Coordination Action FP7-217920

Seventh Framework Programme
Theme 7: Transport

Deliverable D16

Report on possible impact of climatic change on road surfaces and tyres with regard to skid resistance, rolling resistance and noise emission

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under grant agreement n°217920

Main Editor(s)	Sarah Reeves, TRL, UK Phone: +44 1344 770 562, E-Mail: sreeves@trl.co.uk Peter Roe, TRL, UK Phone: +44 1344 770 286, E-Mail: proe@trl.co.uk
Due Date	31st May 2010
Delivery Date	31st May 2010
Work Package	WP4 Environmental effects
Dissemination Level	Public (PU)

Contributor(s)

Main Contributor(s)	Sarah Reeves, TRL, UK Phone: +44 1344 770 562, E-Mail: sreeves@trl.co.uk
Contributor(s) (alphabetical order)	Michael Ainge, TRL, UK Phone: +44 1344 770 596, E-Mail: mjainge@trl.co.uk Martin Greene, TRL, UK Phone: +44 1344 770 278, E-Mail: mgreene@trl.co.uk Peter Roe, TRL, UK Phone: +44 1344 770 286, E-Mail: proe@trl.co.uk Philip Sivell, Phil Sivell Consulting, UK Phone: +44 1483 822 553, E-Mail: phil@philsivellconsulting.com

Review

Reviewer(s)	Marco Conter, AIT Austrian Institute of Technology Manfred Haider, AIT Austrian Institute of Technology

Control Sheet

Version History			
Version	Date	Editor	Summary of Modifications
0.0	29/09/2009	WP4 group	Initial outline
0.1	20/01/2010	Sarah Reeves	Content moved from D12
0.21	23/03/2010	Sarah Reeves	Content expanded.
0.3	25/03/10	Sarah Reeves	Structure rearranged after discussions at WP4 technical meeting.
0.4	12/04/10	Sarah Reeves Peter Roe Martin Greene	Incorporating partner input on chapters 1 to 9.
0.5	05/05/10	Sarah Reeves Peter Roe Phil Sivell Mike Ainge	Incorporating partner comment on whole document. Submitted for Peer Review.
2.0	31/05/2010	Manfred Haider	Release version, only very minor changes from peer review version

Final Version released by		Circulated to	
Name	Date	Recipient	Date
Manfred Haider	31/05/2010	Coordinator	31/05/2010
		Consortium	31/05/2010
		European Commission	31/05/2010

Table of Contents

Abbreviations

Abbreviation	Meaning
AR4	IPCC Fourth Assessment Report
CO_2	Carbon dioxide
EU25	The 25 member states of the European Union
EV	Electric Vehicle
GHG	Green House Gas
H_2S	Hydrogen sulphide
ICE	Internal Combustion Engine
IPCC	Intergovernmental Panel for Climate Change
LCA	Life Cycle Assessment
LGV	Large Goods Vehicle
LHV	Longer Heavier Vehicle
PSV	Polished Stone Value
MOC	Meridional Overturning Circulation
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SRV	Skid Resistance Value
SUDS	Sustainable Urban Drainage Systems
VOCs	Volatile Organic Compounds
WFD	Water Framework Directive
WP	Work Package

Definitions

Term	Definition
Adaptation	Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC definition).
Climate	The average meteorological conditions that prevail over an area over a long period of time (usually thirty years).
Climate change	A change in the long term meteorological conditions of an area. Currently it is often used to refer to the mainly anthropogenic changes in climate.
Contact area	Overall area of the road surface instantaneously in contact with a tyre.
Friction	Resistance to relative motion between two bodies in contact. The frictional force is the force which acts tangentially in the contact area.
Harmonisation	Applied to several different measurement methods, harmonisation is "the adjustment of the outputs of different devices used for the measurement of a specific phenomenon so that all devices report the same value(s) (i.e. report in a Common Scale), except for some inaccuracy". This sense is mostly used in the referenced literature. Applied to European standards by CEN, "harmonised" standards for measurements are standard methods, which all European countries have agreed to use. In principle, CEN aims to get "one method for one property", which is referred to as "standardisation" in this report. Applied to the scope of TYROSAFE regarding "harmonisation of European skid resistance approach" it is dealing with defining a Common Scale. Such harmonisation can be achieved both through harmonisation of measurements by adjustment of the outputs or through standardisation of measurements.
Life cycle assessment	LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout the life cycle of a product (or service) from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle to grave). Commonly assessed impacts are greenhouse gas emissions, acidification, land use and depletion of resources. ISO 14040 provides guidelines on how to carry out an LCA.
Macrotexture	Deviation of a pavement from a true planar pavement with characteristic dimensions along the pavement of 0.5 mm to 50 mm, corresponding to texture wavelengths with one-third-octave bands including the range 0.63 mm to 50 mm centre wavelengths.
Mean profile	Descriptor of macro texture, obtained from a texture profile

depth	measurement as defined in EN ISO 13473-1 and EN ISO 13473-2.
Megatexture	Roughness elements with a horizontal length of 50 to 500 mm. Roughness of this magnitude can influence accumulations of water on the pavement surface (for instance, in unevenness).
Microtexture	Deviation of a pavement from a true planar pavement with characteristic dimensions along the pavement of less than 0.5 mm, corresponding to texture wavelengths with one-third-octave bands and up to 0.5 mm centre wavelengths.
Mitigation	An anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases (IPCC definition).
Skid resistance	Characterisation of the friction of a road surface when measured in accordance with a standardised method.
Weather	Short term meteorological conditions at a specific location.
Wet road skid resistance	Property of a trafficked surface that limits relative movement between the surface and the part of a vehicle tyre in contact with the surface, when lubricated with a film of water.

List of Figures

List of Tables

Executive Summary

The project TYROSAFE (Tyre and Road surface Optimisation for Skid resistance And Further Effects) is a Coordination and Support Action funded by the European Seventh Framework Programme. The project is addressing the lack of awareness of the importance and contribution of skidding resistance to safety, the lack of harmonised systems for comparing skidding resistance (even within member states), and the concern over conflicts with other important characteristics of road surfaces. The project, which began in July 2008 and runs to July 2010, is being carried out by a consortium comprising AIT (Austrian Institute of Technology) (formerly known as Arsenal Research), BASt from Germany, LCPC from France, RWS from the Netherlands, TRL from the United Kingdom, ZAG from Slovenia and FEHRL, the Forum of European National Highway Research Laboratories based in Belgium.

Work Package 4 is concerned with the environmental effects associated with harmonisation and optimisation of skid resistance, rolling resistance and noise. It has two themes: the potential impact on the environment of optimising the road surface characteristics and the potential impact that climate change might have on surface characteristics optimisation in the future. This report is Deliverable D16 and is focused on the potential impacts of Climate Change. Deliverable D12 covers the environmental effects of tyre/road surface interaction and identifies future research areas.

WP4 takes into account the findings of the other Work Packages in particular WP3 on the optimisation of road surfacings and tyres. It considers the environmental effects and climate change impacts on optimised surfacing and tyres.

Europe’s climate is projected to become hotter with a rise in average temperature of up to 5.5°C in some locations by the end of the century under a medium emissions scenario. This will result in hotter summers, milder winters and an increase in heat waves. Precipitation patterns are also expected to change, with drier summers and wetter winters depending on location. There are reports of these changes already affecting tyre/road surface interaction. The material properties of pavements and tyres vary with temperature and precipitation affects skid resistance, rolling resistance and tyre/road noise. Tyre hysteresis and inflation pressure are affected by temperature and bitumen binder softens in high temperatures. Some information is known on how skid resistance, rolling resistance and noise emissions vary with temperature. The impact of changes in precipitation patterns and seasonal changes will impact is less clear, for example changes in seasonal variation of skid resistance, changes in aggregate polishing and the build up of contaminants during drought. It is also unclear if there will be a reduction in winter service and if this would improve surface durability or decrease the restoration of skid resistance during winter.

In addition to these direct effects of climate change there are indirect impacts on tyre/road interactions due to actions taken to reduce greenhouse gas emissions or adapt to the changing climate. For example changes to vehicles, tyre material and design, as well as pavement construction and design. Potential future changes that could have an impact are:

- Vehicle developments – e.g. change in propulsion to electric, lighter cars, or the use of heavier LGVs.

- Tyre modifications – low rolling resistance, changes to material composition and manufacture such as inclusion of silica, non-oil products, and actions to reduce VOC emissions or increase recyclability.
- Pavement developments – inclusion of more recycled and secondary materials, lower temperature construction, use of bio-binders, more durable/lower maintenance pavements, energy recovery pavements, Sustainable Urban Drainage Systems (SUDS) and hard shoulder running.
- Behaviour changes - changes in demand, use patterns e.g. driven by user charging policies for model shift, decrease in speed limits, increase/decrease in congestion, changes in tourism patterns.

By considering the characteristics that optimise a surface for skid resistance, rolling resistance and noise emissions any potential conflicts between optimisation and increasing climate resilience were evaluated.

1 Introduction

The TYROSAFE Project is a Coordination and Support Action (CSA) in the Seventh EU Framework Programme and aims at coordinating and preparing for European harmonisation and optimisation of the assessment and management of essential tyre/road interaction parameters to increase safety and support the greening of European road transport.

This work is being carried out through four technical work packages (WP):

- WP1: Policies of EU countries for skid resistance / rolling resistance / noise emissions;
- WP2: Harmonisation of skid-resistance test methods and choice of reference surfaces;
- WP3: Road surfaces properties – skid resistance / rolling resistance / noise emissions;
- WP4: Environmental effects and impact of climatic change – skid resistance / rolling resistance / noise emissions.

A fifth work package provides for dissemination and raising awareness of the work of the project, with a sixth covering management issues.

WP1 addressed the issues of developing a harmonised approach to policies for skid resistance, rolling resistance and noise across Europe and detailed reports have been prepared covering this topic [1], [2]. Harmonised policies will depend on the provision of harmonised test procedures that could be used to gather data to support them. WP2 was designed to assist in achieving this end in relation to skid resistance measurement by reviewing existing measurement techniques and previous harmonisation attempts before proposing a roadmap to point towards a harmonised road skid-resistance assessment method by 2020 [3], [4], [5]. WP3 is making a detailed study of the various factors that influence skid resistance, rolling resistance and noise emissions, mapping their interactions, then reviewing optimisation and research needs [6], [7], [8].

WP4 is designed to complement the other work packages, interacting with them where appropriate to reach its two objectives:

- Identify research areas for possible environmental effects resulting from optimisation of specific parameters.
- Identify the possible impact of climate change on skid resistance, rolling resistance and noise emissions.

The work in WP4 is being carried out as a single task that began in June 2009 and will last one year. It has involved an initial literature review and an expert workshop (held in Cologne, Germany on the 2 December 2009), in addition to collating the TYROSAFE team's existing knowledge.

The work package has two main strands; the impact that introducing a harmonised approach to skid resistance could have on the environment and the effects that climate change might have on skid resistance. It covers:

- Skid resistance measurement methods and survey techniques
- Altered skid risks from climate change effects
- Optimisation of the provision of adequate skid resistance, including materials supply and replacement, tyre properties and impacts on rolling resistance and noise emissions
- The influence of winter conditions on skid resistance and the approaches taken to ameliorate these effects, such as salting and the use of studded tyres. How these approaches may impact on the environment and the optimisation of surface properties.

Although the primary focus of the project is on skid resistance, tyre/road surface noise and rolling resistance were also considered.

The first written deliverable for WP4, D12 [9], summarises existing knowledge on the environmental impacts of tyre/road surface interaction, identifying the important factors and establishing the gaps in knowledge in order to suggest the important areas for future research. This second deliverable, D16, covers the possible impacts of climate change and the implications for optimisation of skid resistance, rolling resistance, noise emissions.

The EC white paper on *Adapting to climate change: towards a European framework for action* [10] states that climate change adaptation needs to be integrated into EU policy. WP4 will ensure that climate change issues are considered in the harmonisation process.

The remainder of the report is laid out as follows:

Chapter 2 sets out the general background about climate change in Europe.

Chapter 3 describes the climate change impacts on transport.

Chapter 4 examines the relationship between temperature and tyre/surface interaction.

Chapter 5 looks at the impact of precipitation on skid resistance or tyre/road friction, noise emission and rolling resistance.

Chapter 6 describes how the weather influences the seasonal changes on tyre/surface interaction.

Chapter 7 describes how structural damage as a result of climate change can impact on the surface characteristics.

Chapter 8 identifies the influence of climate on the measurement of skid resistance.

Chapter 9 discusses the potential indirect effects of climate change and how this could impact on tyre/road interaction.

Chapter 10 discusses the influences of climate change on harmonisation and optimisation of surface characteristics.

Chapter 11 presents the conclusions of this review.

2 Climate change in Europe

Both the built environment and human behaviour are influenced by climate. Road pavements are constructed to be suitable for the climate historically experienced in a particular location. However, the climate in Europe (and the rest of the world) is changing and is projected to be significantly different by the end of the century. In order to maintain standards of road safety and durability cost effectively it is important to understand and prepare for these changes. This requires information on the type and extent of the climate changes expected and an understanding of how climate variables such as temperature and precipitation affect transport.

2.1 The information available on the future climate

Information on the future climate is provided by models which combine the physical principles of how the climate system works together with the future greenhouse gas (GHG) emissions driven by socio-economic scenarios of global development to project changes in climate variables over time. Advances in computer power and the growing imperative to understand as much as possible about climate change mean that these models are becoming increasingly sophisticated and produce higher resolution data. There are always going to be uncertainties associated with modelling the future climate as models are never perfect representations of a real system and we can only develop plausible scenarios of how the world will develop in terms of population, reliance on fossil fuel and advances in technology. Nonetheless, these models provide a useful tool in understanding how much the climate is likely to change and how quickly the changes are occurring.

