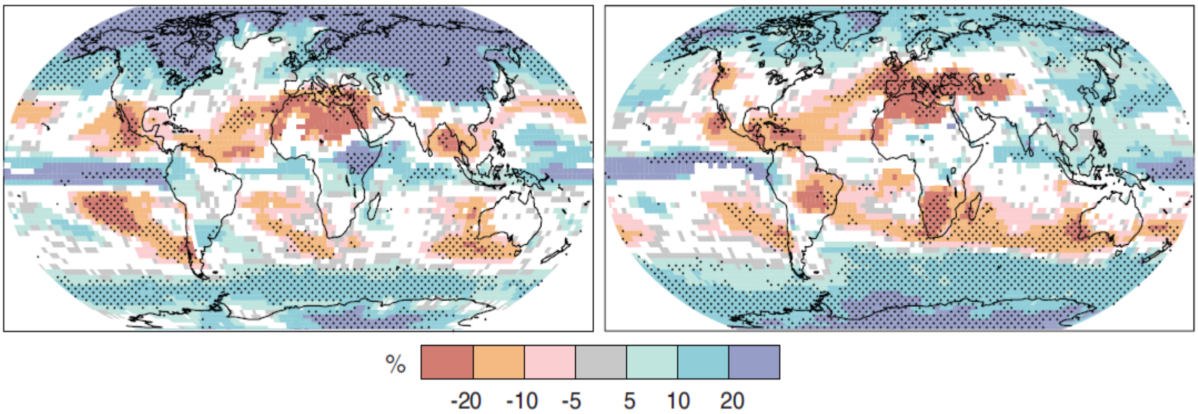

Fig. 4: Changes in precipitations for the period 2090-2099, relative to the period 1980-1999, in winter (left) and summer (right) (IPCC's "synthesis report").

Still a large uncertainty is present regarding the future change in radiative force (defined by Ramaswamy et al., 2001, as 'the change in net irradiance in W/m^2 at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values'); in fact, it depends on many factors (see Fig. 1) that, as already said, are hard to be counted for, like cloud and terrain albedo. An estimate of its variation due to anthropogenic causes is between +0.6 and +2.4 W/m^2. The global changes are summarised in Table 1.

Most probable scenario	**Quantification (by 2100) CCTP**
Increase in temperature	1.1˚C to 6.4˚C
Increase of sea level	18 to 60 cm
Ice reservoirs melting	n.q.
Increased frequency and intensity of extreme weather events	n.q.
Increase in precipitation	Annual net in Europe: 0 to 15%
Increase in radiative force	Anthropogenic: 0.6 to 6.4 W/m^2
Increase of "active layer" thickness	n.q.

Table 1: List of the main global climate-related changes.

The AR4 also analysed the changes in frozen ground, which interests the northern zones of Europe. Permafrost has warmed in recent decades, mainly due to air temperature changes, but also to secondary effects like a change in the insulation provided by snow (positive feedback). As an example, in the last decade the temperature of permafrost in Norway, at a depth of 15 m, has increased by about 0.3°C. The risk is to have permafrost degradation and even thawing due to the surface warming up with consequent ground surface subsidence. Typically, thaw settlement does not occur uniformly, thus creating a chaotic surface with small hills and wet depressions called “thermokarst” terrain. The thickness of the seasonally frozen ground (called “active layer”), i.e. the zone subject to freeze-thaw cycles, has been also monitored. The results demonstrate substantial inter-annual and inter-decadal fluctuations in thickness due to air temperature variations. There is evidence of an increase in active layer thickness and thermokarst development, indicating degradation of warmer permafrost (Brown et al., 1992). Satellite images show that the onset dates of thaw in spring and freeze in autumn advanced five to seven days in Eurasia over the period 1988 to 2002 (Smith et al., 2004).

These climate changes will influence, somehow, many other different sectors, some of which can be, even if only indirectly, related to the road network. Among these there is coastal erosion, ocean acidification, relocation of population and infrastructures.

3 Local scale studies on most likely climate change

Although the climate in some parts of the world is very similar, every "microclimate" responds to the increase of temperature/solar radiation in a different way according to its particular environment, and therefore will need to be studied as a new, separate environment and the changes on a country cannot be considered a priori equal to the changes to another country with, as an example, similar latitude. In particular, the amount of rainfall of a certain region, whether it will tend to increase or decrease, cannot be foreseen until the "boundary conditions" (proximity to the sea, availability of water, mountains etc.) are analysed. This is true especially for those regions with a complex physiography, such as Norway, where, as Benestad (2005) says, the presence of mountains, deep valleys and fjords create a pronounced small-scale structure in climatic variables such as temperature and rainfall, therefore GCMs (Global Climate Models) fail to represent the local climate. The study of the microclimate of the countries involved in this project will be of primary importance, and the changes that the future temperature might imply will be studied in detail. The smaller the mapping resolution is, the more accurate the modelling of a region will be. On the other hand, problems such as the large amount of physical processes involved and the limits of the computers do not allow to have too detailed climate maps. Two examples of projects involved in making future climate change projections on a more local scale follow.

3.1 *UKCP09*

An important study of the future climate change on a "local" scale has been performed by the UK Department for Environment, Food and Rural Affairs (DEFRA). In 2009, DEFRA has released the UKCP09, a new UK Climate Prediction model, which includes the new concept of *probability of occurrence*. As well as projecting key predictions about certain areas of climate change, the model also allows the user to manipulate the findings (mainly time frame and the location of interest of the prediction) in order to gain an output to fit personal needs. The results are based on projections of hundreds of different variants of the *Met Office Hadley Centre climate model*, combined with results from 12 of the world's other leading climate models, and information from past climate observations. The resulting climate projections for UK can be seen following this link: http://ukcp09.defra.gov.uk/.

Three main scenarios, corresponding to different levels of GHG emissions (low, medium and high), have been developed. The most likely scenario that the world will observe in the future is a medium-high level of GHG emissions scenario. The scenarios cover a period of about 100 years; what is striking is that the future increase in temperatures for the next 30-40 years is almost certain. The increase in temperature that was foreseen in the documents prior to UKCP09 has actually occurred.

They have developed maps that cover all UK, every map has a 25x25 km resolution. For the maps, please refer here:

http://ukclimateprojections.defra.gov.uk/content/view/865/521/

Maps cover:

- Temperature (maximum, minimum etc.)
- Rainfall
- Humidity
- Cloud amount

UKCP09 listed these as the key findings of the most probable future changes in climate compared to the period 1961-1990:

- All areas of the UK get warmer, and the warming is greater in summer than in winter (most likely scenario: +1.6C in 2020; +2.3C in 2040).
- There is little change in the amount of annual precipitation (rain, hail, snow etc) (+7% increase in precipitation is expected in the south and up to +5% is expected in the north by 2020, up to a +31% in the south and +26% in the north by 2080), but it is likely that more of it will fall in the winter, with drier summers.
- Sea levels rise (2040: +18 cm, 2080: +36 cm; worst scenario by 2080: +1.9 m), and are greater in the south of the UK than the north.

The probabilistic climate change projections are the result of an innovative modelling approach that explores the uncertainty in the Met Office Hadley Centre climate model, HadCM3, and the regional scale model, HadRM3, by generating a number of perturbed physics ensembles (PPE, see

http://ukclimateprojections.defra.gov.uk/content/view/933/9/ for details).

The projections also include the results of other IPCC climate models, and are constrained by a wide range of observations of past climate. Access to HadRM3-PPE-UK data at the BADC (British Atmospheric Data Centre) is open to everyone, and can be reached following the link: http://badc.nerc.ac.uk/data/hadrm3-ppe-uk/ .

3.2 Regclim

Another important project addressed at studying the climate change on a local scale is the Regclim, whose details can be found in the website

http://regclim.met.no/index_en.html. RegClim is a coordinated research project, aimed at producing scenarios for regional climate change in Northern Europe, bordering sea areas and major parts of the Arctic, given a global climate change (among the others, it also cooperates with the UK Met Office and Hadley Centre).

The results, very important for our project, are shown in the large literature that can be found in the website. Regarding the Norwegian climate, it is said (Petkovic and Larsen, 2009) that in the next 50 to 100 years, temperature will rise between 0.2 and 0.5˚C per decade, and the rise in temperature will bring higher precipitation, more frequent and more intense rainfall. The change in precipitation will show regional and seasonal differences. The highest increase in precipitation (20 – 35%) is expected in areas that already have a lot of rainfall, that is the west coast and the high Arctic, and the increase is expected to be higher during autumn than during summer months. The winter season will however be shorter, with a reduction in the amount of snow at lower altitudes (below 1000 m). Interesting maps of future warming estimates, referring to the period 1980 – 2050, for the Northern Europe can be found.

4 General effects of climate on roads

In this section are presented in detail the different effects that temperature and other climatic "triggers" can have on current roads. A final summary of the most likely future climatic changes that have been derived from the previous section and the possible consequences on roads' performance is listed in table 2.

4.1 Temperature and solar radiation

Temperature is one of the main factors that affect the asphalt performance. Its influence on the subgrade material is, instead, much smaller, almost negligible; temperature becomes of primary importance only when it is close to 0°C, because, as it will be discussed later, problems related to freezing and thawing can appear.

One of the main forms of asphalt deformation is rutting, caused by heavy traffic (especially when moving at slow speeds). At higher temperatures, the mastic is temporarily heated into a more plastic, deformable state. This has the effect of decreasing its binding strength and therefore, over time, repeated heavy loading will cause the mastic to thin and stretch. This takes on the appearance of grooves or ruts in the traffic lane, hence "rutting" (Fig. 5).

Fig. 5: Rutting of an asphalt road (from FHWA).

Another response to a rise in temperature would be an increase in oxidation or premature aging of the asphalt. A distinction needs to be introduced now between increasing levels of solar radiation and increasing temperature. Also caused by the changing climate, a variation in levels of solar radiation (World Resources Institute, 2005) is usually accompanied by a similar variation in temperature. However, the two are not as strictly connected as one might think, because they depend on different factors, and different solar radiation values can be found in days with similar temperatures (and also vice versa). Fig. 6 shows solar radiation and temperature data collected by Fermilab Met Station during 1999. It can be observed that solar radiation is much more scattered than temperature, mostly because of the interaction of cloud cover. It can also be noticed that temperature trend is slightly delayed compared to that of the solar radiation, because temperature is mostly a reaction of solar radiance.

Although high temperatures aid in oxidation, it is solar radiation which is the main driving force behind the process (Milani et al., 2009). In the process, at high temperatures a chemical reaction is undergone that combines elements within the bitumen with oxygen molecules in the air. This process produces by-product molecules (dependent on the binder used) as well as increasing the viscosity of the mastic over time. This leads to the onset of micro-cracking as the brittle binder can no longer tolerate the design stresses, and later on more pronounced stress cracks will begin to appear. These often times are referred to as "alligator cracking" or a series of interconnected cracks that form a pattern similar to alligator scales (Iowa State University, 2006) – see Fig. 7.

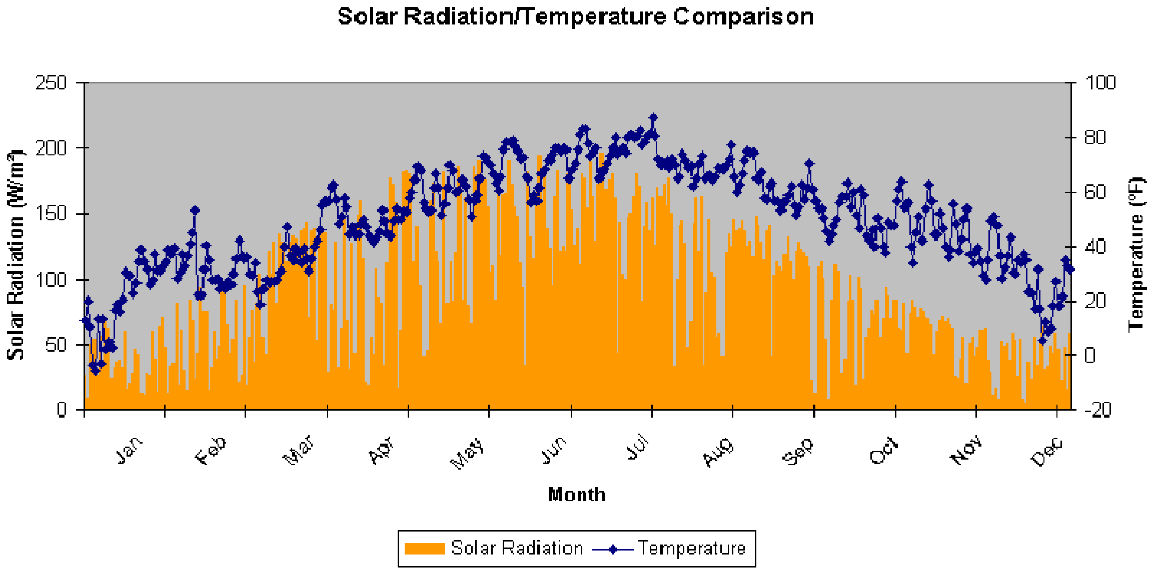

Fig. 6: Comparison between solar radiation and air temperature (from http://www-esh.fnal.gov/Weather/SolarRadiation.htm).