Several of these complex models (referred to as General Circulation Models) exist, producing slightly differing results, but with the same general trend. The Intergovernmental Panel on Climate Change (IPCC) is the international body set up by the United Nations Environment Programme (UNEP) and the World Metrological Organisation (WMO) to review research on climate change. It publishes Assessment Reports at regular intervals reviewing the results of research on climate change carried out throughout the world in order to produce a clear summary of the current understanding. The Assessment Reports include a summary of the climate projections produced by the 23 established and tested global climate models currently available from 11 different countries; France, Germany, UK, Norway, Australia, USA, China, Canada, Japan, Russia and Korea.

2.2 The future climate

All the models show the global temperature continuing to rise. By the end of the century the mean temperature is projected to rise around 1.8°C for the low emissions scenario (the likely range is between 1.1 and 2.9°C) and around 4°C for high emissions (likely range 2.4 to 6.4°C). To put this in perspective the global mean temperature during the last ice age was 5°C lower than today. The emissions scenarios used for the last two assessment reports can be found in the Special Report on Emissions Scenarios (SRES) [11]. There are 40 scenarios describing potential future developments in demographics, social, economic and technology. These scenarios are grouped into four families described by IPCC as:

A1: "The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B)."

A2: "The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines."

B1: "The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives."

B2: "The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels."

The scenario producing the lowest emissions is B1 and the highest is A1FI (fossil fuel intensive). A1B is the scenario most often quoted as it is a medium emissions scenario with a mixture of energy sources and produces the emissions trajectory it is currently thought we are following most closely. None of the emission scenarios takes into account intervention to reduce emissions.

Some models suggest that the Gulf Stream (part of the Atlantic Meridional Overturning Circulation (MOC)) could slow down due to the warming of the northern oceans and decrease in salinity. The MOC currently keeps parts of Europe up to 5°C warmer than they would otherwise be. No model predicts a sudden collapse of the MOC this century and the IPCC Fourth Assessment Report (AR4) states that even if the MOC was to collapse, the effect would not be sufficient to prevent Europe from warming. Recent research shows no discernable trend at this time [12].

A certain amount of temperature rise is now unavoidable due to the inertia of the global climate system. Even if no GHG emissions were emitted from today onwards temperatures would continue to rise for the next 30 to 40 years due to past emissions. After this period (i.e. approximately the 2040s) the degree of rise is dependent on the development pathway taken and the success of international actions to reduce GHG emissions. The EC has stated its commitment to limit the global temperature rise to 2°C above pre-industrial levels, which is thought to be the level required to avoid the most dangerous climate change impacts. This is a challenging target, and even if it is met the future climate will be very different to that experienced today.

2.3 Climate projections for Europe

Global climate models can be downscaled to provide information on a regional scale at a higher resolution. Figure 2-1 and Figure 2-2 show the projections for Europe from the most recently published IPCC Assessment Report (AR4 [13]). Figure 2-1 shows the projected change in mean temperature for 2080 to 2099 compared to 1980 to 1999. The maps shown are for the A1B global development scenario and are an average of the results of 21 different climate models. DJF are the winter months (December, January, and February) and JJA the summer months (June, July and August).

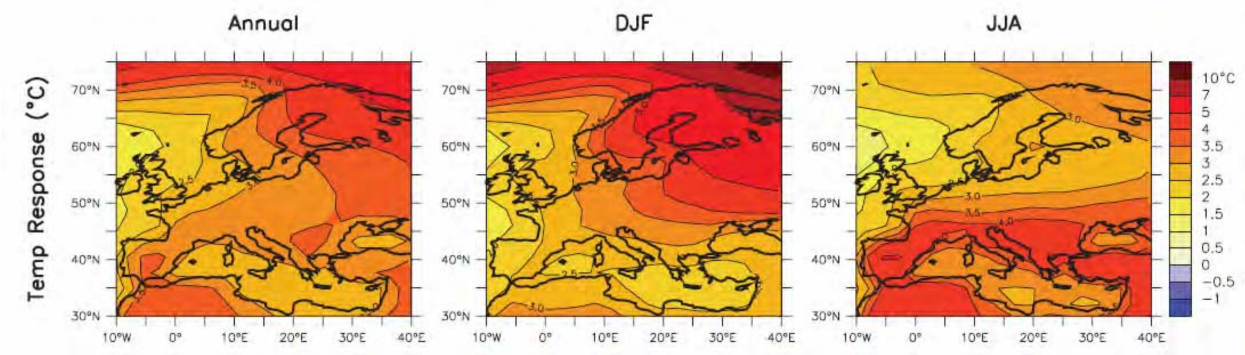

Figure 2-1. Projected change in mean temperature for Europe between 1980 to 1999 and 2080 to 2099, A1B scenario [14]

Europe is warming faster than the global average. The annual mean temperature over land has risen 1.3°C since industrial times. The temperature is projected to rise at a rate of 0.1 to 0.4°C per decade reaching increases of 1°C to 5.5°C (depending on emissions scenario) by the end of the century compared to the 1960-1990 average.

The magnitude of the temperature change varies depending on location and season. The largest warming occurs over northern and eastern Europe in the winter and southern Europe in the summer. This means in northern Europe winters will become much milder, with less snowfall and frost days and southern Europe will experience hotter summers. There will also be changes in extreme temperatures, i.e. more frequent, hotter and longer heatwaves.

As shown in Figure 2-2 the changes in precipitation are more variable. There is an increase in annual rainfall in northern Europe and a decrease in the south, with little change in central regions. However, there is projected to be a change in the seasonal pattern of rainfall with central Europe experiencing wetter winters and drier summers. There are more likely to be periods of intense rainfall (with the potential for flooding) and periods of no or little rainfall (drought).

Annual DJF JJA

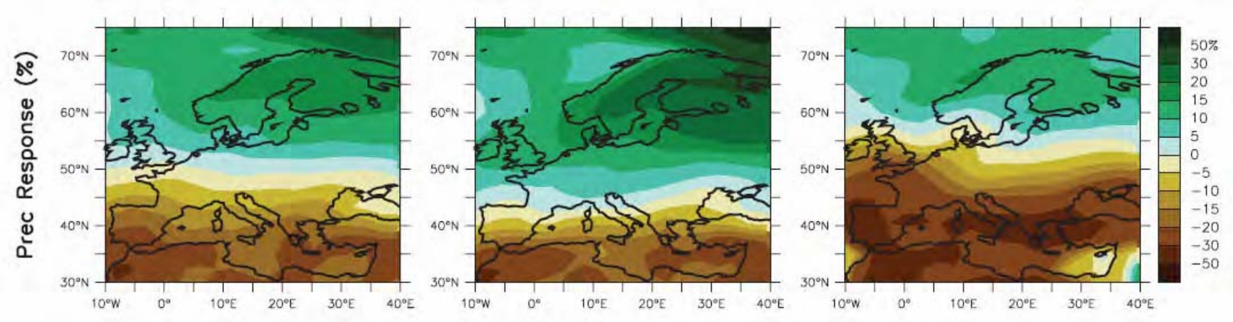

Figure 2-2. Projected change in precipitation between 1980 to 1999 and 2080 to 2099, A1B scenario [14]

AR4 identified the key impacts for Europe as:

- Extreme seasons, in particular exceptionally hot and dry summers and mild winters;
- Short-duration events such as windstorms and heavy rains; and
- Slow, long-term changes in climate which, among other impacts, will put particular pressure on coastal areas e.g. through sea-level rise.

2.1 What this means for the different European counties

Different countries will experience climate change impacts to varying extents and will have different priorities to address. Countries in the south that are already hot and dry during summer will suffer most from extreme heat and drought, whereas countries in the north are more likely to find that an increase in heavy rain will present the greatest challenge. It is generally considered that richer, more developed countries have a greater capacity to adapt to a different climate than poor countries.

One of the aims of the European 6th framework project ENSEMBLES [16] was to develop a high resolution regional model for Europe based on simulations from an ensemble of different global climate models. The results of this project have been used to create a map which illustrates the change in temperature projected for the European capital cities for 2021 to 2050.

Before ENSEMBLES a project called PRUDENCE – Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects [17] was carried out. This was a 5th framework project that developed regional high resolution studies for Europe for 2071 to 2100 by downscaling different global models.

Other relevant European projects include:

CECILIA - Central and Eastern Europe Climate Change Impact and Vulnerability Assessment, a 6th Framework project. [18] This used data from PRUDENCE and ENSEMBLES to look at impacts on different sectors.

ATEAM – Advanced Terrestrial Ecosystem Analysis and Modelling, a 5th framework project.[19]

MICE – Modeling the Impact of Climate Extremes, a 5th framework project. [20]

STARDEX -Statistical and regional dynamical downscaling of extremes for European regions, a 5th framework project.[21]

It can often be difficult to visualise what the projected climate will be like in reality. One method of illustrating the change is by the use of spatial analogues. That is by identifying a location that currently experiences a climate similar to that projected. However, spatial analogues need to be used with care as while selected climate indicators may be similar, the interaction of all climate variables and other factors such as geology and topology can differ.

Figure 2-3 shows the spatial analogue concept applied to ten major European cities. A climate relocation map has been produced by plotted cities at locations which currently experience the mean temperature the city is projected to have by the end of the century [15]. All the cities are projected to experience a climate that more closely matches the climate of countries several thousand kilometres to their south. For example Paris will experience temperatures similar to those currently found in Southern Spain and Helsinki those found in Poland.

More information on how the climate is changing in different European counties is given in the Appendix.

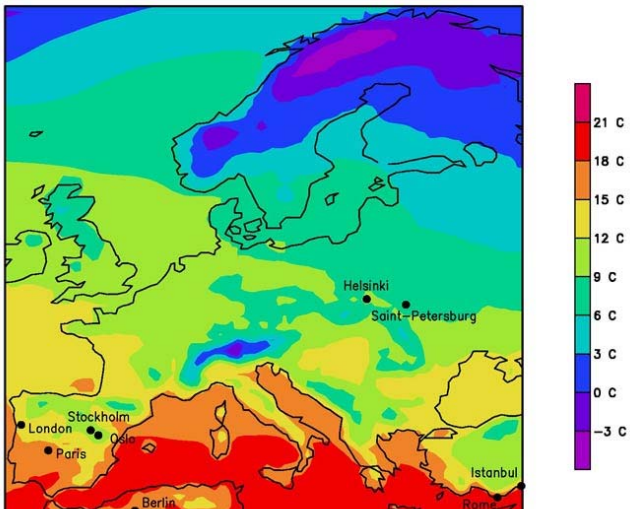

Figure 2-3. A spatial analogue depicting Europe's climate in 2071 - 2100 (Scenario A2, HadRM3H) [15]

3 Climate change impacts on the transport sector

The majority of European countries have been evaluating what the climate changes projected for their countries will mean in terms of the risks to their key industries, critical infrastructure and welfare of their citizens. Several countries (Denmark, Finland, Germany, France, Hungary, Netherlands, Portugal, Slovakia, Spain and the UK) have set up national adaptation programmes, and plans for adaptation to climate change have been included in flood protection plans of the Czech Republic and coastal protection plans of the Netherlands and Norway [13], [18], [24].

Transport has been identified by most national studies as a sector particularly vulnerable to climate change impacts. The large scale disruption and economic cost inflicted on a country if its transport infrastructure is significantly damaged make it important that climate impacts are understood as well as possible. In some countries (e.g. UK, Finland) the national road authority has an adaptation action plan to adapt the road network to climate change and other road owners are assessing the need to change pavement materials and increase the capacity of drainage systems.

In addition to the work being carried out by individual countries there are a number of European research projects on the impacts of climate change on transport.

'Road Owners Getting to Grips with Climate Change' is a trans-national joint research programme initiated by ERA-NET ROAD with partners from the National Road Administrations (NRA) of Austria, Denmark, Finland, Germany, Ireland, Netherlands, Norway, Poland, Sweden and United Kingdom [22]. It is a research programme focussed on increasing understanding of the impacts of climate change on roads. It is funding four projects, whose outputs were due in March 2010:

- IRWIN: Improved local Winter Index to assess Maintenance Needs and Adaptation Costs in Climate Change Scenarios
- P2R2C2: Pavement Performance and Remediation Requirements following Climate Change
- RIMAROCC: Risk Management for Roads in a Changing Climate
- SWAMP: Storm Water prevention - Methods to Predict Damage from the Water Stream in and near Road Pavements in lowland Areas

There are two 7th framework projects looking at climate change and transport; EWENT: Extreme Weather impacts on European Networks of Transport [25] and WEATHER: Weather Extremes: Assessment of impacts on Transport Systems and Hazards for European Regions [26]. These projects are looking at the impacts of extreme weather events on transport at a network level.

3.1 Identifying the impacts

Engineers are accustomed to designing transport infrastructure to withstand the climate experienced at different locations, so understand some of the impacts climate can have. However, infrastructure is currently constructed to be appropriate for the historical climate of a region. As the climate changes the materials and designs formerly used may not be the most suitable. The Stern Report [27] found that there were significant cost benefits from early proactive action instead of reactively dealing with climate change impacts. Therefore identifying the aspects of the transport system which will be most affected by climate change and adapting accordingly is an important economic issue as well as being beneficial in terms of reducing disruption for users.

Various studies have been carried out at national, regional and local scales to identify the impacts of climate change on the transport sector, either as part of a general assessment or as a sector specific study (e.g. Germany [28], London [29], Sweden [30], Australia [31] and the UK [32]). The main impacts on road infrastructure identified in these studies are:

- Water damage as a result of increased flooding and sea level rises
- Deformation in asphalt pavements in high temperatures
- Fatting up of asphalt roads in high temperatures
- Subsidence and heave as a result of changes in soil moisture
- Increased bridge scour
- Increased growing season affecting maintenance of verges
- Landslides
- Tree damage from high winds
- Less deterioration from fewer frost days
- In northern countries permafrost roads are vulnerable to increases in winter temperatures limiting their use.

Skid resistance has been recognised in several studies as an aspect of transport that is being affected by climate change. Structural and surface damage sustained as a result of climate change such as subsidence, heave, binder stripping, deformation, cracking and potholes can also impact on tyre/road surface interaction. For example unevenness can increase rolling resistance and ruts may fill with water during rainfall increasing the risk of aquaplaning.