Fig. 7: Alligator Cracking in Asphalt Concrete (from WALT infrastructural Services Ltd).

Cracking due to thermal effects increases with aging-induced brittleness, therefore it is most related to hot climates, but it can occur in any climate; also large temperature variations between the day and the night or between summer and winter can be detrimental.

Worth of note is the work by Zuo et al. (2007). According to the authors, whenever average pavement temperatures are used to determine the asphalt stiffness, pavement life is overestimated (see also Kameyama, 2002, later on). Such overestimation can even reach the 50-75%. This fact gives a high importance to the so called "higher-than-average" temperatures on the pavement life.

Whereas rutting and oxidation are problems more related to hot temperatures, thus they mainly affect roads in locations with hot summers, there are other effects that, in case of a global rise in temperature, can produce problematic subgrade responses in cooler climates, such as those of Scandinavia. In Northern European climates, long, cold winters usually freeze the ground, and once the temperatures rise again in the spring it will *thaw* out. As the ground thaws from the surface down and bottom up, there remains a layer in between that is effectively impervious. This means that the thawing soil above it is unable to drain and its moisture content increases, causing a severe drop in subgrade stiffness and bearing capacity. Furthermore, frost heave forces water to flow upwards to the freezing point, reducing even more the soil resistance. If the road is then loaded for instance by a heavy truck, *cracking* might occur. The phenomenon of the thawing is clearly explained in the following schematic (Fig. 8). For this reason, traffic boards in affected areas set spring time traffic load restrictions for roads so as to reduce the damage (Van Deusen, 1998, among the others). However, if winter temperatures increase, events could occur throughout the winter where a prolonged period of warmth causes the ground to temporarily thaw unexpectedly. Here load restrictions might not be applied due to a lack of information.

Table 2: Schematic of the main, most likely climatic changes that might affect the road performance in the future (modified from NIWA et al., 2004; Austroads, 2004; Kinsella & McGuire, 2005). The effects marked as "+" increase road performance, viceversa a "-" sign means a decrease of its performance.

Cause	**Possible effects on highways**	**Effect**
Increased mean temperatures in cold regions	Less pavement damage from frost heave	+
	More thawing periods with consequent loss of subgrade strength	-
	Ice roads unavailability	-
Increased mean temperatures in mild/warm climate zones	More evaporation leading to drier subgrades	+
	More rapid ageing increases embrittlement, with a consequent loss of waterproofing of the surface seal. Surface water can enter the pavement causing potholing and loss of surface condition.	-
Increased extreme hot temperatures	Rutting	-
Rising sea level	Coastal erosion degrading the road platform	-
	Higher risk of floods	-
	Higher salinity may lead to debonding of asphalt and cement treated bases attack.	-
Increased water availability during summer	Higher water table level, with consequent risk of lower subgrade modulus	-
Increased frequency and intensity of heavy rainfalls	Increased water on the road during or immediately after heavy rainfall events so pavement more susceptible to potholing & stripping	-
	Increase in subgrade moisture content reduces its stiffness	-
	Increased sedimentation / debris blocking water drainage system	-
	Inadequate culverts	-
	Erosion of road platforms	-
Decrease of small rainfalls	Dryer environment	+
Higher solar radiation due to ozone hole	Reduction of asphalt stiffness, rutting	-
	Risk of oxidation = ageing	-
Increase in vegetation (in temperate zones)	Higher moisture content? in the near pavement zone	-
	Need for more maintenance	-
	More stability at the road sides?	+
Higher wind intensity	traffic safety problems	-

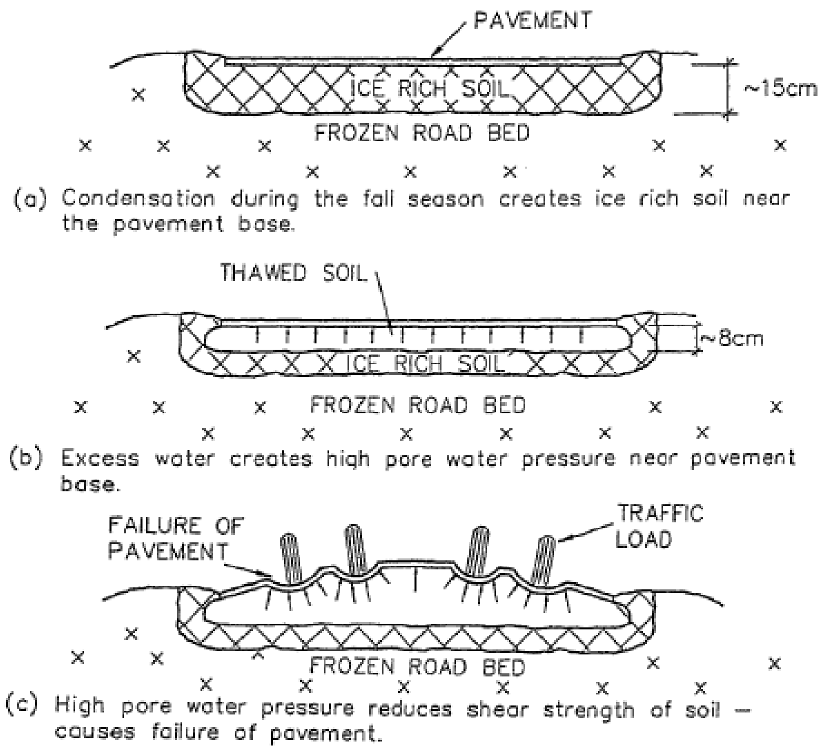

Fig. 8: Process leading to damage of a road surface during a period of thawing (Eigenbrod & Kennenpohl, 1996); however, it should be noted that condensation during the fall season is not an important mechanism compared with cryo-suction effects, the main responsible for water accumulation.

4.2 Precipitations and water table level

Precipitation is another factor that can strongly affect the road's performance. While temperature influences mostly the asphalt layer (although it is of paramount importance for the subgrade when it is within a range that can cause thawing), water is one of the main reasons that can bring the subgrade to failure. This because a change in precipitation can change the soil moisture content, and, thus, its modulus. The physical behaviour of the asphalt, as well, is affected by rainfall changes, even if in a minor way; the problems related are described hereafter. However, should be noted by now that different types of asphalt in the presence of water mean different road performances because they govern the drainage system: in this case, the relationship between asphalt and rainfall affects the road indirectly, because asphalt governs the drainage of the road, and, depending on it, the subgrade will receive more or less water.

One of the most likely responses of asphalt to increased moisture content is ravelling (Fig. 9), which is brought upon by a combination of aged brittle asphalt and standing water within the voids. Here, as traffic passes over the surface, compressive forces generate pressure, pushing the water up and out of the asphalt. As it leaves, this water will break some of the more brittle bonds between the aggregate and mastic, leading to aggregate-free asphalt patches on the road surface, and thus to a reduced grip for the vehicle. Surface water can enter the pavement causing potholing and loss of surface condition. Although ravelling can also be caused by premature aging of the asphalt, it is thought that standing water within the asphalt, as well as drainage patterns within traffic lanes, have a higher probability to cause ravelling damage (Wolters, 2003).

Fig. 9: Ravelling of an Asphalt Pavement (from http://www.pvpc.org/web-content/graphics/images/trans/pave_gif/surf_wear.gif).

But probably the most important problem caused by excess precipitation is *base and subgrade destabilization*. In this situation, if water is not properly drained away from the road as it seeps through the asphalt and base layers, it can drain into the subgrade layer and increase the moisture content, causing the stiffness of the base layers to drop. Also, it can cancel the positive effect of the suction very rapidly. Therefore, as traffic passes over the road above, it will not be the base and subgrade taking the stresses (as designed) but rather the thin asphalt binding and wearing course. This obviously leads to overstressing and cracking of the asphalt pavement. To avoid this, drainage path for road runoff must prevent the base layers from becoming too waterlogged. However, with the onset of higher intensity, shorter duration rainstorms, previous drainage designs may no longer be adequate.

The higher intensity rainfalls and storms can lead to two main problems: the *erosion* of the road platforms and the *blocking* of the drainage system due to the accumulation of debris. Also worth mentioning is the concern over improperly designed drainage *culverts* under roads. If these become blocked due to an increase in flash-flooding, it can be detrimental as observed in Freeport, Maine (an example can be seen at Metacafe, 2009, http://www.metacafe.com/watch/1971770/scarify_a_road_surface/).

A concern of more northern areas of Europe that experience harsh winters is the significant increase in winter precipitation. Depending on weather conditions, several responses to this might be seen. If a warmer winter occurs that fluctuates between extended periods of freezing and non-freezing air temperatures, rain could fall on to frozen roads causing premature thawing and destabilization of the road base as discussed in the section on temperature effects. However, if it there is a cold winter with only a few days above freezing, rain falling on these days could sink into the asphalt and freeze overnight. In this case, the water in the voids of the asphalt would expand as it froze and break apart the aggregate from the binder causing a combination of a cracking and ravelling effect. Also water held in the subgrade, in case of freezing, can heave and thus crack the asphalt surface above. However, if an increase of temperature is foreseen, cracking due to frozen soil might become a minor concern.

Water table below the road can change due to two main reasons: one is the sea level change due to the melting of ices, and the other is the change in precipitation. However, as the environment is a complex system, the groundwater table may be, in turn, affected by many other factors. It is well demonstrated (Hall and Rao, 1999) that a strong relationship exists between groundwater table and the subgrade moisture content; If sea levels and/or rainfall tend to increase, as it is expected, so too will the water table. Should be noted that, while precipitation is highly dependent on the geographic and topography, and the changes predicted still suffer uncertainty, the future sea level increase is almost certain. Higher water table tends to increase the moisture content of the soil above, and also capillary action will increase the moisture content of pavements and decrease the suction force of the not saturated zone, thus decreasing its modulus and accelerating the rate of pavement deterioration (Austroads, 2004). Groundwater table becomes more and more important as it gets shallower, and, when close to the surface, it is the main responsible to determine the subgrade moisture content (Hall and Rao, 1999).

A separate discussion has to be done for those areas that are geographically closer to the sea (Austroads, 2004). Here, coastal erosion and floods can accelerate the degradation of the coastal platform. Also, more elevated water table can create the problem of increased salinity. In the temperate areas, where evaporation is significant, water from the watertable flows upwards in order to replace the water evaporated. This event can lead to a water movement upwards tens of metres above the phreatic surface and it can also lead to salts being lifted to the surface where they can affect the soil properties. It was shown by Chan (2001) that an increase in the salinity can have a significant impact on road systems, as it has the effect of hardening the bitumen and causing brittle cracking and even potholing. Salinity can also affect subgrade that has been treated with binders such as cement, as salt rusts the reinforcement in concrete structures.

5 Previous experimental studies on the different climatic factors, their contribution on the road performance and their evaluation

The evaluation of the impact that climate changes can have on a road is a very challenging task, because of the many variables involved that make it a complex system. The final aim is to quantify how road life expectancy will change as a consequence of the weather predicted, and how this it can be improved. The main steps that will be followed in order to evaluate such changes are the following.

Quantification of the causes from predictions made with models:

- Likely average air temperature rise
- Likely solar radiance change
- Change in the extreme air temperatures daily/monthly
- Change in the amount of rainfall
- Change in the maximum quantity of rainfall in a single event (to take into account heavy rainfalls and storms)
- Possibly, change in the water table level

Evaluation of the consequences using, possibly, both field measurements and theoretical models:

- Increase of mean pavement temperature due to air temperature rise
- Increase of mean pavement temperature due to solar radiance rise
- Temporary increase in maximum pavement temperature due to increase in extreme air temperatures and/or solar radiance changes (temporary sub-zero cold periods aren't of such great concern as the freezing effects are mostly confined to the bound layer where low temperature is largely beneficial)
- Recognition of periods most likely to be subject to subgrade thawing due to the increase in air temperature
- Moisture content changes due to mean increase of the rainfall
- Temporary increase of maximum subgrade water content due to heavy rainfalls
- Change in the subgrade moisture content due to the local predicted change in water table level
- Consequences of the change in water on the pavement surface.

Once the pavement temperature change and the surface and subgrade moisture content change have been quantified, data from previous studies, models or laboratory tests allow the evaluation of the change in the material's stiffness. An implementation in any of the usual pavement design programs will provide the evaluation of the new highway life expectancy.

When it comes to measure the distress of a real road due to climatic effects, as well as try to model its behaviour, not only is there the problem of trying to evaluate the different climatic factors separately, but also the contribution given by climate and that given by traffic are hardly recognisable and thus hardly dissociable. Doré et al. (2005) assert that, while distresses by rutting, roughness and fatigue cracking are attributable to both climatic and traffic effects, longitudinal cracking outside the wheel tracks and transversal cracking are only due to climate conditions. Many studies have been performed with the attempt to weigh the two different contributions of climate and traffic on road damage, but the results are not always in agreement (Doré et al. 2005); however, almost all of them agree that, if the pavement has been designed adequately, at least 50% of road deterioration is due to environmental factors. A few researches have also pointed out that road damage is not much affected by heavy axle loads: for example, according to Nix (2001), there is no strong link between axle load and road damage, but heavy axles may have a much greater impact when the subgrade soil is in poor conditions, i.e. during thawing.

Many researchers have tried to investigate the influence of the different climatic factors on the performance of a road. Unfortunately, it is difficult to take into account the factors singularly, as they are all inter-related: for example, temperature and solar radiation are often strictly connected, and laboratory tests can hardly reproduce the same conditions that are met on site. For this reason, as will be discussed later, analysis of the road performance under different climatic conditions is often studied through a modelling approach. Some of the main results related to experimental measurements are described hereafter.

5.1 Relationship between air temperature, solar radiation and asphalt temperature

In 1968 a report was published by the Highway Research Board on the effects of climate on bituminous pavement temperature (Straub, 1968). In this report is described an experimental field study that was conducted over one year to discover the variation of temperature with depth and time (five minute intervals) in asphalt pavement exposed to the open atmosphere. The long-term objective of the study was to develop a computerized simulation of heat flow into pavement given specific climate parameters (e.g. air temperature and solar energy received by the pavement), and is one of the few existing examples of short-interval tracking of the road condition in relation to the climate. The temperature of the asphalt, affecting its viscoelastic properties, is directly responsible to its ability to sustain loads. The stiffness of different types of asphalt at different temperatures is usually well known and can be deduced by means of laboratory tests; what is not known, instead, is how the asphalt temperature changes according to the external inputs, and this is why this article is very important. The location was in New York State; temperature probes were inserted in the pavement at 2 in. (~ 5 cm) intervals and also in the gravel base beneath the pavement. Air temperature and solar radiation were recorded, together with a qualitative description of the amount of clouds. Some interesting conclusions could be drawn:

- Asphalt temperatures follow the same cycles of air temperatures, with a sinusoidal cycle lasting 24h.
- As the depth increases, the time at which the maximum and minimum temperatures are reached is shifted later compared to the air temperature: the shift is absent on the asphalt surface, is about 1 h at a 10 cm depth, 3 h at a 20 cm depth and 5 h at a 30 cm depth.
- The larger is the distance from the top, the smaller is the variation of temperature within the day (see Fig. 10).
- During cloudy and rainy days, the asphalt temperature tends to be constant throughout the whole day, and the difference in temperature between the air and the asphalt and through the asphalt depth is very similar, almost identical (see Fig. 10).
- Below about 30 cm, the daily temperature change does not affect the asphalt temperature, which remains almost constant.

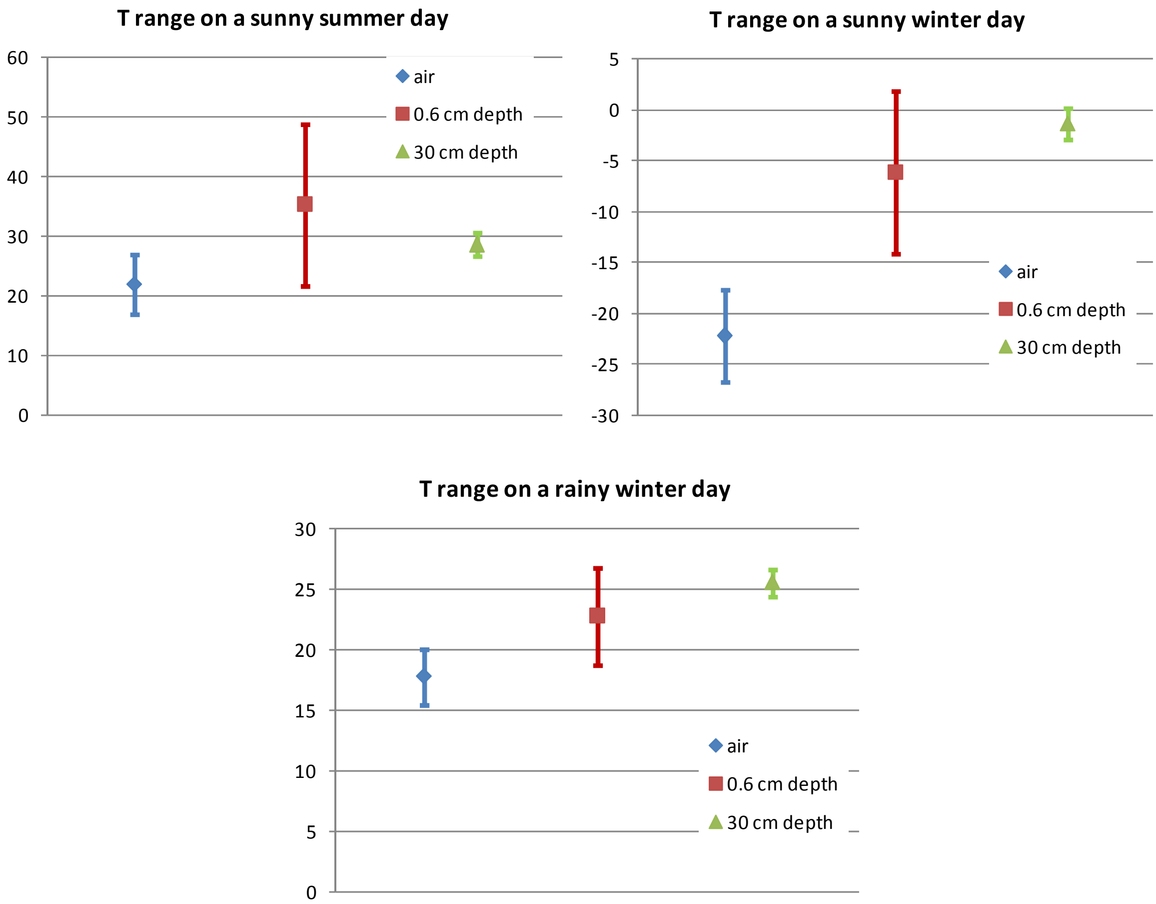

Fig. 10: Ranges of temperatures, in ˚C, in the asphalt at different climatic conditions.

- The asphalt temperature, at any layer, was always higher than the air temperature (see Figs. 10 and 11); on a monthly average, the surface layer was about 7˚C higher than that of the air, the deepest layer about 6 ˚C. This was true for almost the whole year, apart from November, in which the temperatures were very similar: this is maybe due to a prolonged period of clouds/rain.
- At a monthly scale, no time shift is observed (see Fig. 11).
- Asphalt temperature is not affected by its total thickness.
- According to the authors, solar radiation (responsible of the transmission of heat through radiation) has a greater influence on the temperature of the asphalt than does the air temperature (which instead transmits heat through convection). This fact underlines the importance of field solar radiation measurements as well as air temperature.
- The comparison between two days, both completely sunny, that recorded the same air temperature, but a difference in radiation of 1418 Btu/sqft/day (about 186 $W/m^2/day$), gave a difference in surface asphalt temperature (0.6 cm probe) of about 17˚C. Although this is just an example, it is an important indication of the approximate amount of temperature increase due to solar radiance. Given the drastic effect of this seasonal increase, rising levels of shortwave flux will play a major role in the response of asphalt to the changing climate.

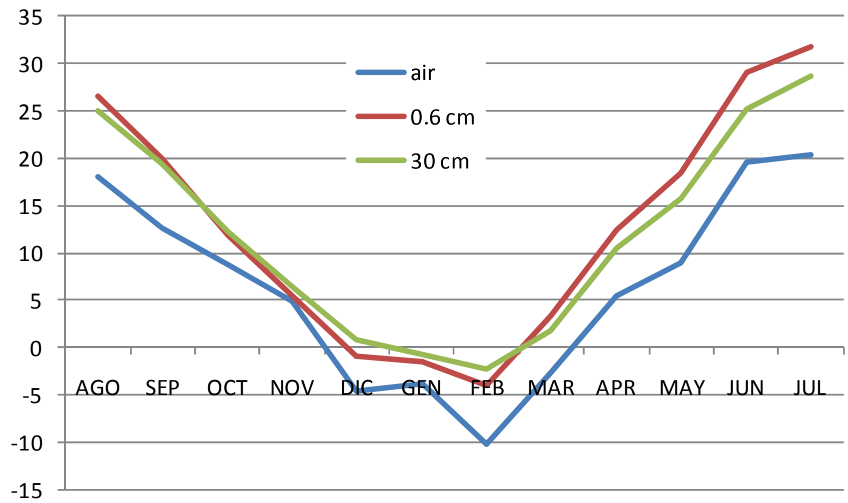

Fig. 11: Yearly cycle of the temperature in the air and in the asphalt; it can be noticed that the asphalt temperature is always higher than that of the air.

It has been said that the relationship with air temperature tends to decrease quickly beneath the pavement, in the subbase layer; this can be clearly seen also from Eigenbrod and Kennepohl (1996): in the interface between the pavement and the subbase, temperature follows the air temperature, with a slight delay (about 2 hours), but the influence of the temperature decreases sensibly at a lower depth (probes 2, 3 and 4, at depths 27 cm, 51 cm and 87 cm below the pavement, see Fig. 12).

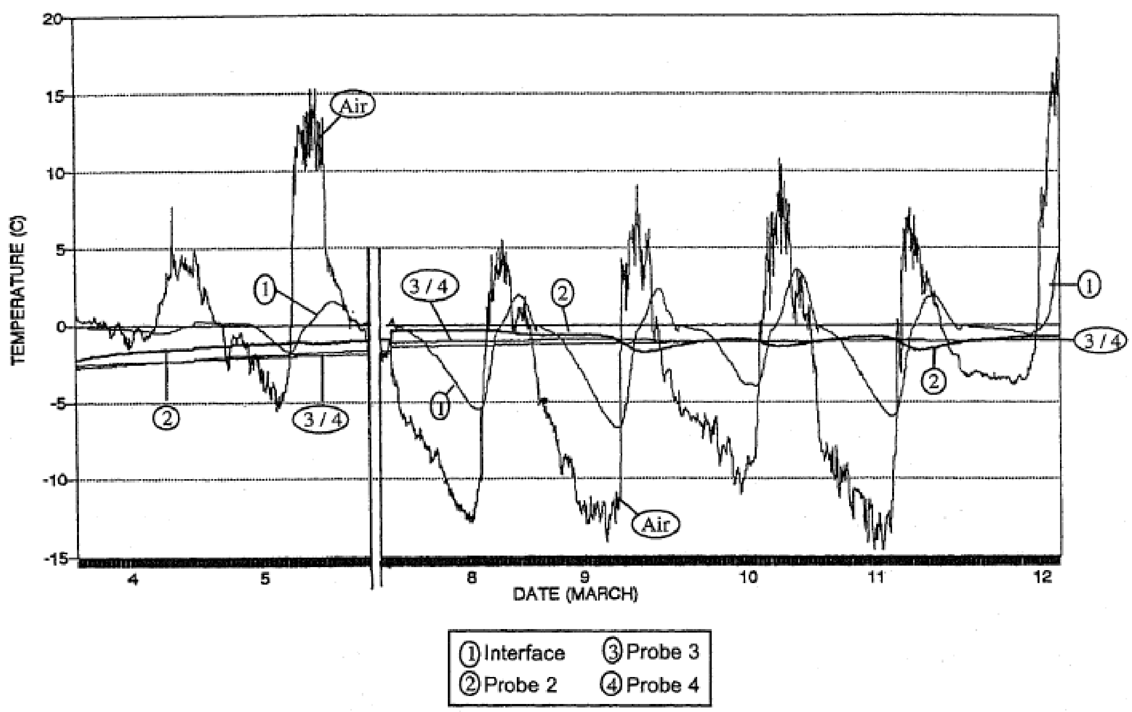

Fig. 12: Temperatures in the air and in the subbase layer during early spring (Eigenbrod & Kennepohl, 1996).