3.2 Climate and tyre/road surface interactions

Climate conditions were identified in WP3 as factors which influence tyre/road surface interaction. The most important climate variables for surface interaction are temperature and precipitation, although storminess can have some impact as it increases the debris on the road surface and sea level rises will increase the risk of flooding on coastal roads. In some cases it can be the combination of climate variables that have an impact, e.g. a long period of drought followed by intense rainfall.

The most commonly identified impact of climate change on skid resistance is the potential loss of skid resistance in extreme high temperatures due to fatting up and aggregate embedment. However, some less visible impacts have been recognised including changes in the seasonal variation of skid resistance [34]. A review of how climate change will affect their road policies and standards by three UK local authorities [35] identified that their skid resistance policy would be affected by hotter and drier summers, more intense rainfall and stronger winds and more storminess. They also considered that high skid resistant surfacing and early life skid resistance would be affected. The UK Highways Agency identified skid resistance as a highly vulnerable aspect of pavements in its Adaptation Strategy [36] and stated it was a high priority for research.

In addition to the direct effects that changes in temperature and precipitation are likely to bring, climate change could have an indirect effect on tyre/surface interaction by driving the actions that society takes. Such action might be directed at the reduction of carbon emissions, for example by changing to electric cars or greater use of recycled aggregates in pavements. These actions could affect skid resistance provision and performance, as could adaptation actions, such as changing the binder in asphalt pavements to cope with higher temperatures. Indirect changes are often harder to predict and prepare for than direct climate changes.

No specific studies on the climate change impacts on tyre/road interaction were found during the review. However, information on how different pavement and tyre materials and designs respond to climate variables, such as temperature and precipitation can be combined with climate projections to identify the most significant impacts of climate change on tyre/road surface interaction. The following sections summarise the findings of a literature review on how temperature and precipitation affect skid resistance, rolling resistance and tyre noise.

4 The influence of temperature on tyre/road surface interaction

Both tyre rubber and asphalt pavements are viscoelastic materials, therefore their properties vary with temperature. The temperature of the road and tyre surface can be very different to the air temperature, but will increase if ambient temperature rises. In some circumstances road temperatures can be around 25°C higher than air temperatures, reaching up to 65°C [38]. Different types of surfacing differ in the speed and scale of their response to ambient temperatures, depending on pavement thickness, albedo, porosity etc. For example a dark freshly laid asphalt surfacing can have a temperature 10°C higher than a lighter concrete surface [37]. However, with aging asphalt becomes lighter and concrete darker reducing the difference in albedo. The relationship between air and road temperature, and air and tyre surface temperature on different types of road surface were investigated by Anfosso-Lédée [39]. The results show no difference in temperature between concrete and asphalt pavements. It appears that other factors which affect pavement temperature such as cloudiness, shade for example from vegetation, aggregate colour, the amount of aggregate at the pavements surface (i.e. pavement type) can remove reduce these differences.

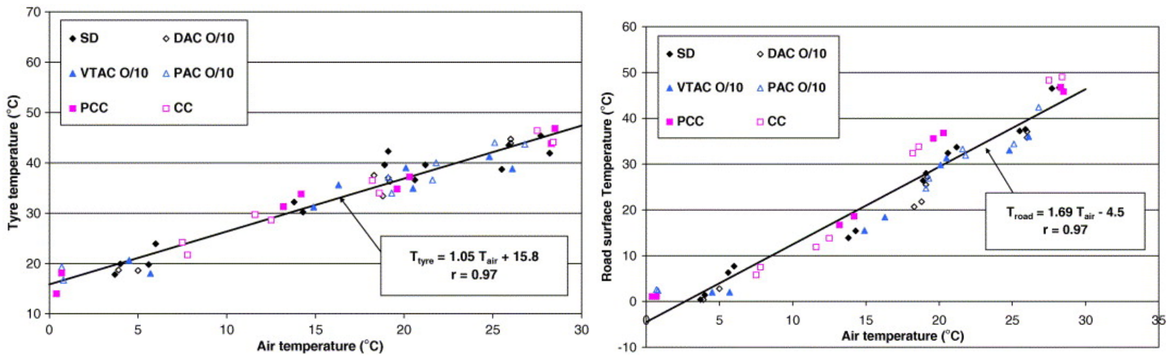

Figure 4-1. Relationship between air temperature and (a) tyre temperature and (b) road surface temperature [39]

Where:

- DAC is a dense asphalt concrete (0/10 grading, 6.2 cm thick on average, with a Mean Texture Depth (MTD) of 0.86 mm;
- PAC is a porous asphalt concrete 0/10 grading, 4 cm thick on average, with MTD of 1.67 mm;
- VTAC is a very thin asphalt concrete 0/10 grading, 2.5 cm thick on average, with MTD of 1.49 mm;
- SD is a rough epoxy bound surface dressing 8/10 grading, with MTD of 4.3 mm;
- SSD is a thin and smooth epoxy bound surface dressing 0.8/1.5 grading, with MTD of 0.70 mm;
- CC is a cement concrete textured with burlap, 12 cm thick plates, with MTD of 0.8 mm;
- PCC is a porous cement concrete, 12 cm thick, with MTD of 1.14 mm.

A combination of the effects of temperature on the pavement and tyre can generate changes in skid resistance, tyre/road noise and rolling resistance. These effects are summarised in the following sections.

4.1 The effect of temperature on the road surface

Asphalt pavements are particularly vulnerable to temperature compared to concrete pavements as bitumen is visco-elastic and so its properties vary according to temperature. The vulnerability of asphalt pavements to deformation at high temperatures depends on the type of binder used (e.g. penetration value). In high temperatures bitumen can soften causing bleeding or fatting up and in cold temperatures it hardens. Fatting up is when the binder comes to the surface of the pavement and fills in any air voids reducing texture. This decreases skid resistance in the wet. When the binder softens, aggregates can also become embedded by the action of traffic, reducing exposed aggregate in the contact area and therefore microtexture. Models developed by Ongel et al. based on field measurements [40] indicated that microtexture is affected by temperature, age, and traffic whereas macrotexture is affected by rainfall, number of freeze–thaw cycles and pavement mix variables. It is thought the cumulative temperature over the lifetime of the pavement is the important parameter in the reduction of microtexture rather than the average annual temperature.

Noise decreases by around 1dB per 10°C increase in temperature as the road and tyre material softens. This effect has been found to vary with the type pavement and tyre design and material. Noise was found to decrease by around 0.1 dB(A) per °C for dense asphalt and 0.06 dB(A) per °C for more porous asphalt pavements. Little correlation was found on concrete pavements. A spectral analysis showed that the temperature effect is highest in the low and high frequency range; from this the authors concluded that generating mechanisms rather than propagation are creating the effect [39].

The temperature affects the aging of the binder, as the oxidation rate and loss of volatile components increases with temperature. The average viscosity of a pavement exposed to average temperatures of 23°C over four years is ten times greater than a pavement exposed to 17°C [37]. A more open pavement structure increases the oxidation rate, although the use of modified binders which give a thicker binder coating can reduce this. As the binder ages, it becomes stiffer which may produce a small decrease in rolling resistance and cause tyre noise emissions to increase.

4.2 The effect of temperature on tyres

Tyre surface temperature is related to air and pavement temperature, but with use it can increase to around 80°C [33]. This means tyres are designed to withstand a large range of temperature. Tyres are categorised (A to C) by manufacturers to indicate their resistance to the build-up of heat. The hysteresis of the tyre material and ambient temperature affects the way heat is dissipated as it is used.

At higher temperatures tyre material is more flexible and returns to its un-deformed state more quickly. This means less energy is lost during deformation and the rolling resistance decreases. The coefficient of rolling resistance decreases approximately one percent for each degree Celsius of temperature rise. The greater flexibility also increases the grip until a maximum is reached. The effect of ambient temperature on tyre rolling resistance has been studied by Firestone Tire and Rubber Co. The results indicated that the initial rolling resistance at -20 °C might be more than twice as large as at 40°C [41]. In a French study [42] the rolling resistance coefficient decreased from 0.025 at 20°C to around 0.016 at 40°C. Surface temperature, internal tread temperature and the temperature of the air in the tube all affect rolling resistance.

Temperature also changes the tyre inflation pressure; for every 5°C change in ambient temperature, the pressure will change by about 0.03 bar (0.5 psi, 3kPa). Incorrect pressure will affect grip and rolling resistance. The manufacturer's level is set at cold temperatures (e.g. 20°C); this may be too low when tyre pressure is measured at much higher ambient temperatures. The advent of tyre pressure sensors may help better regulation of tyre pressure if they include temperature compensation.

Higher temperatures increase the rate at which tyre rubber ages. Over time oxidation and vulcanisation hardens the rubber, decreasing grip and rolling resistance, and increasing noise. Drivers are therefore often advised by manufacturers to replace tyres after six years even if they are not worn.

4.3 Other temperature effects

Temperature has a range of other effects that impact on skid resistance:

Freeze-thaw – Incidences of freeze-thaw depend on the changes of temperature around the freezing point of water. The use of de-icers increases the number of freeze-thaw cycles. Depending on how they are embedded the action of freeze-thaw can shatter some types of aggregate exposing an unpolished surface, thereby increasing skid resistance. However this roughening of the road surface also increases rolling resistance. An increase in winter temperatures could increase or decrease the frequency of freeze-thaw depending on how close current values are to zero degrees Celsius. In addition, snow cover can have an insulating effect preventing frost from penetrating deep into a pavement. In northern countries the loss of the insulating effect of snow as temperatures rise might have a negative effect. Finland has investigated this possibility and found that the effect will be different in different parts of the country. In northern Finland the increase in temperature will be large enough that overall there will be a decrease in frost, whereas in southern and eastern Finland the reduction in the insulating snow cover will increase the depth of frost [43].

Wear – Pavement surface wear increases at lower temperatures as the tyre and binder harden and are more abrasive. Tyre wear increases with increasing temperature as the rubber softens and is more easily abraded. Wear produces particulates and increases road roughness, therefore increasing rolling resistance.

Winter treatments – At low temperatures winter salting, sanding and use of studded tyres are used to increase friction. Salting increases pavement wear in winter through abrasion and increasing the number of freeze-thaw cycles. This results in new aggregate particles being exposed increasing skid resistance and studded tyres can retexture the road surface. A rise in winter temperatures is likely to reduce the amount of winter treatment required, which could create issues relating to polishing in countries which previously did not have a problem. Black ice causes more accidents than snow [44], so in some regions milder winters could mean the temperature hovers around zero and more black ice is formed instead of the more obvious and therefore potentially less dangerous snow.

Vegetation – Climate change is increasing the length of the growing season, impacting on roadside vegetation. An increase in the growing season and increased storminess could generate more leaf fall affecting tyre/road friction. Although this is more of an issue for rail, on rural roads where the traffic volume is insufficient to blow debris off the road, crushed leaves can produce a slippery residue.

5 The influence of precipitation on tyre/road surface interaction

The level and pattern of precipitation can affect the way the tyre and road interact impacting on tyre/road friction, noise emissions, rolling resistance and wear.

5.1 Wet conditions

Tyre/road friction decreases significantly when the road surface is wet as water acts as a lubricant preventing full contact between the tyre and road. More frequent rainfall in winter could extend the period at which drivers are at risk from reduced friction conditions. More intense rainfall will increase the opportunities for water to build up on the road surface, increasing the water film thickness and with it the risk of aquaplaning.

More weathering occurs when the road surface is wet making the surface rougher and increasing skid resistance. Skid resistance is restored less by summer rainfall than winter rain this could be because the surface water evaporates more quickly in the warmer temperatures. In the winter the pavement surface can remain wet for long periods of time.

Water can also act as a lubricant preventing aggregate polishing (see below).

5.2 Drought conditions

5.2.1 Contaminants

During periods of dry weather contaminants such as dust and oil build up on the pavement surface reducing friction. Estimates suggest that contamination can reduce the skid friction co-efficient by 0.1 (measured by SCRIM) [45]. Ongel [40] (2009) quotes work by Hill and Henry, who found in 1978 that skid resistance decreased with the number of days without rain, until a plateau was reached after seven days. A study in Maryland found that a 0.1 inch (2.5mm) increase in daily average rainfall could increase the friction number by 1.25 [46].

The characteristics of the contaminant determine the reduction in skid resistance; large round particles reduce skid resistance more than small angular particles. Silica dust (from pavement wear) and cutting fluid (oil/water) have been found to reduce wet friction, whereas tyre wear contaminants do not [47]. Skid resistance is lower on up gradients than down and is less at signals as the contamination is worse from leaks from stopped vehicles, brake and tyre dust. It has been found that the degree to which contaminants affect skid resistance varies according to the type of pavement [46].

When rain does eventually fall after a drought, there is a high concentration of contaminants in the “first flush” which makes the road extremely slippery (viscous aquaplaning). It also means that the road run-off has a large concentration of pollutants with potential consequences for local water courses already depleted due to the dry weather. A study carried out in Israel [48] which has long dry summers followed by a short wet season showed that contaminants can reduce skid resistance by as much as 20% (see Figure 5-1).

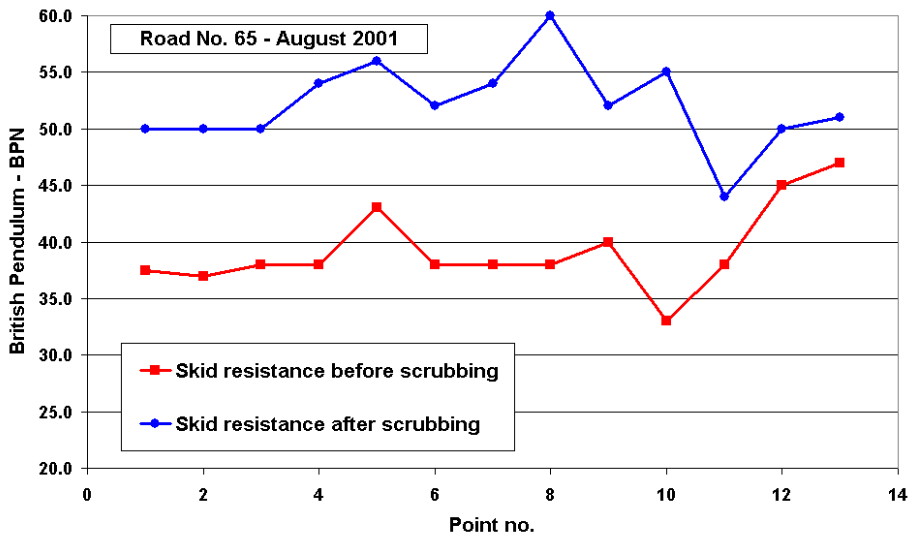

Figure 5-1. Reduction in skid resistance due to contaminant build up during drought [48]

In Israel skid resistance has to be measured at the beginning of the summer to avoid the effect of the build up of contaminates. They carry out additional surveys in areas likely to have large amounts of contamination at the end of the summer and these are treated (e.g. by water blasting) if necessary or warning signs erected. They also have problems with polishing during the dry summers especially on highly trafficked roads.

5.2.2 Polishing

Aggregates are polished by the action of traffic on the fine dust that collects during dry periods decreasing the skid resistance. Water acts as lubricant, so reduces polishing. The type of contaminant as well as the type of pavement aggregate is important [49]. Hard fine (less than 10µm) contaminants decrease skid resistance, hard course (greater than 1mm) contaminants restore it.

Soft contaminants when dry, slightly increase skid resistance, when damp under the action of traffic they can further increase skid resistance on aggregates that have a softer grain matrix and a variable particle size. The difference in the hardness and geological make-up of the contaminants and the aggregate surface being polished determines the change in skid resistance.

6 The impact of seasonal weather patterns on tyre/road surface interaction

The combination of temperature and precipitation effects produces seasonal variations in tyre/road surface interaction as shown Figure 6-1 and discussed in more detail in the TYROSAFE Deliverable D10 [6]. This seasonal effect of skid number variation has been recognized as far back as in 1931 by Bird and Scott [50] and it can be as much as 30 SN [51]. However recently it has been suggested that this pattern is being modified as a result of the changing climate [34].

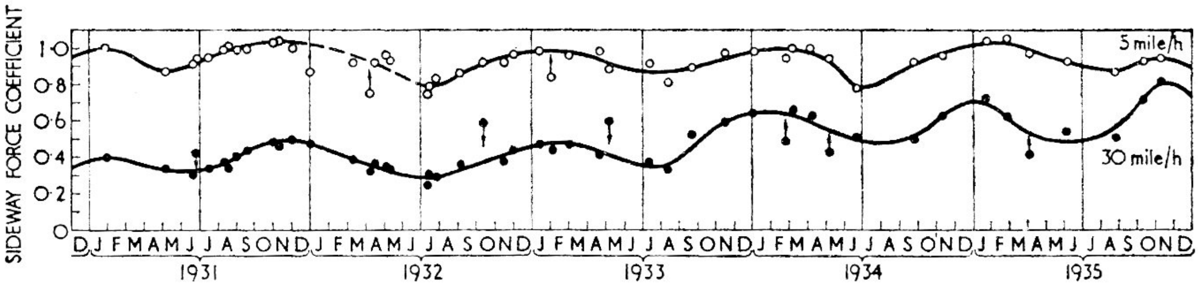

Figure 6-1. Seasonal changes in skidding resistance for a section of road [52]

6.1 Climate influences on this cycle

Studies show that in countries such as Australia where the hottest season is the wettest, not the driest, there may be different seasonal patterns indicating that both temperature and precipitation play a role in the phenomenon. However, the period that the pavement is wet has been identified as the key parameter [45].

It has also been observed that a particularly hot dry summer produces lower than normal skid resistance values and a wet summer can produce higher [53]. If hot dry weather occurs early in the year, the minimum value will be reached earlier and the skid resistance will be lower for longer [45]. Similarly, if the autumn is dry and mild, then the skid resistance will not recover so quickly.

In the 1976 study conducted by Hosking and Woodford [53] skid resistance values throughout the year from 1958 to 1968 in the south east England were monitored. The study showed that during the dry summer of 1959 skid resistance was low and after the severe winter of 1962/1963 the skid resistance was high. They found that the summer SRV varied from 0.43 to 0.55 depending on the type season.

These differences between countries and years shows that the combination of precipitation and temperature plays a large role in determining the timing and magnitude of formerly experienced. This suggests that as the combination alters due to climate change the cycle will change.

6.2 Changes to the cycle

A survey was carried out by WDM for the UK Highways Agency looking at how skid resistance changed according [34]. The survey studied 39 sites in the UK over the period 2002 to 2007. The authors observed that the seasonal skid resistance pattern changed from

2005 onwards with the August to September period exhibiting a lower skid resistance than the May/June period when previously it was similar. They concluded that the skid resistance is not recovering as early in the season as historically, perhaps due to milder autumns. They also found greater variation in skid resistance values compared to previous years. Additionally, they observed that the impact of the change in seasonal climate varied significantly at the sites surveyed. Some sites appeared more susceptible than others. The authors said that a further study was planned to investigate why this was the case.

The authors found that there was lower skid resistance in the dry summer of 2006 and also in the summer of 2007 even though this was a relatively wet summer. Perhaps as suggested in other work [54] summer rainfall does not increase skid resistance, possibly as the rainfall evaporates too quickly for weathering to occur. It is cold wet winters that are required to restore skid resistance and 2006/2007 was wet, but mild. It was suggested that the increase in summer traffic could counter-act the weathering effect. The winter of 2005/2006 was cold, but 2006 figures were low due to polishing during the dry summer.

This was the only study found studying how seasonal variation changed over time. Further long term studies are required to indicate if there is a change occurring as a result of climate change.

7 The impact of pavement structural damage on surface effects

Pavement damage by climate change impacts such as subsidence, heave, cracking, deformation, ravelling and potholes can impact on the road surface/tyre interaction. Defects that produce unevenness will increase rolling resistance and there is the potential for potholes and ruts to fill up with water increasing the risk of aquaplaning. It is not the remit of TYROSAFE to describe all the potential impacts of climate change on roads, more details on the possible damage to different types of pavement can be found elsewhere e.g. [55], but a brief indication of some types of structural damage that could occur and how these could impact on skid resistance, noise and rolling resistance are given below.

7.1 Increase in temperature

Higher temperatures can affect the frequency of different types of damage to pavements. Table 7-1 gives a list of pavement defects and their potential effects on skid resistance, noise emissions and rolling resistance.

Table 7-1 . Possible surface effects of temperature dependant structural damage to pavements

Defect type and cause	Potential surface effects of defect
Higher temperatures increase the risk of deformation such as rutting and shoving (especially in heavy traffic with a high proportion of LGVs).	The resulting unevenness from pavement deformation can increase rolling resistance. Dips in the surface profile may fill up with water during heavy rainfall increasing the risk of aquaplaning.
The rate of aging increases with temperature. The oxidation rate doubles for every increase of 10°C [37].	Aging increases the stiffness of the binder which may result in surface cracking under trafficking. The surface damage could increase rolling resistance.
In high temperatures the binder softens, which can cause fatting up/bleeding where bitumen flows to the pavement surface.	Excess bitumen on the pavement surface can reduce texture depth adversely affecting skid resistance.
The number of freeze-thaw cycles may decrease or increase depending on location.	Freeze-thaw can create cracking and deterioration, particularly where the pavement is already in a poor condition and moisture can enter the structure. Loose aggregate could be a skid hazard, generate more noise emission and increasing rolling resistance.
Where studded tyres are used, the expected reduction in use could reduce the abrasion damage to pavements. This would mean less ruts and a more even surface.	A reduction in surface damage would decrease rolling resistance and the risk of aquaplaning. However, there would be less restoration of the skid resistance lost due to polishing.
The thermal expansion of concrete	This can cause unevenness increasing rolling

pavements can cause slabs to warp or in extreme cases "blow out" (compression failure).	resistance.

7.2 Changes in precipitation

Changes in precipitation patterns could result in an increase in the types of defect identified in Table 7-2.

Table 7-2. Surface effects of moisture dependant damage to pavement

Defect	**Potential surface effects**
Subsidence and heave caused by changes in soil moisture. This is particularly a problem where there are highly plastic soils such as clay. Differences in the soil moisture between verges and the pavement sub-grade can produce longitudinal cracking.	Unevenness can result in increased rolling resistance. Dips may fill up with water during rainfall increasing the risk of aquaplaning.
Flooding and more intense rainfall increases the probability of moisture entering the pavement and thus the risk of binder stripping. Warmer and wetter winters have been observed to increase occurrences of this defect.	Binder stripping can cause ravelling, rutting, cracking and other surface deterioration. Loose aggregate can present a skidding risk and the unevenness increases rolling resistance. Dips may fill up with water during rainfall increasing the risk of aquaplaning.
If water enters a concrete pavement through the joints, it can weaken the foundation, cause erosion of the sub-base and vertical movement at the joints.	A reduction of the structural strength of the pavement can mean deformation and cracking during trafficking. This can cause the surface problems listed above.
If water enters the foundations of the pavement it can weaken the sub-grade, cause erosion and reduce the stability of the granular foundation layers.	If the strength of the foundations is damaged the surface layers will rapidly deteriorate.
A high water table can cause water ingress into the pavement. In porous pavements this can come to the surface and water pumping by the traffic can damage the pavement.	Water on the pavement surface effects skid resistance.

7.3 Other damage

Other potential damage of pavements by climate change includes damage by tree roots searching out water during drought conditions, increased vegetation growth (increased leaf fall affecting skid resistance), landslides and coastal erosion (debris).

It is often a combination of climate and other factors, e.g. an increase in traffic, which causes the most damage.

8 The impact of climate on skid resistance monitoring strategy and methodology

Skid resistance measurements are normally taken in summer months when skid resistance is at its lowest (e.g. May to September in the UK, May to October in Germany). An average of three measurements is often taken to obtain a mean summer value. Some countries normalise their values by using a rolling four season average for their skid resistance co-efficient to take account of difference between dry summers where skid resistance is particularly low and wet summers where it is higher. In addition, there is less variation in the measured skid resistance during summer compared to winter.

8.1 Temperature

As temperature affects tyre rubber and pavement characteristics it might be expected that skid resistance measurements are affected by temperature, however mixed results have been found. The temperature sensitivity is also affected by the measurement technique employed. In the late 1960s Lander and Sabey studied the impact of tyre temperature on SCRIM measurements. They found that an increase in temperature decreases the SFC by around 0.003 units per °C [45] and that surfacing with a higher coefficient of friction suffered at greater reduction. They concluded that a quarter of the decrease in skid resistance in the summer (see Section 6) was due to this effect. In 1978 TRL compared skid resistance value measurements taken in Malaysia with those in the UK and also found that skid resistance decreases with increasing temperature [56]. A study from the USA found that a one degree F (0.56°C) increase in average daily temperature can decrease friction number[1] by one unit [46]. It was thought this was combination of tyre and pavement effects.

However, a New Zealand laboratory study in 2005 found that surface and ambient temperature had no effect on skid resistance when using a DFTester [56] and unpublished work by TRL in 1998 on the affect of temperature on SCRIM measurements found no significant difference. It was hypothesised that this was due to the cooling effect of the water on the test tyre. In Germany, tests using heated water in the tank have shown a temperature effect and a correction of surface and water temperature is applied to the measured values [57]. Not all countries apply temperature correction factors to SCRIM measurements as the effect is small and it is thought that taking a mean summer value compensates for any variation. Values from a Pendulum Tester are normally standardised at 20°C and a correction factor applied.

In regions with long dry summers followed by warm autumns the measurement period may be extended.

[1] A friction number is produced from the information generated by a Pavement Friction Tester. It is calculated from peak and sliding force measurements taken as a test wheel is braked and skids across the surface.

8.2 Precipitation

The measurement of skid resistance is not normally influenced by precipitation. Rainfall may affect the measurements when the survey vehicle travels through a large puddle, but as the measurements are averaged (normally over 10 metres) this does not have a significant effect on the results. If measurements are taken after a long period of little or no rain, containments on the surface may affect the results. In Israel for example, they may have to clean the surface before measurements can be taken. They found that SR values can be reduced by as much as 20% by contaminants on the road surface [48].

The large amounts of water required for skid resistance measurement can be a concern during periods of drought when water is scarce. Using current methods with less than the specified amount of water would affect the measurements. Research into methods of measuring skid resistance with less or no use of water, e.g. contactless methods could help to alleviate this problem.

9 Indirect impacts of climate change

In addition to the direct impacts changes in climate variables have on tyre/road surface interaction, there are also indirect effects. These are the results of actions people take as a result of climate change, either to reduce carbon emissions or adapt to the changing climate. Road/tyre interaction will be affected by future changes in vehicles, tyres, driver behaviour and roads. The changes identified which could impact on the road/tyre interaction are described below.

9.1 Changes to vehicles and tyres

9.1.1 Lighter cars

To date, the trend has been towards increasingly heavier vehicles. As awareness of the need to reduce greenhouse gases from transport has grown, there has been growth in smaller lighter cars to reduce emissions reversing this trend. This has the following implications for road/tyre interaction:

- Lighter cars have less friction, but shorter stopping distances. They are more susceptible to aquaplaning.
- Smaller, lighter cars usually produce less tyre noise than larger cars
- They have lower rolling resistance
- They produce less tyre wear

Also, tyre width is influenced by vehicle weight, with heavier vehicles tending to have wider tyres. Wider tyres provide more traction in dry weather, but narrow tyres are less likely to aquaplane in wet weather.

9.1.2 Heavier vehicles

The maximum weight for LGVs was increased in the UK from 38 tonnes to 44 tonnes (6 axles) in 2001. Other European countries have higher limits e.g. 50 or 60 tonnes. There has been a proposal to introduce heavier megatrucks (60 tonnes) in Europe. It has been suggested that fewer, larger LGVs would decrease CO_2 emissions, although opponents believe it will encourage a modal shift from rail to road. Trials of the megatrucks are taking place in some European countries [57]. Road haulage is increasing in Europe and the quantity of goods transported is much greater than that carried by rail and water.