Barker et al. (1977) provide a relationship that links the asphalt temperature with the air temperature (in °C) that is:

$$T_{asphalt} = 1.2 \cdot T_{air} + 3.2$$

This is a very simplistic equation, and new, more elaborated versions have been developed recently.

An example of more elaborated derivation of an equation able to describe the relationship between pavement temperature and air temperature (which, however, does not take into account any other environmental factor such as solar radiation, wind speed etc.) is offered by Lavin (2003). The author points out that, to select an appropriate asphalt binder able to withstand the environmental conditions, pavement temperatures are needed, usually defined at a depth of 20 mm, but no measurements of such temperatures are available. For this reason, equations to convert air temperature data into pavement surface data, based on theoretical analyses, have been implemented the SHRP SuperPave design software in order to assist the designers in selecting the proper binder. The models used to implement such equations consider constant, typical values for solar radiation and wind. The highest pavement temperature at 20 mm depth, in ˚C, is given by the following formula:

$$T_{20mm} = (T_{air} - 0.00618\ Lat^2 + 0.2289\ Lat + 42.2)(0.9545) - 17.78$$

where T_{air} is the highest temperature on a week's average and Lat is the geographical latitude (in degrees). The pavement design low temperature at any depth (included the surface), instead, can be found using the following equation:

$$T_{low} = -1.56 + 0.72\ T_{air} - 0.004\ Lat^2 + 6.26 \log_{10}(H+25) - Z\ (4.4 + 0.52\ \sigma_{air}^2)^{1/2}$$

where T_{low} is the pavement design low temperature, H the depth, T_{air} is the low air temperature, Lat the latitude, σ_{air} the standard deviation of the mean low temperature; Z is equal to 2.055 if a 98% reliability is requested. Unfortunately, these equations take into account only the air temperature, but give an idea of the relationship between the air and the pavement. Another empirical formula relating air temperature and pavement temperature, based on measurements from weather stations on 30 sites of Northern America and developed by Superpave and Long Term Pavement Performance programs, is offered by the USFHWA (2002), and defines the highest temperature in the pavement as:

$$T_{high} = 54.32 + 0.78\ T_{air} - 0.0025\ Lat^2 - 15.14 \log_{10}(H + 25) + Z\ (9 + 0.61\ \sigma_{air}^2)^{1/2}.$$

5.2 Relationship between precipitation and subgrade moisture content

It has already been said that the three main climatic factors that affect road performance are temperature, solar radiation and precipitations. These factors, and especially the latter, have great influence on the moisture content of the subgrade, but it is somehow more difficult to quantify their individual impacts.

A first, clear idea of the quite strong relationship that exists between amount of precipitation and moisture content (thus stiffness) of the soil underneath the road pavement is given by the following graph (Fig. 13), representing data collected for the "Watmove" project (Watmove, 2008).

The relationship is obvious, though it is probably heightened by the fact that the measurements were taken near the pavement edge, where water from the surface can infiltrate more easily. The subgrade soil is essentially clay, thus it is very sensitive to the presence of water, and can retain a large amount of it. The base, instead, is a granular material, which means that it can drain (and evaporate) quite easily. These two assertions can be observed in the graph: the subgrade moisture content peaks are much larger than those of the base, which instead are smoother, and show a very good correlation with the rainfall amount; if, during days with no or little rain, the subgrade moisture content is approximately equal to 7%, when rains are more abundant, above approximately 2 mm/h, subgrade moisture content increases from 10 up to 20% and above. The variation in moisture content due to rainfall, on the other hand, seems to be of no more than 2% for the granular base; a decrease can be observed, instead, in June and September, and it can be hypothesised that its level remains low for the whole summer, and this is due to the effect of the increase in temperature, by which, being closer to the surface, the base is much more influenced than the subgrade.

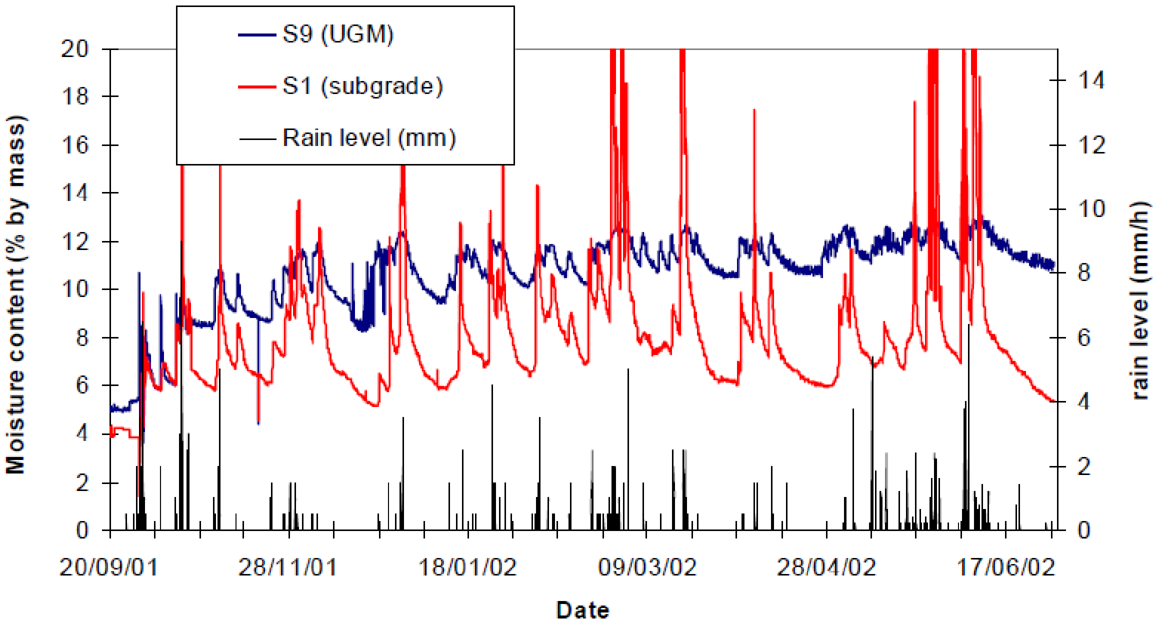

Fig. 13: Water content variations in the granular base (S9) and in the clayey subgrade (S1) of a low traffic pavement, near the pavement edge (Watmove, 2008).

An important detail regarding the relationship between rainfall and subgrade moisture content is given by Bandyopadhyay and Frantzen (1983). The authors assess that the time required for the subgrade stiffness to be influenced by the rainfall is quite long, from 12 to 21 days, on average. A time shift was observed by many authors, for example, Hall and Rao (1999, see next paragraph) found a delay of 1 to 2 months. The time delay is probably affected by the road structure and conditions: if the road is old and a lot of cracking has ruined its surface, the time the rain takes to infiltrate into the subgrade is surely much shorter.

A type of road that deserves a different attention is the gravel road: because unpaved, it can be particularly susceptible to precipitations (i.e. to moisture changes). Huntington G. (2007) monitored 20 sections of gravel roads in Wyoming with the intent of understanding the deterioration speed under various conditions. Potholes, washboards and rutting deteriorated with time, while gravel quality, gravel sufficiency, drainage, and dust ratings did not change significantly with time. The author conveyed that, as expected, the interaction between precipitations and maintenance of a gravel road strongly influences the performance, and most of the deterioration occurs shortly after precipitation (Fig. 14). In particular, precipitation strongly affects potholing formation and, partly, rutting; no correlation, instead, was observed between rainfall and washboarding. Climatic effects on gravel roads are related to precipitation more than seasonality (at least in Wyoming's dry-freeze climate).

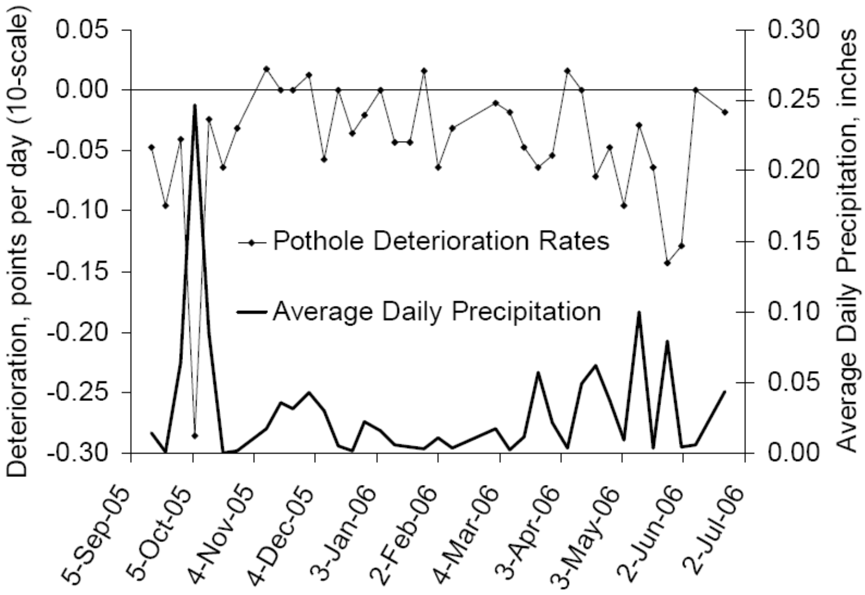

Fig. 14: Relationship between precipitation and potholing formation (Huntington, 2007).

5.3 Combined effects of precipitation and air temperature on soil moisture content and thawing problem

A quite exhaustive experimental analysis of the moisture content and thawing problem on a road has been performed by Erlingsson et al. (2002). In a project funded by the research fund (BUSL) of the Public Roads Administration of Iceland and the EC 4th framework project COURAGE, seasonal variability of moisture and temperature were monitored for three years in the base and the subbase layers of three old test road sections in Iceland. The diagrams of the findings are shown in Fig. 15 and 16. Some conclusions were drawn by the authors (and some more are hypothesised):

- Thawing seems to be related to both temperature and precipitation, although with different weights.
- In particular, temperature seems to influence the moisture content much more than rainfall (although the freezing of water might mislead the moisture readings): rainfall is responsible of small irregularities in moisture content, which can increase of about 2%, but large drops of moisture content seem to be related to temperature drops (see Fig. 15).
- It seems that single days of heavy rainfall affect the moisture content more than prolonged periods of medium-light rainfall (for example, in Fig. 15, from November to March the quantity of rain is fairly constant, and the moisture content seems to follow the same trend of temperature, while the heavy rains in the middle of October and in March cause a substantial difference between the two trends).
- On the other hand, particularly dry periods can cause a relatively large drop of the moisture content (see Fig. 16, during November 2000)

- The response of the moisture content to a significant temperature change is delayed of a few days.
- A short decrease in the moisture content took place on the 6/11 as a result of a small freezing period on the 4-5/11 (Fig. 15): this fact gives the idea that, even if the reaction is shifted in time, it actually takes place if there is a substantial change in temperature, even if for as a short period as two days. If this is true, it means that, during the freezing period, even just a day of temperature above zero might, potentially, give thawing problems. The variation of moisture content, however, might not be as relevant as the variation in temperature, as can be seen, for example, in the temperature peaks observed during December, and it the temperature drops the 4th and 15th November: it seems that, if the variation in temperature lasts for less than 2 or 3 days, then the moisture content is affected, but not largely.
- The spring thaw period started in early March; it is seen as four separate peaks with maximum moisture value as Optimum Moisture Content (OMC) + 2.3% and the whole period lasted more than a month or until the middle of April. During all the four peaks the OMC of the layer was passed.
- Referring to Fig. 16, it can be seen that most of the fluctuations due to rainfall were seen closest to the surface but they decreased with depth.
- During winter in 2000, fast high peaks in the moisture content show short periods of thawing. The fact that it rained very seldom allowed the thawing to be very limited. In late March or April the spring thaw started. The moisture content was high during this period but afterwards reduced gradually. During these periods the moisture content was frequently above the OMC.
- The moisture content increase, in some cases about 2 - 3% during days of high precipitation, reduced rapidly soon after the rainfall stopped, symptom of the fact that that the layers have adequate permeability properties. In the base layer, the moisture content fluctuated frequently, although moderately, even during low or moderately intense rainy periods. This fluctuation was, however, moderate (1-2%), probably because base layers had adequate permeability properties and therefore could not retain the moisture.
- The large moisture peaks observed in the deepest subbase in the middle of January and of April can be explained as prolonged thawing periods, or, more probably, other factors, such as an increase in the water table below, might have affected this layer.