Pavements are designed for an estimated msa (million standard axles) i.e. an accumulated load. A ‘standard axle’ is defined as an axle exerting a specified force (e.g. 80kN in the UK; 10 tonnes in Germany). Wear is calculated using vehicle axle loads using the Fourth power law (weight of axle to the power of four). In order to withstand greater loads, the stiffness of the binder or the depth of pavement can be increased. Some recycled aggregates cannot be used for higher specification pavements. Modifications to produce stronger pavements could have consequences for surface parameters, for example using a stiffer binder could decrease rolling resistance.

9.1.3 Alternative fuels and engine improvements

The need to reduce GHG emissions has resulted in the use of a range of alternative fuels, such as biofuels, natural gas (CNG and LPG) and hydrogen (H2ICE). It would be expected that tyre noise would remain the same whichever fuel is used. The significance of its contribution to overall vehicle noise could change though. For example, engine noise is reported to be slightly less with biodiesel than conventional diesel as a greater amount of cethane in the biodiesel makes it muted. Engine modifications such as improvements in design and sound insulation can also reduce engine noise. Modern engines are generally quieter than older engines and this tread is likely to continue. A reduction in engine noise may increase the significance of tyre noise at lower speeds.

9.1.4 Electric vehicles

Electric vehicles are more efficient than those powered by the internal combustion engine and generate less greenhouse gas emissions, even if the electricity used to charge them is produced from fossil fuel. Electric vehicles (EV) are likely to become more prevalent in the future as their technology advances and cost reduces. In the interim hybrid cars are growing in popularity. Hybrids use both a traditional internal combustion engine (ICE) and also an electric motor and battery to improve fuel efficiency. The electric motor is used at low speeds and both the ICE and electric motor at higher speeds. Some people in the industry predict that by 2025 all new passenger cars in Europe will be electric or hybrid [60].

Most electric and hybrid vehicles utilise conventional tyres, normally ones with low rolling resistance to increase energy efficiency and so range. Therefore it would be expected that the interaction of the tyre and road would be similar to current vehicles. However EVs have a number of differences to vehicles powered by a traditional ICE that could potentially affect tyre/road surface interaction.

9.1.4.1 Vehicle weight

EVs and hybrids tend to be heavier than ICE cars, due to the weight of the battery. The first EVs used lead acid batteries, which can make up 20 to 50% of the vehicle's weight. More recent EVs use lighter batteries such as lithium-ion. This means the weight of the battery and electric motor (which is lighter than an ICE) is closer in weight to an ICE and full tank of fuel. Reducing the battery weight is the focus of a great deal of research in the industry and work is also taking place to make other car components lighter, for example by using carbon fibre for the vehicle body. Hybrid cars need to carry both an ICE and electric motor, but if the ICE is used to power the electric motor not all ICE components are required, and normally a smaller engine and less batteries are used.

Compressed hydrogen and fuel cells are ⅛ to $^{1}/_{14}$ of the weight of currently used batteries [61], although space for hydrogen storage can be an issue. Fuel cell EVs at the moment are less popular than battery EVs, as there are other potential problems such as operation at low and high temperatures and generation of the hydrogen. There has been a number of prototype fuel cell vehicles produced, including buses. It is expected to be 2015 before fuel cell vehicles are commercially available.

Heavier vehicles have greater rolling resistance, may generate more tyre noise, but possess greater friction. However, the stopping distance of heavier vehicles is longer.

9.1.4.2 Noise emissions

The engine noise of an electric car is significantly less than that powered by a conventional ICE. This means at low speeds (e.g. below 20mph) where the engine noise predominates the vehicle noise, EVs are much quieter. This could change the importance of tyre noise at low speeds. Currently, the tyre noise of EVs appears to be the same as conventionally powered vehicles.

Although reducing vehicle noise is a goal for all EU countries the use of quieter vehicles has led to concerns over the safety of pedestrians. It is of particular concern to the blind as they rely on vehicle noise to warn them of approaching vehicles. Consequently there have been proposals to make it a legal requirement to add sound, such as the noise of a conventional ICE to EVs. This artificial sound is more directional, so should cause less noise pollution than real ICE vehicles. Some people in the industry believe that people will adapt to quieter vehicles and that artificial noise should not be added.

9.1.4.3 Torque characteristics

Electric cars usually use a 3 phase AC electric motor, the DC from the battery or fuel cell is fed into a DC/AC inverter and converted into AC. AC is better suited to regenerative braking and the maximum speed is not limited by voltage, although DC is cheaper. With AC motors the frequency is used to control the RPM. Most electric motors deliver full torque over a wide range of RPM (unlike ICEs where torque increases with RPM to a maximum plateau and then decreases). The car's electronics control torque and acceleration. The continuously variable transmission (CVT) used in many EVs means no gears are required. CVT delivers variable outputs and torque. It is unknown if this change in torque characteristics has an impact on skid resistance requirements.

9.1.4.4 Road dust

Electric and hybrid vehicles use regenerative braking to charge the battery, which results in lower brake emissions. Greater traction control and no gears should result in less tyre wear, although the heavier the vehicle the faster the tyres wear. A motor on each wheel reduces tyre wear and increases traction control.

9.1.4.5 Skid resistance measurement

If the majority of vehicles in the future are electric, skid resistance measurements may be carried out using electrically powered vehicles. It is unknown what difference if any this will make to measurements.

9.1.5 Changes to tyres

The trend has been towards wider larger diameter tyres, which has been driven largely by aesthetics (i.e. wider tyres are seen as sporty). However, wider tyres can generate more noise. There has also been a growth in the use of SUVs which normally have larger tyres.

This trend for increased use of SUVs now seems to be reversing due to concerns over climate change, increased tax based on emissions, etc.

There have been a number of prototype tyres with a more fundamental change in design. These include Michelin's Tweel; a non-pneumatic tyre, the composite wheel invented by Hansson, porous tread tyres and solid polyurethane tyres [62]. It is possible that in the next ten years one of these tyre designs will produce tyres with significantly lower rolling resistance and noise emissions than the designs currently used.

Tyre composition is also being modified. Silica is now often used in place of some of the carbon black to improve rolling resistance and grip. New additives and tyre manufacturing processes are being developed to reduce the environmental impact of tyre manufacture or improve tyre characteristics (see D12 [9]).

9.2 Changes to the road surface

Pavement design and road materials are changing to improve properties such as durability, noise and ease of maintenance. A large driver for changes to pavement design and materials is the need to increase the sustainability of construction, reducing waste, energy use and consumption of natural materials. In particular the use of recycled and secondary aggregates has grown enormously and there has also been a growth in technologies such as cold and warm asphalt mixes to reduce energy use. The majority of these changes affect the lower layers of the pavement, so are unlikely to influence the tyre/road interaction; however this is an issue to be aware of.

9.2.1 Sustainable construction

In many European countries recycled and secondary aggregates are regularly incorporated into the lower layers of pavements and there is a growth of their inclusion in surfacings. For example, mixing asphalt planings from the old surface back into the new. This enables more scarce high PSV aggregates to be reused. Recycled asphalt can be incorporated into cold mix (as an aggregate) or in hot mix where the existing binder mixes with the new. Cold mix is normally used in lower pavement layers. Cold-mix asphalts use an emulsion of bitumen in water and do not require heat. There has also been increased use of cold and warm asphalt mixes which can be produced at lower temperatures reducing the energy required and therefore GHG emissions.

There are often limits on the amount of different types of recycled and secondary materials allowed in different pavement layers. This is to ensure that durability and safety are not compromised. Thorough testing and trials are carried out before specifications are modified to allow different materials. For example the UK Specification for Highway Works (SHW) [63] states that the amount of reclaimed bituminous material permitted shall be 10% in surface course and 50% in all other layers. Trial pavements have been laid incorporating up to 30% reclaimed asphalt in the surface layer. The trials were undertaken to establish if inclusion of reclaimed asphalt affects the texture depth and durability of the surfacing. It was found that 10% reclaimed asphalt is easily added without impact, but increasing the proportion to 30% requires more care to ensure that grading and the residual binder do not impact on the mix. The harder oxidised bitumen in the reclaimed asphalt could effect on the overall pen value of the binder, but this can be compensated for by using a softer binder. In Germany amounts up to 80% are permitted depending on the uniformity of the material, but 30 to 50% is more normal in practice. There are stricter uniformity requirements for the inclusion of reclaimed material in the surface layers. It is unknown if adding reclaimed asphalt changes the flexibility of the pavement thus impacting on noise emissions and rolling resistance.

9.2.1.1 Examples of recycled and secondary materials affecting tyre/road surface interaction

As part of a trial, the contractor Ringway laid a quiet surface (Ultraphone) [64] with a 6mm single size aggregate from steelworks slag. The sharp angular aggregate gave the asphalt a high void content and open texture to reduce noise. Inclusion of the steelwork slag is also reported to help improve skid resistance.

The use of recycled tyres in pavements is reported to make the pavement 5dB quieter compared to conventional dense asphalt as the rubber absorbs the sound. Rubber asphalt pavements are also reported to be more durable, less susceptible to temperature and have better skid resistance. They are more flexible (3% crumb rubber increases flexibility by 25% and 5% by 45%), so could increase rolling resistance. The surface-dressing rubber makes the pavement less prone to "fatting" up and rutting in hot weather conditions under heavy traffic. The tyre rubber contains polymer, carbon black and anti-oxidants which creates a high viscosity binder with increased adhesion and cohesion. This is said to improve resistance to rutting, shoving, thermal and reflective cracking, ravelling, delimitation and oxidative aging [65].

9.2.2 Use of saline water in pavement construction

Saline water is used in drought conditions in the construction of pavements in Australia [66]. This may become a more common practice in regions which experience frequent water shortages. The accumulation of salt in the pavement structure could have consequences for the durability of the pavement and therefore indirectly surface effects.

9.2.3 Quieter roads

In addition to reducing traffic noise through tyre design, pavement design can also be modified to reduce noise. The construction of quieter roads is growing and it can be expected that greater amounts of low noise surfacing will be laid in the future. As concrete roads are generally noisier than asphalt this could mean fewer concrete roads. Concrete roads have less rolling resistance than asphalt but a high amount of embodied carbon.

Open textured asphalt such as porous asphalt, SMA and thin surfacing are designed to reduce noise. In the UK, thin surfacings have taken over from Hot Rolled Asphalt (HRA)[2] as the predominant type of surfacing laid on trunk roads. The Highways Agency has thin surfacings on 60% of their road network. Other European countries are also laying more porous surfacing, with negative texture to reduce noise. Research [68] has shown that the smaller aggregate size, the texture shape and the subcutaneous drainage properties of thin

[2] Hot Rolled Asphalt is a mix of coarse and fine aggregate with a high binder content and mineral filler. It can be overlaid with pre-coated chippings to generate the required skid resistance.

surfacing produces an altered tyre/ wet surface interaction. This can have the following impacts:

- *Skid resistance* - The wear and polishing of thin surfacings is different to HRA. In their early life thin surfacings have a reduced skid resistance at higher speeds and in the dry until the bitumen binder is worn away from the surface aggregates. The aggregates are then polished until equilibrium is reached. Seasonal variation is superimposed on this. Skid resistance decreases with traffic volume until the seasonal equilibrium is reached. Use of a smaller aggregate size increases resistance to polishing.

- *Rolling resistance* - Studies have found no evidence to suggest rolling resistance on dense and porous asphalt surfacing is different.

- *Noise emissions* - Thin surfacings produce around 3dB less tyre noise than HRA. However, when wet these benefits are reduced.

- *Other environmental effects* - Thin surfacings require a greater volume (300 to 500% more) of high quality aggregate than HRA as it is used throughout the surface layer rather than only in the surface chippings. Pavement and tyre wear differs according to the type of pavement affecting the PM_{10} emissions. SMA is more wear-resistive to the use of studded tires than DAC [69], however in the UK it was found that thin surfacings wear is increased compared to HRA [68].

9.2.4 Cooler roads

The urban heat island (UHI) effect is likely to become an increasing problem with the advancement of climate change. Research has been carried out on designing new pavement surfaces which could help reduce the UHI. Trials have been carried out on the use of white/lighter road surfaces to reduce pavement albedo, pavements which retain moisture reducing UHI through evaporation and heat shield pavements which are coated with materials which absorb infra red radiation.

Trials using ultra thin white topping (concrete), lighter coloured aggregates in asphalt or pigments added to the asphalt mix to reduce pavement albedo have found that a lighter surface can reduce the pavement temperature by as much as 20°C [66]. This helps to minimise the urban heat island effect as well as improving the durability of the pavement.

Pavements which retain moisture and heat shield pavements have been found in trials in Japan [70] to reduce pavement temperature by 16°C and 20°C compared to conventional asphalt. The researchers suggest this could improve the environment for nearby pedestrians.

9.2.5 Higher performance pavements

Increased traffic and greater use of heavier vehicles (for example megatrucks or electric vehicles) may lead to higher performance pavements being required. These stronger pavements could have different tyre noise/skid resistance/rolling resistance characteristics to current pavements.

9.2.6 Influence of travel demand on pavement maintenance

An Ausroads study [31] on the impacts of climate change on roads, identified the influence climate change would have on travel demand and the implications of this on road maintenance. The authors felt that changes in population settlement, for example away from drought stricken areas together with population growth would increase the traffic flow in some areas dramatically and that this would be the largest impact climate change would have on the road network. Changes in tourism patterns and travel behaviour may also influence the condition and maintenance of roads, with potential consequences for surface characteristics.

9.2.7 Improved maintenance

Climate change adaptation could encourage funding for increased maintenance as better maintained pavements are less susceptible to climate impacts. Reducing the unevenness of pavements would also improve noise and rolling resistance. Similarly, less ice and snow in winter may increase pavement durability which would lead to less noise and rolling resistance.

9.2.8 Other types of road design

There are other types of novel road design being developed, for example modular roads; Sustainable Urban Drainage Systems (SUDS) and energy recover systems such as interseasonal heat transfer. In many cases the effect if any on the tyre/road surface interaction is unknown.

9.3 Changes to driver behaviour

It is not only the physical aspects of transport (i.e. vehicles and roads), that are altered by climate change. Tyre/road surface interaction is also influenced by driver behaviour and travel patterns which could change as a result of climate change. This could be as a result of actions to decrease GHG emissions or the change in climate as described below.

9.3.1 Reducing transport GHG emissions

European governments are actively encouraging the public to change their travel behaviour as part of efforts to reduce transport GHG emissions. The goals of behaviour change initiatives can be categorised into: reducing travel; using more sustainable modes of transport and improving fuel efficiency. Policy measures include road user charging, the incorporation of eco-driving techniques in driving tests, reductions in speed limits and increased taxes for higher emission cars. The trend in travel behaviour until this point has been for an increase in road traffic, with people making more journeys and travelling further. These types of policy measures and greater public awareness of climate change have the potential to change travel behaviour and the way people drive, which could have implications for tyre/road surface interaction.

Actions that reduce traffic volume, especially commercial vehicles could slow down deterioration of skid resistance. Measures that decrease speed will reduce noise, increase grip and decrease fuel consumption. If road user charging is applied with a price difference between types of road it could encourage more/less motorway driving depending on pricing.

Charging more for use during certain hours could change the time of day people drive. This could result in a change in the surface requirements for different types of roads. Eco-driving results in less severe braking and acceleration. Less severe braking should reduce loss of skid resistance at junctions etc.

9.3.2 Climate influences on travel behaviour

The change in climate could influence travel behaviour, for example by influencing tourism patterns. In some countries, drier summers could result in an increase in summer day trips and there could be less travel to airports and ports and more travel to domestic holiday destinations. Conversely some tourist destinations could become too hot and cooler destinations could become more popular.

In adverse weather conditions, people reduce unnecessary travel and change their driving behaviour, for example reducing their speed during intense rainfall thereby improving their levels of grip. Disruption to main roads from climate impacts such as flooding or fallen trees may result in the diversion of traffic on to minor routes which were not designed to cope with heavy traffic.

There could be more significant changes in traffic flows in some counties where populations move away from drought stricken or flood prone areas.

10 Climate change and the optimisation of surface characteristics

This section applies the information gathered in the literature review to the findings of WP3 to establish how climate change will impact on the harmonisation of skid resistance and the optimisation of road surfaces and tyres for skid resistance, rolling resistance and noise emissions. Within the TYROSAFE project the three surface parameters are assigned equal importance and optimisation means obtaining a balance of all three parameters, with no parameter becoming worse than current levels. There are a range of other important parameters such as durability, value for money, environmental impacts and climate change resilience. It may not be feasible to improve all positive aspects of pavements and tyres at this time, but that it is possible to obtain a balance where each desired property is at an acceptable level.

Part of the work carried out by WP3 was to identify the characteristics road surfaces and tyres require so that the tyre/road interaction is optimised for skid resistance, rolling resistance and low noise emissions. In this section these characteristics are evaluated for their impact on climate resilience and possible conflicts between optimisation and climate change resilience are discussed.

10.1 Variations in pavement and tyre characteristics

Different types of pavements are constructed according to the type of road, the expected traffic conditions, the typical climate conditions, and the policy and priorities of the asset owner. Advancements in technology and the understanding of the role different characteristics such as texture depth and aggregate mineralogy have on the overall pavement properties have also resulted in changes to pavement parameters. Tyres are less tailored than pavements to specific conditions, but still differ according to the type of vehicle and the climate to some extent (e.g. winter and summer tyres). Tyre design and materials also change with technological developments.

Pavement characteristics differ between countries according to climate, the policy priorities e.g. reduction of traffic noise in the Netherlands, safety and skid resistance in the UK, and historical practices. However the overall trends in road designs and materials in Europe are towards materials such as SMA, thin surfacings and porous asphalt with negative texture and greater porosity. There has been a move away from concrete roads and a greater use of recycled materials and lower energy mixes.

Optimising pavement and tyre characteristics for a specific location requires a number of aspects to be considered and balanced. TYROSAFE is focusing on the three surface parameters, but these parameters cannot be examined in isolation. The impact of modifying pavement and tyre characteristics on other aspects such as pavement durability and the environment are also important. Part of the remit of WP4 is to look at this wider picture, in particular looking at any changes in the environmental effects and climate change resilience.

TYROSAFE D14 [7] describes the parameters that need to be considered when aiming to optimise surface and tyre characteristics for skid resistance, rolling resistance and noise emissions. In addition to these, resilience to climate change impacts needs to be taken into account. Pavements are tailored to the prevailing climate conditions in their location, but this is usually based on historic climate conditions and future changes in climate variables are not generally considered. When implementing harmonisation and optimising surface parameters it is important that any recommended modifications do not create an adverse impact on the climate resilience of pavements and if possible improve resilience. In some cases improved resilience will be a co-benefit to optimising skid resistance and in others there will be no effect. However, if there are any potential conflicts these need to be identified at an early stage so that priorities can be ascertained or compromises made.

10.1.1 Tailoring a pavement to climatic conditions

The characteristics which are modified to tailor a pavement to different climates include:

- **Binder stiffness:** The binder pen is selected according to the temperature range expected. Stiffer pens are used in hotter regions. Polymer modified binders may be preferred where pavements need to withstand large ranges in temperature.
- **Porosity:** More porous pavements may not be durable enough for cold, wet climates and may make pavements more vulnerable to oxidation in hot regions.
- **Texture:** Greater texture depth may be specified in wetter areas.
- **Aggregate grading:** Larger aggregates can provide more texture in wetter regions**.**
- **Aggregate hardness**: Harder aggregates are utilised in regions where studded tyres are used.
- **Aggregate adhesion:** Aggregates susceptible to binder stripping may not be used in wetter areas.

10.1.2 Tailoring tyres to climate conditions

Tyres can also be tailored to the prevailing weather conditions, for example winter tyres are designed to deal with greater water depths, ice and snow, and summer tyres with higher temperatures. There are other tyre characteristics which impact on the suitability of the tyres for different climates that are not deliberate, such as the use of wider tyres which are more susceptible to aquaplaning at lower speeds. Again many co-benefits may be found such as narrower tyres reducing noise as well as reducing the potential for aquaplaning, but any conflicts need to be identified.

10.2 The climate change resilience and environmental effects of an optimised road

The most relevant surface and tyre parameters for optimisation of skid resistance, rolling resistance and noise were identified in D14. In this section the potential impacts of modifying these parameters on climate change resilience and the environmental effects of tyre/road surface interaction are identified. Table 10-1 and Table 10-2 list the parameters associated with the pavement and Table 10-3 the parameters associated with tyres.

Table 10-1. The possible effects of an optimised asphalt pavement on resilience and environmental impacts

Pavement parameter	Potential impact on climate resilience	Potential environmental impacts
PSV greater than 50 for dense asphalt and greater than 55 for porous asphalt	• Improved durability to summer polishing in drier summers • Better grip in intense rainfall events	• Increased particulates from tyre wear • Increased aggregate transport emissions
Max coarse aggregate size of 5 – 8 mm	• Smaller aggregates mean less texture depth. • Smaller aggregates increase low speed wet skid resistance • Small aggregates are more prone to damage from studded tyres. This will be less of an issue with milder winters.	• Increased dust from producing smaller grading
Cubic aggregate shape - SI_{20}/FI_{20} for dense asphalt, SI_{15}/FI_{15} for porous asphalt	None	None
Angularity of aggregates- dense asphalt $C_{100/0}$, $C_{95/1}$, $C_{90/1}$, porous asphalt $C_{100/0}$	• Angular aggregates can increase binder stripping if moisture enters the pavement structure. • Angular aggregates can increase rutting resistance.	None
A texture depth of 0.4 - 0.8 mm at wavelength of 0.5 - 10 mm	• Increased texture depth provides drainage and grip in intense rainfall. • Increased salting less of an issue in warmer winters. • Stays wet longer.	• Increased salting likely to have a detrimental effect on roadside vegetation, local water courses and soil.
Bitumen viscosity. Polymer modified bitumen.	• High viscosity decreases binder stripping • Less susceptible to deformation at high temperatures	• Life Cycle Assessment is required to ascertain any change to environmental impacts.
Void content. For porous 25 v-%	None	None
Aggregate size for chipping	• Smaller aggregates mean	• Increased dust from

material 5mm (for use in gritting SMA surfaces in early life)	less texture depth • Smaller aggregates increase low speed wet skid resistance • Small aggregates are more prone to damage from studded tyres. This will be less of an issue with milder winters.	producing smaller chippings.
Polishing resistance for chipping material of 50 (for use in gritting SMA surfaces in early life)	• Higher PSV will be a benefit during drier summers.	• Greater transportation emissions due to potentially longer transport distances. • Consumption of natural resources.
Texture - High micro and macro texture, low mega texture.	• Improved texture would have a positive influence during increased rainfall.	• Lower mega texture would have a benefit for rolling resistance and therefore emissions.

Table 10-2. The possible effects of an optimised concrete pavement on resilience and environmental impacts

Pavement parameter	Potential impact on climate resilience	Potential environmental impacts
Polishing resistance - minimum PSV 50 for dense concrete and 55 for porous.	• Higher PSV will be a benefit during drier summers.	• Greater transportation emissions due to potentially longer transport distances.
Shape of aggregates – SI_{20}/FI_{20} for dense, SI_{15}/FI_{15} porous.	None	None
Angularity of aggregates – $C_{100/0}$, $C_{90/1}$ for dense and $C_{100/0}$ porous.	None	None
Max aggregate size of 8mm.		• Increased dust from producing smaller aggregate.
Surface texture type- exposed aggregate concrete or brushed concrete in the transverse direction	• Improved texture is a benefit in more intense rainfall.	• Increased dust.
High micro and macro texture, low mega texture.	• Improved texture would have a positive influence during increased rainfall.	• Lower mega texture would have a benefit for rolling resistance and

		therefore emissions.

Table 10-3. Impacts of an optimised tyre

Tyre parameter	Potential impact on climate resilience	Potential environmental impacts
Tread depth minimum of 4mm	• Increased tread depth would be a benefit in more intense rainfall.	• Shorter tyre length, therefore increased consumption of tyres
Tread pattern optimised to avoid aquaplaning	• Less susceptibility to aquaplaning would be a benefit with more intense rainfall.	None
Rubber compound optimised. (Softer will increase friction, but increase rolling resistance and noise)	• Better grip during intense rainfall would be a benefit	• Increase in rolling resistance will result in increase in emissions. • Increase in noise.
Nanoprene additive	• Improves wet grip, which would be a benefit in intense rainfall.	• Needs an LCA to ascertain impact of manufacturing, but reduces rolling resistance so may be a positive effect.

10.3 Possible co-benefits and conflicts

10.3.1 Climate change resilience

An evaluation of the impacts that optimisation of the key surface parameters would have on climate change resilience shows that there are many potential co-benefits. Actions to improve skid resistance in the wet will be of benefit during the greater frequency of intense rainfall events projected for Europe. Appropriate use of higher PSV aggregates would also help to minimise the effects of increased summer polishing due to more dry periods. The only potential conflicts identified were the use of angular aggregates that are more prone to binder stripping during the wetter warmer winters that will be experienced in north Europe, and the use of smaller aggregates which reduces the texture depth possibly leading to more surface water during intense rainfall. Similarly for tyres, modifications that increase the wet grip will increase the climate resilience of the surface/tyre interaction.

In general the trend for SMA/thin surfacing should make pavements more resilient to climate change as it less vulnerable to deformation in high temperatures and the negative texture reduces spray during rainfall. Fewer voids and a thicker binder reduce susceptibility to increased aging from high temperatures and deterioration from warmer wetter winters. Although it is more difficult to achieve texture depth and maintain durability in thin surfacing, especially with smaller aggregate sizes.

Stiffer binders are being introduced in many countries to withstand greater traffic levels, which will be of benefit in hotter summers. Other future surface trends include the combination of concrete and asphalt surfaces layers, multilayer porous surfaces, simplified construction techniques, high durability surfaces/perpetual roads and low rolling resistance road surfaces.

Northern countries where more porous surfaces are not used for durability reasons, may find that the decrease in use of studded tyres and increase in precipitation falling as rain rather than snow may make more porous surfacings worth considering.

10.3.2 Environmental impacts

Many of the optimisation actions appear to have little impact on the environment; however some actions such as softer tyre rubber and greater use of higher PSV could have a detrimental effect. There are also some positive effects; more even roads would decrease rolling resistance and hence emissions of greenhouse gases and other exhaust pollutants, and new tyre additives such as neoprene have the potential to reduce rolling resistance as well as increasing wet grip.

Environmental impacts are discussed in more detail in D12 [9].

10.4 Climate change impacts on the benefits of optimisation

Climate change could potentially limit the benefits that optimisation brings by reducing the benefits to skid resistance, rolling resistance and noise emissions. The following benefits could be affected:

- The noise benefits of porous surfacing are negated by rain, so more frequent intense rainfall and wetter winters could reduce the positive impacts of laying this surface.
- More frequent periods of drought can increase the clogging of porous pavements reducing noise benefits and texture.
- More open road surfaces will be more susceptible to the increased aging expected due to higher temperatures.
- The benefits of using higher PSV aggregate may be reduced by the potential increase in summer polishing.

11 Conclusions

Information on the future climate is available from climate models, which are increasing in sophistication and the amount and resolution of information they can provide. These models show that temperatures will continue to increase throughout Europe, producing milder winters and hotter summers. In the north of Europe the greatest change in temperature will be seen in the winter temperatures, leading to a decrease in frost and snow. In the south the largest increase is in the summer temperatures, with extreme heatwaves becoming more frequent.

Changes in precipitation are more variable depending on location, with an increase in annual rainfall in northern Europe and a decrease in the South. There will be a change in the seasonal pattern of rainfall with wetter winters and drier summers. There will also be more frequent periods of intense rainfall events.