Trials using a Falling Weight Deflectometer (FWD) were then performed. The resulting deflections and stiffness moduli obtained with the FWD showed good correlation with the moisture content: this is expected, as moisture content strongly influences the stiffness of soils. During the spring thaw period in April, when moisture content in the subbase was highest (15.2% = OMC + 2.4%), the stiffness modulus of the combined base and subbase courses reached its minimum value. On the other hand, while moisture content gradually decreased during the summer period to 11% (OMC - 1.8%), the modulus increased until it reached its maximum value in August (see table 3). A stiffness reduction of more than 50% was observed during the spring thaw period compared to stiffness values observed in late summer.

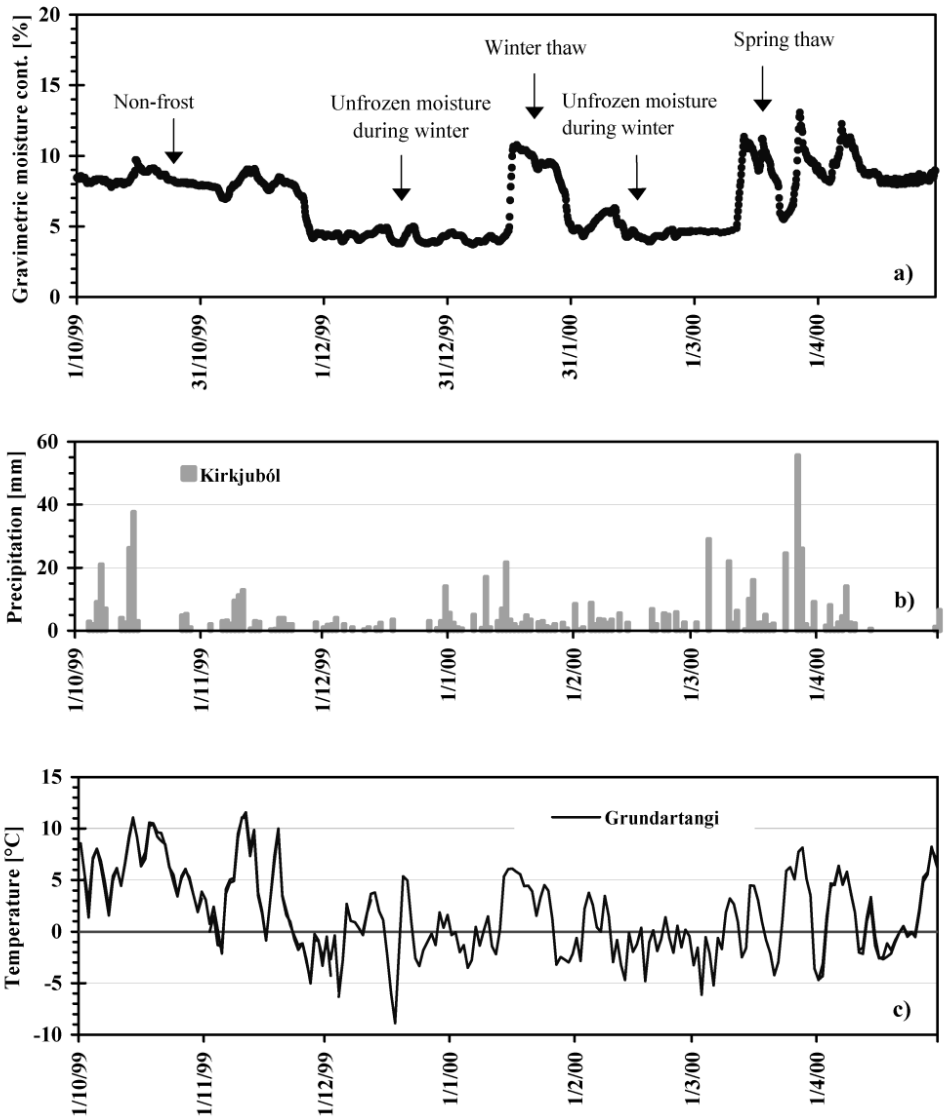

Fig. 15: Environmental data from a subbase at depth 25 cm below the surface (Erlingsson et al., 2002).

Stiffness [MPa]			Stiffness increase
Layer	Spring thaw	Late summer	[%]
Base & subbase	172.6	373.7	116.5
Subgrade	38.7	64.7	67

Table 3: Recorded maximum and minimum stiffness moduli (Erlingsson et al., 2002).

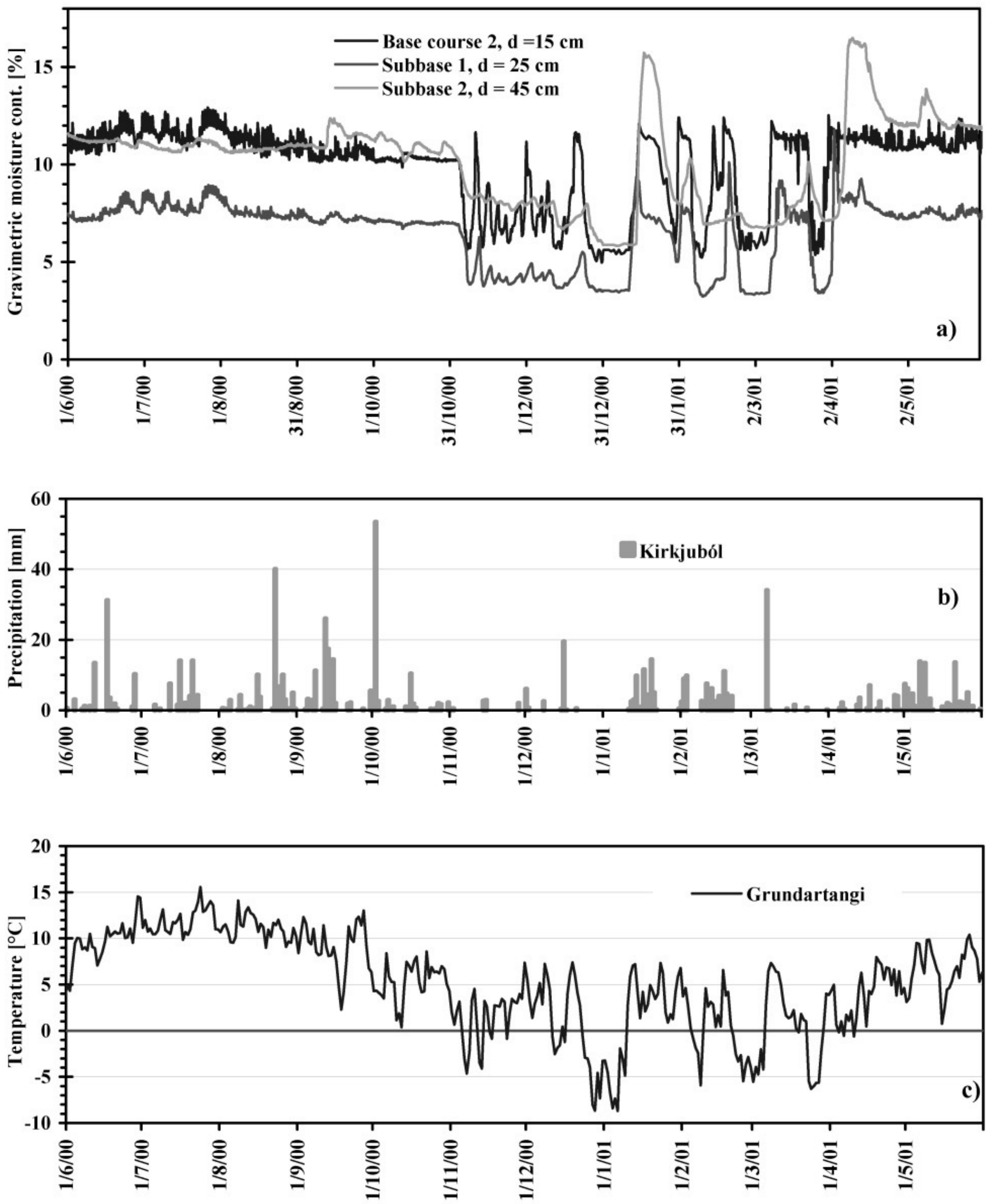

Fig. 16: Environmental data from a base 15 cm below the surface, and from the subbase, respectively 25 and 45 cm below the surface (Erlingsson et al., 2002).

Stiffness tests by means of a FWD over various seasons, to investigate the stiffness modulus variation with the environmental conditions, were performed also in southern Ontario, Canada, by the Applied Research Associates, Inc. (ARA) and the Centre for Pavement and Transportation Technology (CPATT), University of Waterloo (Popik & Tighe, 2006). In this area, the monthly mean temperatures typically vary from –10˚C to 26˚C, while precipitations in the spring/summer months vary from 64 to 93 mm, and during autumn and winter snow accumulation ranges from 13 to 41 cm. The modulus of the subgrade layer was found to vary from 13.7 MPa, in thaw-weakening conditions, to 50 MPa, in winter conditions. This finding shows that fluctuations in environmental conditions can have severe effects on the strength, and thus durability, of the subgrade. It shall be noted that, while the minimum pavement strength (based on FWD measurements) usually occurs during spring thaw, on the other hand pavement is in its strongest conditions when it is frozen.

Many authors (White & Coree, 1990, among the others) support the opinion that, in cold climates, spring thaw is the seasonal phenomenon that influences road deterioration the most. As an evidence of this is the fact reported by White & Coree (1990) that 60% of the failures during AASHTO road test occurred during spring; St. Laurent and Roy (1995) evaluated the relative damage caused by a given load during springtime was 1.5 to 3 times higher than the average annual damage. Of the same opinion are Watson and Rajapakse (2000) who found that the environmental parameters that most influence the resilient modulus of a road are the surface temperature for the asphalt layer, and the thawing index for subbase and subgrade layers.

Another example of tests aimed at investigating the correlation of subgrade moisture changes with temperature and precipitations is given by Hall and Rao (1999), who took measurements in 18 sites across Arkansas. Moisture content measurements were taken by means of a Campbell Pacific Nuclear depth probe from a depth 46 cm below the asphalt surface downwards at intervals of 30 cm down to 300 cm. Some conclusions could be drawn from this research:

- A relatively low correlation between temperature, rainfall and moisture content can be found (see Fig. 16 for the latter), indicating the influence of other factors; although the results from Erlingsson et al. were different, it should be born in mind that the geography of the two places is completely different.
- As expected, the data showed that correlation between moisture and temperature is usually positive, indicating lower water contents during winter.
- Moisture contents at shallow depths are more correlated to temperature than not at deep depths.
- Well drained soils do not show almost any correlation between moisture content and precipitation.

However, as Hall and Rao (1999) point out, the subgrade moisture content tends to stabilise with time, until it approaches a sort of equilibrium value usually some years after the construction of the pavement above (Fig. 17). A large increase of moisture content from the beginning to the end of the road construction, and in the first period of life has been observed by many authors (Vaswani, 1975, among the others).

An important consideration concerns the maximum depth below which the moisture content of the soil is not influenced anymore by seasonal fluctuations. Eigenbrod and Kennepohl (1996) found that, below 260 mm, the moisture content was always constant (around 5%). This is only an example, and the depth of influence should probably vary from soil to soil and from climate to climate, but it gives a first indication. Molenaar & Van Gurp (1991) measured the subgrade modulus in different areas and found that no seasonal effects could be observed in those sections where groundwater levels were high, i.e. higher than 0.6 m below the pavement surface. This is almost certainly due to the suction effect from the groundwater table that predominates on all the other effects.

Simonsen et al. (1997) performed interesting tests on an instrumented road in order to evaluate the ability of the FROSTB model to predict frost and thaw conditions and consequences. The road tested consisted of a 65 mm asphalt layer over 460 mm silty sand with gravel. The subgrade was sandy silt. This section was instrumented with sensors to monitor seasonal variation with climate: moisture sensors based on domain reflectometry technology (TDR) inserted at 15, 46, 76, 107 and 137 cm below the surface, and termistor probes were used to measure temperature of the air, of the asphalt surface, and below at 3, 15, 46 and 107 cm depths. Also, rainfall was measured with a tipping bucket sensor and ground water level was monitored by means of 4.5 m deep water well equipped with a pressure sensor. Deflections were measured using a FWD. Typical results are shown in Fig.