Most European Governments are studying the projected climate for their country and assessing the potential implications for their critical infrastructure including transport. Research is being carried out at a national and European level on the impacts of climate change on roads and potential adaptation actions. The EU has stated in the white paper on *Adapting to climate change : towards a European framework for action [10]* that climate change adaptation needs to be integrated into EU policy. As part of the TYROSAFE project a literature review was carried out on the impacts of climate change on skid resistance, rolling resistance and tyre noise. This information was used to assess the impact optimisation of these three parameters would have on climate change resilience and the impact climate change would have on optimisation.

11.1 Direct impacts

No specific studies looking at the impact of climate change on tyre/road interaction were found during the literature review, although skid resistance has been identified as an aspect of pavements that is vulnerable to climate change. Information was gathered on the affects that climate has on skid resistance, rolling resistance and tyre noise and this was used to identify potential impacts:

Higher temperatures could result in:

- More fattening up in asphalt pavements which would reduce skid resistance;
- More rutting in asphalt pavements, which consequently fill up with water during rainfall causing hazards;
- Less freeze/thaw damage, but less restoration of skid resistance from winter weathering;
- Less ice and snow; increasing skid resistance;
- Less winter salting and use of studded tyres.

More frequent drought could result in:

- Increased summer polishing;
- Build-up of contamination;
- Viscous aquaplaning during first flush;

- Water pollution from run-off becoming more of a problem (implications for the Water Framework Directive (WFD));
- Water consumption during skid resistance measurement being restricted as a result of drought conditions.

More periods of intense rain could cause:
- Aquaplaning;
- More tyre noise;
- Increased rolling resistance.

Change in seasonal patterns could cause:
- Changes to the seasonal variation to skid resistance, e.g. less restoration of skid resistance during winter.

Some of the pavement defects brought about by climate change such as ravelling, rutting, binder stripping etc. have an effect on the surface/tyre interaction. For example ruts can fill with water during rainfall and become an aquaplaning hazard and loose aggregate can reduce road surface/tyre friction.

11.2 Indirect impacts

In addition to the direct impacts of climate change, it is generating changes in society and technology to reduce GHG emissions and adapt to the changing climate. These indirect impacts of climate change include:
- Greater use of lower carbon cars which could be heavier and require different surface characteristics;
- Lighter cars to reduce fuel consumption;
- Heavier LGVs to reduce the number of vehicles on the road and therefore reduce emissions;
- Inclusion of different recycled materials (e.g. rubber crumb from tyres) in pavement construction which could have surface impacts;
- Additives in tyres to improve rolling resistance;
- Changes in travel patterns and behaviour.

11.3 The key impacts and priorities

The key impacts of climate change were identified as:

- Changes to the seasonal variation of skid resistance
- Contamination build up during drought, followed by viscous aquaplaning
- Increased polishing during drought conditions
- Increased tyre noise in the wet
- Indirect impacts from changes to vehicles and tyre designs, e.g. more electric vehicles

Temperature was felt to be less of a problem as surfacing can be more easily designed to withstand higher temperature, for example by using a stiffer binder.

11.4 Optimisation and climate change resilience

The implications of the climate change impacts for optimisation were evaluated. The optimised parameters produced by WP3 were examined for the implications on climate change resilience. It was found that there are many co-benefits in particular actions that improve wet friction, which would be beneficial with the projected increase in frequency of intense rainfall events. The only negative effects were that angular aggregates are more prone to binder stripping which will increase in wetter warmer winters and that smaller aggregates reduce texture depth which could be a problem in intense rainfall events.

Some of the benefits of optimisation could be reduced by climate change including rainfall negating the noise reduction properties of porous pavements and increased summer polishing reducing the improved skid resistance that higher PSV aggregates bring.

12 References

[1] P Nitsche, R Spielhofer et al. Report on policies and standards concerning skid resistance, rolling resistance and noise emissions. TYROSAFE Deliverable D06, February 2009.

[2] D Kokot et al. Recommendations for future harmonised EU policy on skid resistance, rolling resistance and noise emissions. TYROSAFE Deliverable D08, June 2009.

[3] M.-T. Do, P. Roe, E. Vos, J. Groenendijk, State of the Art of Skid-Resistance Test Methods, TYROSAFE Deliverable D04, December 2008.

[4] J. Groenendijk, E. Vos, P. Roe, M.-T. Do, Analysis and Findings of Previous Skid Resistance Harmonisation Research Projects, TYROSAFE Deliverable D05, March 2009.

[5] M.-T. Do, P. Roe. Report on state-of-the-art of test surfaces for skid resistance TYROSAFE Deliverable D07, March 2009.

[6] M Kane, K Scharnigg, M Conter, P Roe and G Schwalbe. Report on different parameters influencing skid resistance, rolling resistance and noise emission. TYROSAFE Deliverable D10, August 2009.

[7] K Scharnigg, G Schwalbe, Interdependencies of parameters influencing skid resistance, rolling resistance and noise emissions, TYROSAFE Deliverable D14, March 2010.

[8] K Scharnigg, G Schwalbe, Report on knowledge gaps and proposals for further research concerning optimisation for road surfaces and tyres for skid resistance, rolling resistance and noise emissions. TYROSAFE Deliverable D15, May 2010.

[9] S Reeves, P Roe, M Ainge, P Sivell, A summary of the environmental impacts of tyre/road surface interaction and the identification of future research areas, TYROSAFE Deliverable D12, February 2010.

[10] European Commission, White Paper: Adapting to climate change : towards a European framework for action, 2009, 52009DC0147 http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2009:0147:FIN:EN:HTML

[11] IPCC, Special Report on Emissions Scenarios, 2000. http://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf

[12] Willis, J. K. (2010), Can in situ floats and satellite altimeters detect long-term changes in Atlantic Ocean overturning?, Geophys. Res. Lett., 37, L06602, doi:10.1029/2010GL042372.

[13] IPCC, The Fourth Assessment Report, Working Group 2, Chapter 12: Europe http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter12.pdf

[14] Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Figure 11.2, Cambridge University Press.

[15] S. Kopf, M. Ha-Duong and S. Hallegatte, Using maps of city analogues to display and interpret climate change scenarios and their uncertainty, Natural Hazards and Earth System Sciences, 2008. http://www.nat-hazards-earth-syst-sci.net/8/905/2008/nhess-8-905-2008.pdf

[16] EU project ENSEMBLES http://www.ensembles-eu.org/ and http://www.cru.uea.ac.uk/projects/ensembles/PointPDFs/

[17] EU project PRUDENCE- Prediction of Regional scenarios and Uncertainties for Defining EuropeaN Climate change risks and Effects http://prudence.dmi.dk/

[18] EU project CECILIA (Central and Eastern Europe Climate Change Impact and Vulnerability Assessment) http://www.cecilia-eu.org/

[19] EC Project ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) http://www.pik-potsdam.de/ateam/

[20] EC Project MICE (Modelling the Impact of Climate Extremes) http://www.ist-world.org/ProjectDetails.aspx?ProjectId=19a3c09b244a40a38dc04d6591e43cce

[21] EC Project STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions) http://www.cru.uea.ac.uk/projects/stardex/

[22] ERA-NET ROAD research programme- Road Owners Getting to Grips with Climate Change, http://www.eranetroad.org/index.php?option=com_content&view=article&id=76:sro3-road-owners-getting-to-grips-with-climate-change&catid=62:researchactivities&Itemid=79&el_mcal_month=1&el_mcal_year=2012

[23] European Environment Agency, National Adaptation Strategies, http://www.eea.europa.eu/themes/climate/national-adaptation-strategies

[24] Partnership for European Environmental Research, Europe Adapts to Climate Change: Comparing National Adaptation Strategies, 2009 http://www.peer.eu/fileadmin/user_upload/publications/PEER_Report1.pdf

[25] EWENT- Extreme weather impacts on European networks of transport, EC Seventh Framework Project. http://cordis.europa.eu/search/index.cfm?fuseaction=proj.document&PJ_LANG=EN&PJ_RCN=11092470&pid=0&q=40203C5BD5FC9C0D456A40BE1F8CEA3A&type=sim

[26] WEATHER- Weather Extremes: Assessment of impacts on Transport Systems and hazards for European Regions. http://ec.europa.eu/research/transport/news/article_9958_en.html

[27] Stern N., 2006, Stern Review on the Economics of Climate Change, http://www.hm-treasury.gov.uk/sternreview_index.htm

[28] Federal Ministry of the Environment, Nature Conservation and Nuclear Safety, Climate Change in Germany: Vulnerability and adaptation of climate sensitive sectors, Research Report 201 41 253, 2005, http://www.umweltbundesamt.de/klimaschutz-e/index.htm

[29] Greater London Authority, Climate change and London's transport systems, 2005 http://www.london.gov.uk/lccp/publications/docs/climatetransportsept05.pdf

[30] Swedish Commission on Climate and Vulnerability, Sweden facing climate change – threats and opportunities, 2007 http://www.sweden.gov.se/content/1/c6/09/60/02/56302ee7.pdf

[31] Austroads, Impact of climate change on road infrastructure, Austroads Publication No. AP–R243/04, 2004 http://www.bitre.gov.au/publications/92/Files/climate_change.pdf

[32] URS on behalf of Defra, Adapting Energy, Transport and Water Infrastructure to the Long-term Impacts of Climate Change, Ref. No RMP/5456, January 2010 http://www.defra.gov.uk/environment/climate/documents/infrastructure-full-report.pdf

[33] Bridgestone Tyres website (accessed May 2010) http://www.bridgestone.co.za/content.asp?id=97

[34] J Donbavand and C Kennedy, Safer Roads 2008, Long term study of skid resistance on in-service roads in England (A study for the HA by WDM). http://www.saferroads.org.uk/2008papers.asp?download=y&file=John%20Donbavand%20-%20Long%20Term%20Study%20of%20Skid%20Resistance%20on%20in-service%20Roads%20in%20England.pdf

[35] C Walters, The 3 Counties Alliance Partnership, Scott Wilson, The Effect of Climate Change on 3CAP's Highway Network Policies and Standards, 2009 http://www.leics.gov.uk/climate_change_adaptations.pdf

[36] Highways Agency, Highways Agency Climate Change Adaptation Strategy and Framework, 2009. http://www.highways.gov.uk/aboutus/24180.aspx

[37] Sandberg U, Ejsmont J A, Tyre/Road Reference Book, Informex, 2002.

[38] M Pomerantz, H Akbari, J Harvey, Cooler Reflective Pavements Give Benefits Beyond Energy Savings: Durability and Illumination, 2000 http://www.osti.gov/bridge/purl.cover.jsp?purl=/789110-hfzCDE/native/

[39] F Anfosso-Lédée and Y Pichaud, Temperature Effect on Tyre-Road Noise, Applied Acoustics, Volume 68, Issue 1, pp1-16, 2007.

[40] A Ongel, Q Lu, J Harvey, Frictional properties of asphalt concrete mixes, ICE, Transport 162, February 2009 Issue TR1, Pages 19–26,

http://www.icevirtuallibrary.com/content/article/10.1680/tran.2009.162.1.19;jsessionid=iqr9p1199l4.z-telford-01

[41] Firestone Tyre and Rubber Company and the University of Helsinki, Department of Mechanical Engineering, http://www.metrompg.com/posts/tire-pressure-rolling-resistance.htm

[42] Descornet, G 1990 Road-Surface Influence and Tire Rolling Resistance, in Surface Characteristics of Roadways: International Research and Technologies, Meyer, W E and Reichert, J, editors (Philadelphia, PA: American Society for Testing and Materials) pp 401-415

[43] Ministry of Agriculture and Forestry of Finland, Finland's National Strategy for Adaptation to Climate Change, 2005 http://www.mmm.fi/attachments/mmm/julkaisut/julkaisusarja/5kghLfz0d/MMMjulkaisu2005_1a.pdf

[44] A K Andersson, Winter Road Conditions and Traffic Accidents in Sweden and UK: Present and Future Climate Scenarios, PhD Thesis, University of Gothenburg, Sweden, 2010. http://gupea.ub.gu.se/dspace/bitstream/2077/21547/1/gupea_2077_21547_1.pdf

[45] Kennedy C. K., Young A. E., Butler I. C., Measurement of skidding resistance and surface texture and the use of results in the United Kingdom, W E Meyer, J Reichert, Ed., Surface Characteristics of Roadways: International Research and Technologies, ASTM STP 1031, 1990, http://books.google.co.uk/books?id=hGoJxlkTrckC&pg=PA92&lpg=PA92&dq=skid+resistance+and+climate+change&source=bl&ots=cKlpL-vlDL&sig=tigeGlawb3EG1UVTDw5JDSGck6g&hl=en&ei=_GpwSrDiFYTLjAeFybyPBQ&sa=X&oi=book_result&ct=result&resnum=9

[46] Stacy Williams, Surface Friction Measurements of Fine Graded Asphalt Mixtures, MBTC 2066, Final Report, University of Arkansas, 2008, http://ww2.mackblackwell.org/web/research/ALL_RESEARCH_PROJECTS/2000s/2066/MBTC%202066%20FINAL%20REPORT.doc http://www.uark.edu/rd_engr/MBTC/MBTC_2066_FINAL_REPORT.pdf

[47] W R Tyfour, Tire Skid Resistance on Contaminated Wet Pavements, Jordan Journal of Mechanical and Industrial Engineering, Volume 3, Number 2, January 2009, pp129- 124, http://jjmie.hu.edu.jo/files/v3n2/5.pdf

[48] R. Yaran and S Nesichi, Alleviating the Skid Resistance Problem - The Israeli Experience, Safer Roads 2005, http://www.saferroads.org.uk/Papers_PDFs/1%20%20YARON%20R%20-%20Alleviating%20the%20skid%20...FP.pdf

[49] D J Wilson and P Black, The Effects of Rainfall and Contaminants on Skid Resistance Variability 22nd ARRB Conference – Research into Practice, Canberra, Australia, 2006

http://rakan.jkr.gov.my/cawangan/cjalan/documentation/seminarCourseNotes/arb/Papers/Wilson-2.pdf

[50] G Bird and W J O Scott, Measurement of the non-skid properties of road surfaces, Road Research Bulletin, London, pp1-19, 1931.

[51] P W Jayawickrama and B Thomas, Correction of Field Skid Measurements for Seasonal Variations in Texas. Transportation Research Record 1639, Transportation Research Board, National Research Council, Washington, D.C., 147-154. 1998.

[52] Bird, G & Scott, W A O 1936, Studies in road friction. 1. Road surface resistance to skidding. Road Research Laboratory Technical Note No. 1, HMSO, London.

[53] J R Hoskings and G C Woodford, Measurement of Skidding Resistance, Part II, Factors Affecting The Slipperiness of a Road Surface, TRRL, Crowthorne, 1976.

[54] B Thomas, Use of artificial neural networks for predicting skid resistance of hot mix asphalt concrete (HMAC) pavements, Thesis Texas Tech University, 2001, http://etd.lib.ttu.edu/theses/available/etd-07312008-31295018169440/unrestricted/31295018169440.pdf

[55] T Willway, S Reeves and L Baldachin, Maintaining Pavements in a Changing Environment, TRL on behalf of the Department of Transport, TSO, 2008.

[56] H J Kwang, G Morosiuk, J Emby, An assessment of the skid resistance and macrotexture of bituminous road surfacing in Malaysia, 1992, TRL, Crowthorne UK. http://www.transport-links.org/transport_links/filearea/publications/1_475_PA1277_1992.pdf

[57] Technische Prüfvorschriften für Griffigkeitsmessungen im Straßenbau, Teil: Seitenkraftmessverfahren, 2007, Forschungsgellschaft für Straßen und Verkehrswesen.

[58] D Wilson and R Dunn, Polishing Aggregates to Equilibrium Skid Resistance, Safer Roads 2005, http://www.saferroads.org.uk/Papers_PDFs/3%20%20WILSON%20D%20%20-%20The%20effects%20of%20contaminants%20...%20FP.pdf

[59] A McKinnon, Should the Maximum Length and Weight of Trucks be Increased? A Review of European Evidence, ISL 2008 Conference, http://www.sml.hw.ac.uk/logistics/downloads/lhvstudy/LHV%20presentation%20(ISL%202008%20conference).pdf

[60] EUobserver, EU States Plug into Electric Cars, 27 August 2008 http://euobserver.com/882/26594

[61] Thomas, C. E., Fuel Cell and Battery Electric Vehicles Compared, H2Gen Innovations, US Department of Energy. http://www1.eere.energy.gov/hydrogenandfuelcells/education/pdfs/thomas_fcev_vs_battery_evs.pdf

[62] M Hanlon, The TWEEL- Radical New Wheel Technology, Gizmag (accessed January 2010). http://www.gizmag.com/go/3603/ A N Brooks, TB Gage, The Itzerol Electric Sports Car, Part II, Auto Speed, http://autospeed.com/cms/title_The-Itzerol-Electric-Sports-Car-Part-2/A_111314/article.html

[63] Highways Agency, Volume 1 of the Manual of Contract Documents for Highway Works - Specification for Highway Works, November 2009 Edition. http://www.standardsforhighways.co.uk/mchw/vol1/index.htm

[64] Ringway, Quiet Surfaces Draws Public Praise, Modern Asphalts, http://www.modernasphalts.com/archive/22/articles/MA22ringway.pdf

[65] Asphalt Rubber Technology Service, Benefits of rubberized asphalt, http://www.ces.clemson.edu/arts/benefitsofRA.html

[66] US Environmental Protection Agency's Office of Atmospheric Programs, Reducing Urban Heat Islands: Compendium of Strategies – Cooler Pavements. http://www.docstoc.com/docs/7822633/Cool-Pavements-(PDF)/

[67] Guyette J, Coll Pavement: Light-colored aggregate can help roads beat the heat, 2000, Pitt and Quarry Magazine. http://findarticles.com/p/articles/mi_m3095/is_10_92/ai_n27558537/

[68] Highways Agency, Research Compendium, Reduced use of high psv aggregate in thin surfacing, http://www.ha-research.gov.uk/projects/index.php?id=914

[69] T Hussein, C Johansson, H Karlsson, H Hansson, Factors affecting non-tailpipe aerosol particle emissions from paved roads: On-road measurements in Stockholm, Sweden, Atmospheric Environment 42, 2008, pp 688–702. http://www.parks.sfgov.org/wcm_recpark/SPTF/2008FactorsTHansson.pdf

[70] Kubo K., Kido H., Ito M., Study on pavement technologies to mitigate the heat island effect and their effectiveness, Japanese Public Works Research Institute, http://www.pwri.go.jp/eng/activity/pdf/reports/kubo.06.08.12.pdf

[71] P Youman, The implications of climate change on road infrastructure planning, design and management, coastal conference, 2007. http://www.coastalconference.com/2007/papers2007/Paul%20Youman.pdf

Appendix: Country climate projections

A1. Germany

The mean annual temperature in Germany is expected to rise between 0.5 to 1.5°C in the period 2021 to 2050 and around 1.5 to 3.5°C in 2071 to 2100. The largest temperature rise is expected to be in the south west of the country. The increase in winter temperature will be greater than the rise in summer temperature.

Germany is projected to experience increased winter precipitation of around 40% with increases up to 70% in parts of Rhineland-Palatinate, Hesse and north east Bavaria. There will be decreased summer precipitation, with southwest Germany and central parts of east Germany experiencing the most effects. Overall the annual precipitation is expected to change very little.

For more information see:

- http://www.anpassung.net/SharedDocs/Downloads/DE/DAS-Kabinettbericht,templateId=raw,property=publicationFile.pdf/DAS-Kabinettbericht.pdf)
- http://www.anpassung.net/cln_117/nn_948304/DE/Fachinformationen/RegionaleStudien/regionaleStudien__node.html?__nnn=true
- http://www.anpassung.net/cln_110/nn_948320/DE/Home/homepage__node.html?__nnn=true

A2. UK

The most recent climate projections for the UK were launched in June 2009 (UKCP09). Unlike the previous scenarios, these are probabilistic – designed to be a form that decision makers can use to assess risk. The projections show that all areas of the UK will get warmer, with the greatest warming occurring in summer. The largest increase in temperature will be in the southern England and the least in north Scotland; this north-south gap increases in summer. By the 2080s it is expected that winter temperatures will be around 2 to 3°C above the 1961 to 1990 baseline and that summer temperatures will be 2.5 to 4°C higher.

There will be less summer precipitation and more winter precipitation. In winter precipitation will increase from 10 to 40% and in summer it will decrease by 40% in south west England, but there will be little change in north Scotland. Sea levels will rise, with the greatest rise along the south coast. The maximum increase in storm surge for 2100 is 9cm in the Severn Estuary and Bristol Channel.

For more information see:

- http://ukclimateprojections.defra.gov.uk/content/view/868/531/
- http://www.ukcip.org.uk/index.php
- http://www.defra.gov.uk/environment/climate/adaptation/index.htm

A3. Finland

The most recent scenarios for Finland were developed as part of the project FINSKEN. The average temperature and rainfall in Finland is expected to increase with the most change occurring during the winter months. The mean temperature is expected to rise 1 to 3°C compared to the 1961- 1990 average in the 2020s, 2 to 5°C in the 2050s and 2 to 7°C by the 2080s. It has been observed that the daily range of temperature is decreasing, which has been attributed to increased cloudiness.

Mean annual precipitation is expected to increase 0 to 15% in the 2020s, 0 to 30% in the 2050s and 5 to 40% in the 2080s. Extreme weather events (storms, droughts, heavy rains) will become increasingly common.

For more information see:

- http://www.ymparisto.fi/default.asp?contentid=165496&lan=en
- http://www.mmm.fi/en/index/frontpage/ymparisto/ilmastopolitiikka/ilmastomuutos.html
- http://www.ymparisto.fi/default.asp?node=18703&lan=en
- http://www.finessi.info/finsken/sce/
- http://www.mmm.fi/attachments/mmm/julkaisut/julkaisusarja/5kghLfz0d/MMMjulkaisu2005_1a.pdf

A4. Netherlands

The latest climate change scenarios for the Netherlands were published in 2006 and updated with supplement documents in 2009. They project that the Netherlands will become warmer in winter and hotter during the summer. Annual temperatures are expected to rise between 1 and 6°C by the end of the century. Over the past 20 years February and March have seen the greatest rise in temperature.

Annual precipitation is projected to increase with a slight increase in summer (1 to 4%) and a larger increase in winter (6 to 25%). Extreme rainfall events are expected to become more frequent and sea levels to rise by 20mm to 110mm by the end of the century.

For more information see:

- http://www.knmi.nl/klimaatscenarios/knmi06/achtergrond/WR23mei2006.pdf
- http://www.maakruimtevoorklimaat.nl/
- http://www.pbl.nl/en/publications/2006/ClimateAdaptationintheNetherlands.html

A5. Spain

The report *Preliminary Assessments of the Impacts in Spain due to the Effects of Climate Change* was published in 2005. The climate changes described for Spain are an increase in the annual mean temperatures, with the largest increase in the summer months. In some scenerios the whole of the Iberian Peninsular will experience an increase in summer temperature of 6°C by the end of the century. The rise in winter is around 2°C less.

In most regions the precipitation in winter is projected to increase or remain constant, however it is expected to decrease in summer and spring. Overall annual precipitation will decrease.

For more information see:

- http://www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/eval_pre_imp_esp_cc.htm
- http://www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/pdf/pna_v3.pdf
- http://www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/pnacc.htm
- http://www.mma.es/portal/secciones/cambio_climatico/areas_tematicas/impactos_cc/eval_impactos.htm
- http://www.mma.es/secciones/cambio_climatico/areas_tematicas/impactos_cc/pdf/01_el_clima_de_espana_2.pdf

A6. Sweden

By the 2080s average annual temperatures in Sweden will have increased by 3 to 5°C, with the most warming in the winter. Winter temperatures could increase by up to 7°C by the end of the century in the north east of the country where the most warming will occur. The thickness and duration of snow cover will decrease. The Norrland coast in January and February will experience the most warming. Summer temperatures will also rise, but to a lesser degree. Southern Sweden will experience more days where the temperatures is above 20°C.

Annual precipitation in Sweden will increase. There will be a strong increase in winter precipitation, with an additional 50mm a month in the north west by the end of the century. There will be more intense rainfall and more precipitation that falls as rain rather than snow. In southern Sweden in the summer, there may be less precipitation depending on the model used.

Sea levels are projected to rise more than the global average (18 to 59cm) in the North Sea and Baltic Sea. Along some parts of the southern coast it could increase by 80cm. The amount of sea ice will decrease.

For more information see:

- http://www.sweden.gov.se/sb/d/574/a/96002
- http://www.mistra-swecia.se/
- http://www.sweden.gov.se/content/1/c6/09/60/02/56302ee7.pdf

A7. Hungary

Hungary is expected to experience the most warming in summer, and the least in spring. Summer increases by the end of the century are 3.7°C to 5.1°C and spring 2.4 to 3.2°C.

Precipitation will increase in winter and decrease in summer and autumn, with an overall slight annual decrease. Summer precipitation is expected to decrease by 10 to 33%, whereas winter precipitation is expected to increase by 20 to 37%. This would result in a reversing of the wet and dry seasons in Hungary. Historically the wet season would be summer and the dry season winter.

For more information see:

- http://www.kvvm.hu/cimg/documents/nes080214.pdf (in Hungarian)
- http://web.ceu.hu/envsci/climate2007/JanosMika.CCHungary.pdf
- http://www.ecology.kee.hu/pdf/0501_001017.pdf
- http://www.springerlink.com/content/63573317875k3256/

A9. Portugal

Project SIAM (Scenarios, Impacts and Adaptation Measures) was set up in 1999 to look at the impacts of climate change on Portugal. The outputs of the project are summarised in the report Climate Change in Portugal. Scenarios, Impacts and Adaptation Measures published in 2001. In 2006 this was updated by SIAM II.

Portugal is projected to experience a rise in mean annual temperature and a decrease in precipitation, with a shorter and wetter rainy season. The inland regions will experience the largest increase in summer temperatures and decrease in summer precipitation and the coastal regions the least. The north may experience a small increase in winter precipitation, but on balance annual precipitation will decrease particularly in the south. There will be a decrease in the diurnal temperature range.

For more information see:

- http://www.siam.fc.ul.pt/SIAM_Book/2_ClimateScenarios.pdf

A10. Denmark

Denmark is projected to experience the following changes for 2071-2100, compared to 1961-1990:

- A rise annual mean temperature of 3 to 5°C, with the greatest warming at night.
- 25% decrease in snow cover
- 10-40% increase in winter precipitation and 10 to 25% decrease in summer precipitation
- More periods of intense rainfall especially in autumn and more periods of drought in summer.
- A sea level rise of 0.1 to 0.9m and an increase in the maximum height of storm surge by 5-10%.

For more information see:

- http://klimatilpasning.dk/en-US/Service/Climate/Sider/Forside.aspx

A11. Slovenia

Depending the emissions scenario, by the end of the 21st century the average annual temperatures in Slovenia are projected to increase by 3°C to 4°C, with the most warming in the summer (5°C to 6°C). Precipitation in winter will also increase by an average of 0.2mm to 1.0mm per day. In summer there will be a decrease in precipitation by a similar amount.

The Alps is the only area in the south Europe and Mediterranean region to be projected an increase in winter precipitation. The other parts of this region will experience a decrease in both winter and summer precipitation. Climate change will influence not only the average precipitation, but also the frequency and duration of rainfall. No major changes in precipitation patterns are projected in the spring and autumn, however more frequent and intense rainfall is projected for winter and longer and more intense periods of drought are projected for summer.

For more information see (in Slovenian, accessed on May 5th, 2010):

- http://www.arso.gov.si/podnebne%20spremembe/Podnebje%20v%20prihodnosti/Projekcije%20podnebja%20v%20prihodosti.pdf