18. Some comments could be drawn:

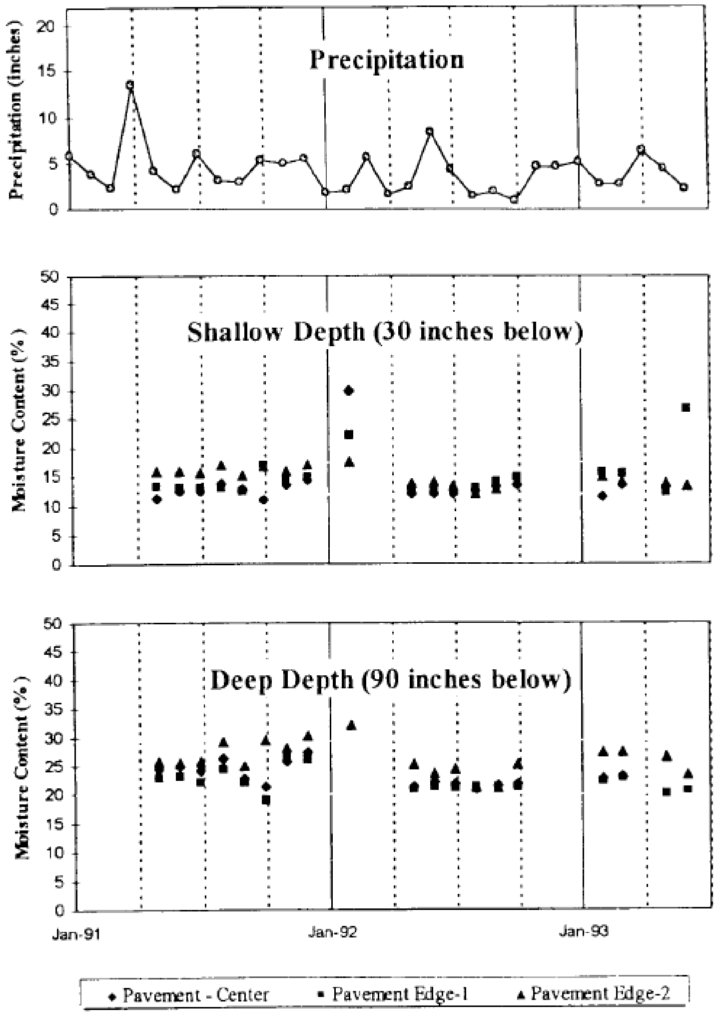

Fig. 17: Subgrade variation with precipitation, example from a site (Hall and Rao, 1999).

- During heavy rain period, the moisture content at 76 cm depth increased from about 16% to a maximum level of 20%.
- At 15 cm depth, the influence of water was much more considerable. In particular, it can be seen that the moisture content at such depth was fluctuating even during the freezing period, suggesting an infiltration of rain and melt water even when temperature of the pavement was well below 0˚C.
- During freezing, the moisture content at 76 cm depth slightly reduced from an average 16% to about 13%.
- Infiltration due to heavy rainfall and melting water during freezing period could be observed also at 76 cm depth (see the peak in January).
- As for the case of Straub (1968), it can be seen that, while asphalt surface temperature floats very frequently (the daily change cannot be seen only because the data are a daily average), at a depth of 106 cm only seasonal temperature fluctuations can be seen.

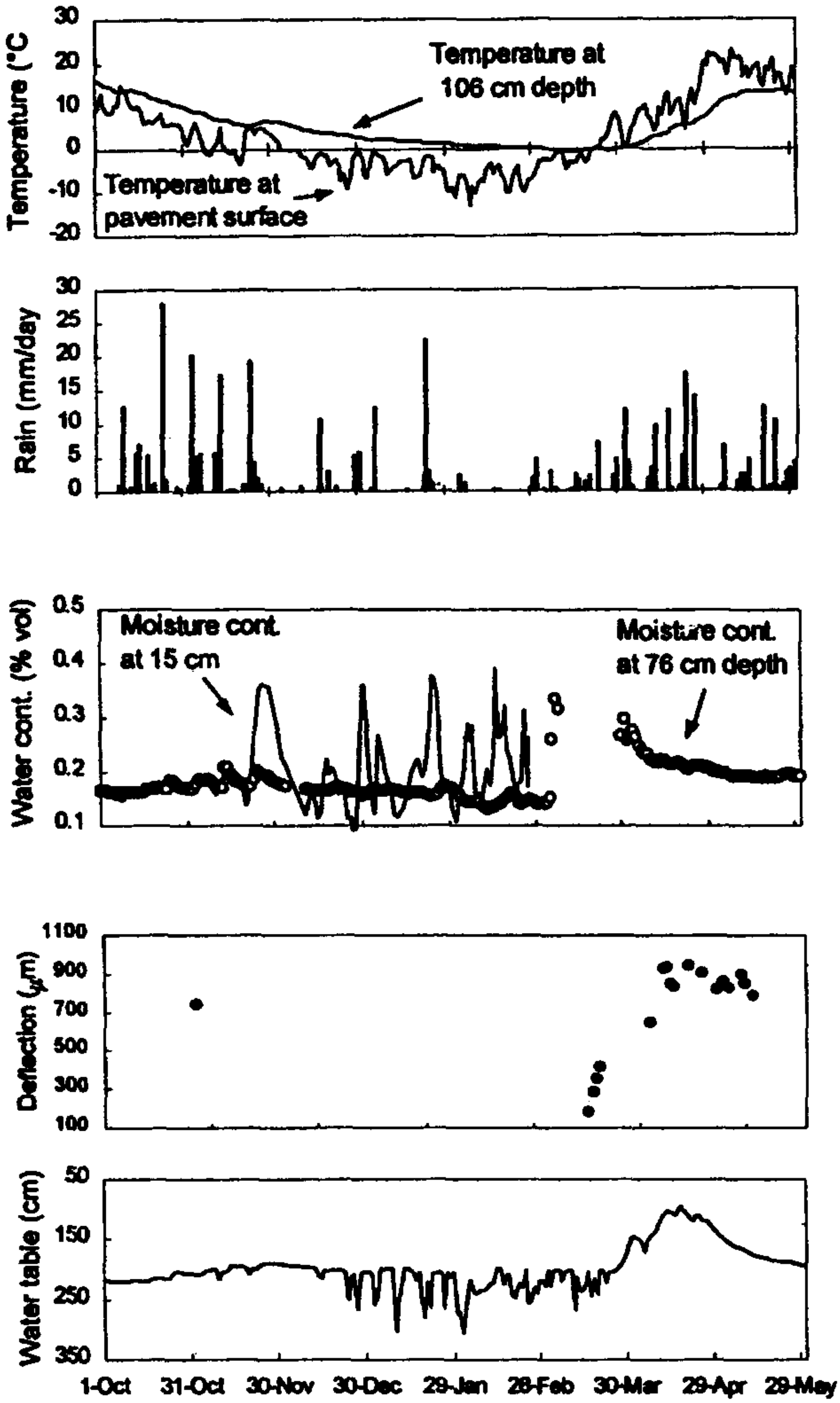

Fig. 18: Typical data collected (Simonsen et al., 1997).

- Surface deflection is almost null at the beginning of March, when the soil is still frozen (thus in its strongest state), but increases quickly as soon as the pavement temperature goes above 0˚C (middle of March), which corresponds to the starting of the thawing period. The maximum peak is reached only after 2-3 weeks.
- The surface deflection increased by a factor of about 6 between the frozen state (in which the soil, being frozen is very stiff) and the thawed state (the worst situation), but increased only by a factor of 1.3 between autumn (normal conditions) and spring (thawing conditions).
- The moisture content at 76 cm depth increased sensibly during spring thaw (although the data are not complete).

Some specific comments are warranted for the water level, as this is a detail that is rarely taken into account. The maximum moisture content during spring thaw did not exactly correspond with the maximum level of groundwater table, which occurred about a month later. This is probably due to the fact that water table increases when there is water income from snow melting, and this takes longer than thawing of the soil below the road surface. However, the maximum deflections measured with the FWD do seem to correspond to the groundwater level. It is unclear whether groundwater level did or did not play a role in the road stability. The maximum water level reached was 1 m below the road, and the subgrade material was sandy silt, therefore the water table might have influenced the lower layers of material (thus the increase of deflection), but suction was not strong enough to reach the layer at 76 cm from the surface. Unfortunately, the available data could not give us more information.

6 Previous government projects on the likely effects of climate change on roads

Some countries have started financing projects whose aim is to study the influence of the future climate change on the performance and the traffic of the national highway network, and the possible adaptation strategies, i.e. the possible ways to limit the road problems that might arise. These studies are of primary importance for us, because they provide not only results to be compared with, but also examples of different approaches that can be followed during the current research.

A very important study has been carried by "Transit", the governmental agency who is responsible of the highway network in New Zealand. In an article by Kinsella & Mc Guire (2005), the authors study the impact of the climate changes on the state highway network of New Zealand. The interesting aspect of this study, for what concerns our project, is that the climate of New Zealand is, in some parts, similar to that of Northern Europe. According to the authors, the most significant effects are the rising sea level that causes coastal erosion, thus degrading the coastal platform, and the increase of coastal floods, which affects the maintenance of the roads nearby. The reduction of frost during winter reduces the pavement damage due to frost (which means less need of maintenance), but also increases the vegetation (which might be an issue instead). Increased heat during summer brings more rapid ageing of pavement. While in the west of the island an increase of rainfall is expected, with consequent increase of erosion and risk of landslides, in the east the rainfalls are supposed to reduce, leading to a minor need of maintenance. Finally, high wind gusts may affect traffic safety. Transit identified the most potentially vulnerable asset types to climate change impacts: these are bridges, culverts, coastal roads, pavement surfaces, surface drainage, hillside slopes. Not all of these are of primary interest for our project, however, the two-stage assessment process used by Transit to identify those areas requiring action can be very useful:

- Stage 1: Assessing the *necessity* of acting in the present to manage future potential climate change impacts (this depends on the level of certainty the impact will occur to the magnitude predicted, the intended design life and the capacity of current practice to manage the climate change impact, see Fig. 19);
- Stage 2: Assessing the *feasibility* of acting now to manage future potential climate change impacts (mostly related to the costs).

Three key approaches were analysed:

- The "do nothing" approach, which consists of continuing to use the current design specifications.
- The "total retrofit" option, which consists of retrofitting all potentially affected structures now to avoid future climate change impacts
- The "future design" option, which consists of repairing the road when required, and in the meantime designing all new highways to accommodate future climate changes to 2080.

Taking the design of a bridge as an example, the analysis showed that, if the 'Do Nothing' option is considered, the annual costs of maintenance could increase by a factor of two for any one year; the cost of the 'Total Retrofit' option, whilst small in relation to the replacement cost of state highway bridges and culverts if no action is taken, is nonetheless significant. Thus, the results showed that the best solution was to repair the asset at a time when the specific loss or need became evident, as current asset management practice seems to be adequate to cope with most predicted climate change impacts.

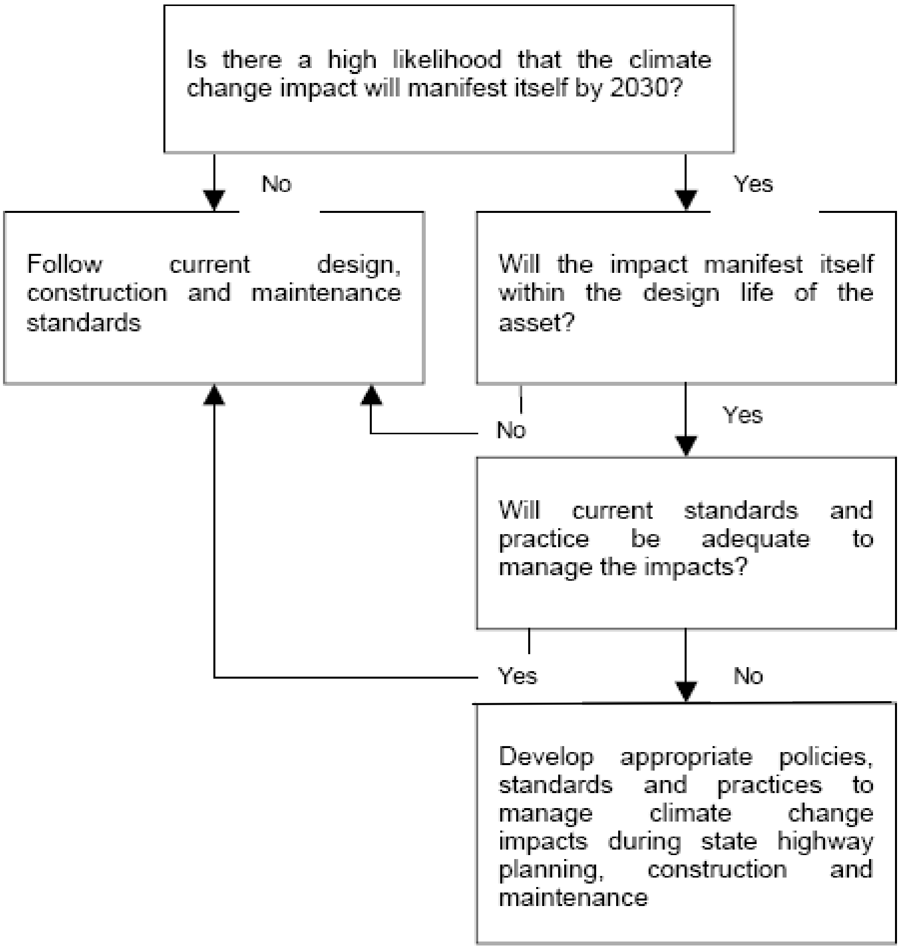

Fig. 19: Initial climate change impact assessment framework (Kinsella & Mcguire).

Another important project was carried out by Austroads, and aimed at investigating all the different aspects of the relationship between climate change and Australian roads. Using the scenarios produced by IPCC, they created 50x50 km maps of the continent describing monthly means of average, maximum and minimum temperature, precipitation, solar radiation, and potential and actual evaporation. The predictions show a land that is expected to become hotter and drier: annual temperatures will increase by 2º to 6ºC by 2100, although not in a uniform way, but rather with more extremely hot days; for example, the number of days of winter days below 0°C in Canberra is likely to drop from 44 at present to 6–38 by 2070. The Australian climate and environment is very different from the northern European, and the problems they will encounter are almost certainly very different, nonetheless this study is very interesting because it includes a detailed description of the indirect impacts of climate change on road infrastructure. These indirect impacts are:

- population and settlement patterns: fertility, mortality, and international and internal migration movements all influence the future network; for what concerns Australia, it is believed that coastal areas are likely to become more attractive, birth rate will decrease, while immigration will increase, and people will tend to move mostly in few large cities. The same conclusions are not likely to be applicable to Europe, and an European most probable “population pattern” needs to be studied.

- Road transport demand: it has been estimated that demand will increase mostly in those areas where population is supposed to increase, the proportion of heavy freight vehicles will rise slightly, fewer vehicles will transport the same volume of freight, average freight payload will rise by about 25% from 2000 to 2100, and average 'Equivalent Standard Axles' (ESAs) per articulated truck will double due to higher axle mass limits. This might be the same situation of Europe.

Should be noted that road maintenance costs are roughly proportional to the ESA loading (ESAs per lane per annum) on the road surface (Rosalion and Martin 1999), and that ESAs increase dramatically with load due to the '4th power law':

$$\mathit{ESAs} = (\mathit{axle\ load} / \mathit{reference\ load})^4$$

where the reference load is determined from the load that causes the same damage for each axle configuration as a standard single axle.

The output of the Austroads project outlines some road design and maintenance features that should be considered in the future:

- An increase of pavement maintenance and construction costs if the climate tends to become wetter. The capacity of existing culverts and waterways may prove inadequate.
- Increase in temperature will accelerate the rate of deterioration of seal binders and thus require earlier surface dressings/reseals.
- The impact of climate change on existing roads can be taken into account at the time they require rehabilitation or improvement, but not immediate action.
- Because higher water tables can accelerate the rate of pavement deterioration due to capillary action with consequent increasing of the road subgrade moisture content, road agencies may need to raise the levels of existing embankments when pavements reach the ends of their useful lives.

The future increase in traffic has been also investigated by the U.S. Department of Transportation (2002), who predict that, by 2025, U.S. transportation energy use and emissions will be strongly influenced by the growth in light-duty trucks (pickup trucks, and vans, under 3850 kg gross vehicle weight rating). Also, according to the Federal Highway Administration's Freight Analysis Framework, freight tonnage will grow by 70% during the first two decades of the 21st century (DOT 2002). This information can be useful because the future changes in traffic on the European roads is likely to change in a similar way to that in U.S., although factors such as political choices and geography will certainly play an important role.

U.S. is among those countries that yet have started investigating possible adaptation strategies to climate change impact on highways. The major problem for the U.S. road network was identified to be flooding because of global rising sea levels coupled with storm surges. For this reason, particular importance is given to emergency and evacuation plans.

The importance of climate change on the road system has been recognised by the Government of Canada, and thus a research project to examine its impacts on the pavement infrastructure in the southern Canada was held by the collaboration of Environment Canada, the University of Waterloo the Government of Canada Climate Impacts and Adaptation Program. During this project, an analysis of the potential climate change impacts on the southern Canada road network was investigated following four steps: first of all, climate data from stations placed in 17 chosen sites representing a wide range of different roads and road conditions were collected, and data of daily minimum, daily maximum and mean temperature for the period 1951-2001 were obtained from the archives. Secondly, two climate change scenarios were adopted in order to evaluate future possible climate changes in Canada. One emission scenario, A2x, was based on the CGCM2 model, while the second, B21, resulted from the Hadley Climate Model 3 (HadCM3). Because the output of such models is coarse, the third phase consisted of a downscaling by using the 1951-2001 temperature and precipitation data. The relevant climate indicators of deterioration were identified in a first phase. Finally, the Mechanistic-Empirical Pavement Design Guide and software were used to conduct case studies on the investigated sites in order to determine future changes in deterioration rates due to the combination of several factors such as moisture, traffic, maintenance etc. . They found that IRI, rutting, longitudinal, transversal and alligator cracking are all sensitive to climate changes, although changes in traffic seem to be more important in determining pavement deterioration. A greater application of environmental data into pavement design was highly recommended, especially historic climatic and road weather observations should be incorporated into pavement deterioration designs.

A project that can be potentially very important for us, but not yet completed, is being carried out by the Norwegian Public Roads Administration. It is called ”Climate and Transport”, a 4-year R&D program initiated in 2007, and investigates all the topics important for effective adaptation of planning, design, operation and maintenance of roads under changed climate conditions. The results will be analysed when available.

7 Pavement performance models

7.1 Possible modelling solutions for increasing temperature

Many relationships have been developed, and can be found in the literature, in order to estimate the pavement temperature in an indirect way, i.e. from climatic data, based on the heat flow theory, or in a more empirical way.

Theoretical models based on the heat-flow theory take into account the different ways in which heat is transferred to the pavement and soil, that are:

- Conduction (heat transfer in a solid phase, higher at high water contents)
- Radiation (energy moving through the medium, usually negligible in soils)
- Diffusion (movement of vapour towards a lower vapour pressure zone, responsible of the evaporation phenomenon)
- Convection (macroscopic movement of fluid particles towards lower densities).

Conduction dominates the heat transfer process for temperatures from below 0°C up to about 25°. Convection gains importance when temperatures are positive (so that water is in its liquid state) and the soil is very porous. At temperatures higher than about 30°C, conduction is still the most important mechanism if the soil is saturated, while, if the water content is low, vapour transport gets more and more important. Only in coarse soils at high temperatures radiation would get involved, but only in a minor way.

Although theoretical models are based on exact relationships, they cannot cope very well with complex systems, such as the environment, where the number of variables is very high and they are interrelated. For this reason, empirical models can be more reliable. One of these empirical models is described by Marshall et al. (2001). The prediction model BELLS needs, as inputs, the pavement thickness, the 5-day mean temperature, the infrared surface temperature (or FWD measurements, in another version of the model) and the time of the day. The resulting equation is empirical, based on daytime surface temperatures collected between 1997 and 1999 in an instrumented site. It is:

$$T_d = 0.95 + 0.892\ T_s + (\log\ d - 1.25) \cdot \left[1.83 \sin\left(\frac{2\pi A}{18}\right) - 0.448 T_s + 0.621 T_{avg} \right] + 0.042 T_s \sin\left(\frac{2\pi B}{18}\right)$$

where T_d is the pavement temperature (˚C), Ts the infrared surface temperature, T_{avg} the average of the high and low air temperatures on the day before testing and d the layer middepth. A and B are factors depending on the time of the day.

Another model based on empirical data was developed, as previously mentioned, by Straub (1968). The data collected were used to develop a computerized simulation of heat flow into pavement given the change in air temperature and solar energy received. This meant that instead of carrying out long, tedious observations on newly laid asphalt to discover its reaction to climatic effects, a couple of input parameters could be substituted into a devised modelling program to give a precise readout of temperature in the pavement with depth and time. Although only the report and not the actual model itself could be obtained, a model such as this could be very useful in assessing future impacts of climate change on bituminous pavements. If a model like those just described could be obtained, it could be combined, with known theory such as Van der Poel's Nomograph (or others) to gain an idea of what the asphalts properties would be. The next step of the present research will deal with such task.

Some interesting information about how to estimate in a more realistic way the damage of the roads due to temperature variation are described by Kameyama et al. (2002); according to the authors, whenever average pavement temperatures are used to determine the asphalt stiffness, pavement life is overestimated, and also the temperature and moisture effects cannot be considered separately and superimposed, they must be considered together. In practise, for a more exact understanding of how asphalt will react, a model must not only link changes in solar radiation and mean/maximum ambient temperature to pavement temperature, but also the extent of asphalt response in terms of asphalt stiffness/viscosity. For instance, if, over the next 40 years, there is a 3°C increase in average summer temperature, with an 8°C higher maximum summer temperature and a 2% increase in solar radiation, these climate variables would then be inserted into the model as input data to achieve a record of pavement temperature with depth. It can then be figured out using equations from pavement design programs (or manuals) how the mechanical properties of the asphalt differ with this increase in temperature and thus how the design life will be affected.

Another model addressing and assisting with the problem of mid-winter thawing would also be very useful to create for individual road construction projects, however it would be difficult to apply to different projects. This is due to the inhomogeneous and non-isotropic aspects of base and subgrade layers. And although models have been devised to complete such a function, they are often crude, highly theoretical forms of measurement used only to a broad effect, for instance BISAR (Bitumen Stress Analysis in Roads).

7.2 Possible modelling solutions for increasing moisture content

Similar to the model discussed for temperature, a two-part model would be needed to gain worthwhile output data as to the effect of increasing precipitation. Here though, the model would need to be able to predict the moisture content in the asphalt and each base layer (including subgrade) for a given amount of precipitation. This information would have to be simultaneously compounded with equations relating the moisture content of the various layers to their corresponding resilient moduli. Using this constructed model, it would be possible to predict the likely amount of pavement deterioration for a given increase in precipitation and hence the expected design life of the road. This subject will be described in more detail in the report “state of the art of materials’ sensitivity to moisture change”.

7.3 Existing experience on climate change modelling solutions

In the project developed by Austroads, the effect of climate change on the road stability and network performance were investigated using two pavement deterioration models: the Pavement Life Cycle Costing (PLCC) model and the Highway Development and Management model, version 4 (HDM-4). In these models, climate change was represented by the Thornthwaite Moisture Index, a function of precipitation, temperature and potential evapotranspiration.

The PLCC model estimates the effect of climate and of traffic changes on the maintenance and rehabilitation costs based on roughness predictions for a set of defined road categories. The whole Australian National Highway System was modelled. In order to do that, the network was split into 60 different road ‘sections’, the division being based on similar climate characteristics, traffic levels, vehicle mix and pavement characteristics derived from current and predicted future climate data and transport demand data. The typical PLCC’s inputs, apart from those inputs that are common to any road design (road description, category), are:

- Deterioration factor
- Length (km)
- Average age of pavement
- Pavement strength (SNC)
- Roughness (minimum NRM count)
- Average Thornthwaite Index value
- vehicles per day
- % heavy vehicles
- ESA's per vehicle

The PLCC pavement deterioration model predicted rates of pavement deterioration ranging from 1.4 to 2.5 NRM/year for the National Highway road network. This was considered reasonable as these roads are generally kept in very good condition (Austroads, 2004). The optimal road agency costs and the road user costs under current climatic conditions and in 2100 are summarised in the following table.

	2000 Base Climate	2100 Average Scenario Climate
Road User Costs (RUC) ($million)	11,660	22,247
Road Agency Costs (RA) ($million)	287	376
Total Costs ($million)	11.947	22,623

Table 4: Optimal road agency and road user costs.

The HDM-4 software, instead, is addressed at investigating pavement performance in a more detailed level (on this purpose, only certain representative regions in each state have been chosen) and provides more detailed information (for example, changes in pavement strength, rutting and cracking) than the PLCC model. Many inputs are in common with the PLCC: Equivalent Standard Axles per heavy vehicles, pavement type (materials, strength, thickness), pavement condition (age, initial pavement roughness), Thornthwaite index and so on; but it also requires additional data, for example more climatic variables (temperature, rainfall), Minimum roughness after reconstruction (set at a default value of 45 NRM), curvature and so on. Also, HDM-4 employs a much more detailed pavement deterioration algorithm. The HDM4 analysis assumes a minimum periodic maintenance case (the base case), which is essentially an estimate of the routine maintenance costs required to keep the pavement in sound operational condition. The HDM-4 results show that the changes in costs are primarily due to the increase in transport demand, while the effects of climate change are, in comparison, minor. Pavement performance analysis showed a marked increase of roughness over time, as shown in Fig. 20.

There is an ongoing adaptation of a suite of innovative performance models, based on HDM-4, for asphalt pavements for use in mild (Mediterranean) climates; the modifications and improvements that are being applied are described by Loizos et al. (2002). It is now being implemented within a Road Infrastructure Management System (RIMS) being developed for the Greek Government.

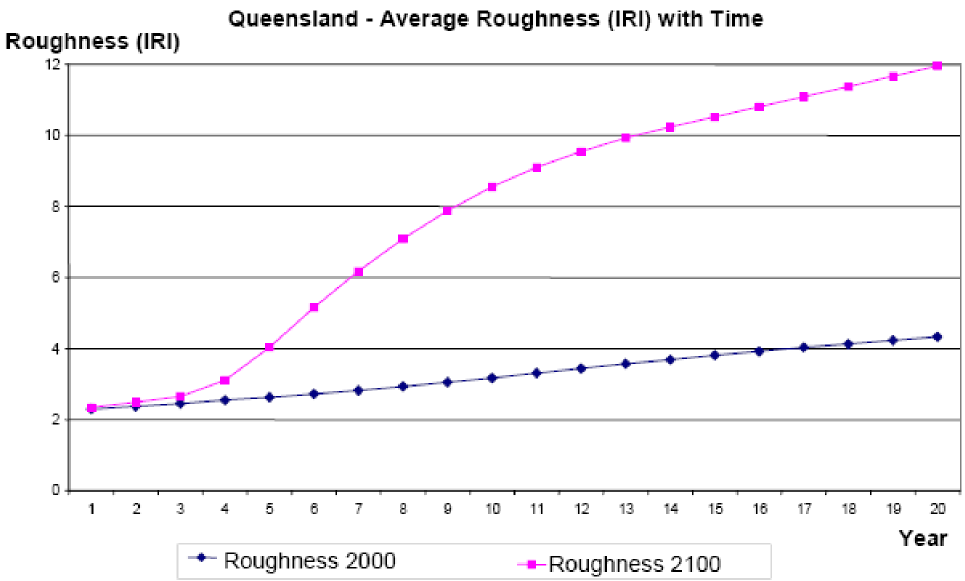

Fig. 20: Average roughness for a road in Queensland during a 20 years period in the present (blue line) and in 2100 (red line) (Austroads, 2004).

The introduction of climate change models into design work is being more and more explored using mechanistical-empirical approaches. For example, the M-EPDG or the Mechanistic-Empirical Pavement Design Guide (NCHRP, 2004) has been introduced in Canada recently. Here two test sites were set up in Alberta and Ontario to measure the sensitivity of pavement performance to climate change (namely increased precipitation and temperature). It was hoped that by procuring a model for these areas of how pavement responded to predicted climate change, that design could be altered to combat these responses. Although not on as detailed a level as what is proposed, this provides the general concept behind what is hoped for. Future studies for the M-EPDG included, improving the sensitivity and broadening the scope of analysis to include the other provinces of Canada.

7.4 Deterioration models currently used is Scandinavian regions

The performance of the models currently in use by Scandinavian countries to assess the deterioration of the roads due to climatic processes was reviewed in a project called NordFoU (Saba, 2006). A list of such currently used models is presented in table 5. The results showed that the majority of the prediction models developed are local, i.e. suitable for a given region and under specific traffic and climatic conditions, but cannot always be successfully applied to different conditions. Thus, a comprehensive model able to accurately predict pavement performance has not yet been found.

Q: Describe the deterioration models you use briefly	
Denmark	Statistical deterioration models for condition index (used for local roads) and IRI and bearing capacity (for state and county roads) are implemented in PMS. Mathematical model of pavement performance (a simulation model) is implemented in pavement design system.
Finland	At network level, a probabilistic model for rutting, IRI, sum of defects, and bearing capacity is used. At the program level simple extrapolation is used for rutting, IRI and sum of defects based on the last measurement.
Iceland	RoSy PM system based on visual inspection.
Norway	A simple linear extrapolation based on registered data is used in PMS. Performance models of USA's MEPDG were recently calibrated for Norwegian conditions.
Sweden	In PMS, simple statistical model is applied. In the current design system for flexible pavements modified Kingham's criteria (fatigue damage) is used. A new system known as Active Design, which involves on the site calculation of future rutting in bound and unbound material is under implementation on five road building projects in western Sweden. The deterioration models used in this system come from USA's new design guide, Dresden technical university (Germany) and LCPC (France).
Q: Do the deterioration models you use consider effect of climate change on pavement performance? How?	
Denmark	Yes, the variation of layer moduli is described through seasonal factors and for asphalt materials the damage rate is determined as a function of temperature.
Finland	Yes, the empirical statistical model includes both traffic loads and climate, but it is impossible to separate them.
Iceland	No
Norway	Yes, MEPDG (USA's), which is being implemented in road asset management system, has a climate model.
Sweden	Yes, we have a frost heave calculation model based on temperature data. The model uses thermodynamics.

Table 5: List of road deterioration models commonly used in Scandinavian countries (Saba, 2006).

8 Conclusions

The future climate changes will have repercussions on road performance and on the highway network. In this report a review of the most probable climatic changes that can be expected in the future and the consequences for the road asset have been described.

The most likely climate changes to be expected in the future have been investigated by the Intergovernmental Panel on Climate Change (IPCC) project and are listed in the AR4 report produced. Such climate predictions are based on the changes in CO_2 concentration in the atmosphere that will be likely to be observed if different economic, industrial and ecological behaviours will be followed. A range of possible scenarios (from optimistic to almost catastrophic) has been developed based on many climate models, more or less complex. From the IPCC's AR4, some general conclusions, independent on the geographical zone and on the scenario chosen, can be drawn. An increase in temperature is expected everywhere (especially extreme temperatures), which will consequently cause a melting of terrestrial ice and thus an increase in sea levels. Spring thawing in cold regions is likely to occur earlier. Also storms and surges are likely to be more frequent in the future decades, while the amount of precipitations seems to increase in Europe, at least during winter. Some further, consequential issues of relevance to roads are increasing coastal erosion and the relocation of population due to climate change.

While the IPCC has addressed a global description of future climate, other studies have been performed on a local scale. In particular, the UKCP09, for the UK, and Regclim, aimed at producing scenarios for climate change in Northern Europe, have been reviewed. The former is of particular importance as it introduces the concept of "probability of occurrence" for the different scenarios.

Temperature, solar radiation, rainfall and groundwater level rise are the climate change-related issues that will most affect roads. The predicted rise in temperature and in solar radiation, can cause rutting and ageing of the asphalt, with consequent development of cracking. In cold areas, thawing can become a more significant issue if the temperature floats daily around 0˚C during winter, as daily or multi-daily thawing can take place, with consequent temporary loss of strength on the road and need of traffic limitation. An increase in rainfall will lead to asphalt ravelling problems, and even cracking formation. When rainfall water reaches the unbound subgrade, destabilisation can take place if the drainage system is not able to remove it quickly. Drainage can be blocked by high intensity rainfalls, and the presence of cracks in the asphalt will represent a means for water to reach the subgrade even if the asphalt is almost impermeable. The increase of sea level and the probable increase of rainfall might change the groundwater level, and if this is too shallow, it can reduce the strength of the soil underneath the road. Some performance improvements can also result from climate change; the rainfall increase is likely to be concentrated in winter, while summers will not probably undergo large differences from the present, but the rise in temperature will increase the evaporation in thin asphalt layer roads, resulting in a drier subgrade; as a consequence, the road will gain strength. However, the effects of water and temperature changes are inter-related and thus cannot be considered separately.

Some experimental studies regarding the consequences of climatic factors on the road properties 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 on particular materials. Part of the difficulty lies in quantifying the different factors singly. However, some general aspects have been found. The temperature of the asphalt follows the same daily and seasonal changes of the solar radiation, although such temperature variation is less and less marked with depth. Air temperature has been shown to be less important than solar radiation. The temperature of the road surface is always higher than that of the air; on average such difference is about 7˚C. Some simple equations that link air temperature with asphalt temperature do exist (Barker et al., 1977; Lavin, 2003 etc.); although they do not take into account all the factors, they can be valuable for our purposes. The relationship between rainfall and subgrade moisture content is, instead, much less clear. The rainfall amount does influence the moisture content, but, if some data show a strong influence (Watmove, 2008), other studies, instead, show an almost negligible effect (e.g. Erlingsson et al., 2002). Also 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 a month. This is because soil, road surface, drainage and surrounding conditions can heavily affect the response of the road to rainfall. Thawing problems seem to be more related to temperature than rainfall, and can occur on a daily basis. However, rainfall prior to freezing (e.g. in the Autumn) has a large influence, as well. It is generally recognised that moisture content related problems and, in cold regions, thawing problems, are the main cause of pavement failure. Also the effect of the change in groundwater level is not very clear; the only field data found, presented by Simonsen et al. (1997), seem to show an influence on the moisture content of the subgrade's lower layers.

Projects involving an assessment of the climate change impact on roads and the development of plans to address the possible problems that will arise have been performed, on a national scale, by New Zealand (Transit) and Australia (Austroads). Transit identified the most vulnerable assets and analysed them in terms of necessity of acting in the present to manage future potential related problems, and in terms of feasibility. The results showed that the best solution was to repair the asset at a time when the need becomes evident, as current asset management practice seems to be adequate to cope with most predicted climate change impacts. Austroads' analysis of climate change impact stresses the importance of population and settlement patterns (especially where the highest concentration of population in relation to climate changes) and the change in road transport demand. The output shows that no immediate action is needed, although higher maintenance costs should be expected while future road reconstruction designs might need changes to overcome climate-related problems.

Models capable of describing the road performance with changes in temperature, rainfall etc. need to be used for our purposes; literature can be found about existing solutions. To take into account costs-related issues, PLCC and HDM-4 have been used by Austroads. MEPDG seems to be an interesting tool to study the sensitivity of pavement performance to climate change, and it is currently used in Canada and, recently, also in Norway.

8.1 Implications

The implications of the study are that a more detailed description of how climate is likely to change in the part of Europe of the project's interest is needed. The predictions shoul be on a short and medium term, as the road life expectancy is usually less than 50 years; thus, long-term predictions are not needed, except insofar that design standards will need altering.

To assess the road performance for a variation in temperature, solar radiation, rainfall and groundwater level, theoretical models have shown to be not always adequate, so models based on experimental, field data are needed. Some information was found regarding the relationship between air temperature and road temperature, and therefore these existing relationships only need to be validated, for example applying the existing equations to experimental data collected from the literature. Maybe, also some modification will be needed, for example in order to take into account different materials and the solar radiation. Once the relationship between climate and asphalt temperature is known, the properties of asphalt related to its temperature are well known and documented in the literature. The effects of climate on subgrade moisture content are instead much less clear due to the greater number of dependent variables. This subject will therefore need more investigation;

this will be concentrated on water infiltration, mitigation and pavement deterioration by means of modelling and laboratory tests. The change in soil strength related to moisture content changes will be finally studied, to have a complete description of a road's performance with climate change.

The cost-related analyses of the future interventions carried out by Transit New Zealand and Austroads seem to be a very important starting point for our project, especially for WP 5. In particular, an analysis of the population migration, age, demographics and immigration are likely to be a major issue that must be taken into consideration. This aspect gains even more importance if we consider that, according to Austroads, the increase of costs caused by a change in climate will be much higher for the road users than for the owner, and this means that changes in road design and maintenance will be induced more by the user expectation than by the owner's response to climate induced damage.

Both the Transit and Austroads projects deduced that it is not economical nor sensible to look at short-term changes and thus start to modify the maintenance methods from now, because the uncertainty is too high; rather, road design methods should be changed in order to introduce climate changes in the design models in order to overcome the possibility of climate change-related lower performance of current road designs. This means that, in the P2R2C2 research study, we might decide not to consider maintenance problems related to short-term climate changes, but rather to concentrate on the development of new road design methods that take into account climatic issues and on the study of suitable materials.

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