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Report on future research areas for environmental effects

A summary of the environmental impacts of tyre/road surface interaction and the identification of future research areas

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Abbreviations

Abbreviation	**Meaning**
CO	Carbon monoxide
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
PAH	Polycyclic Aromatic Hydrocarbons
PSV	Polished Stone Value
PM_{10}	Particulate Matter with a diameter under 10 microns
$PM_{2.5}$	Particulate Matter with a diameter under 2.5 microns
$PM_{0.1}$	Particulate Matter with a diameter under 0.1 microns
RRC	Rolling Resistance Co-efficient
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SMA	Stone Mastic Asphalt
SO_2	Sulphur dioxide
VOC	Volatile Organic Compounds
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 refers to defining a Common Scale. Such harmonisation can be achieved both through harmonisation of measurements by adjustment of the outputs or through standardisation of measurements (as formulated elsewhere in the definitions).
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 depth	Descriptor of macro texture, obtained from a texture profile measurement as defined in EN ISO 13473-1 and EN ISO 13473-2.
Megatexture	Roughness elements with a wavelength 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.

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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 skid resistance to safety, the lack of harmonised systems for comparing skid 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 influence that provision of harmonised skid resistance has on the environment and the potential impact that climate change might have on surface characteristics optimisation in the future. This report is Deliverable D12 and its primary purpose is to identify potential areas of research deriving from environmental impact considerations. A further report (Deliverable D16) will deal specifically with the second theme, potential impacts of Climate Change.

Behind this report are a literature review (covering both themes) and an Expert Workshop held in Cologne in December 2009. The report summarises the findings of the literature review in relation to the first theme (environmental impacts of optimisation) and uses this, incorporating ideas from the expert workshop, to identify gaps in current knowledge and suggest potential research areas to address these gaps. Although the Climate Change section of the review is not covered in detail in this report (it will be included in D16), account has been taken of relevant Climate Change issues in arriving at suggestions for research. The key findings emerging from the review and workshop are summarised below.

Environmental impacts

In addition to skid resistance, tyre/road surface interaction produces undesirable environmental impacts such as tyre/road surface noise, greenhouse gases and other pollutants (from the contribution of rolling resistance to fuel consumption) and particulates from road and tyre wear. The factors identified in Work Package 3 of TYROSAFE as influencing skid resistance – such as type of aggregate, pavement texture, tyre material, tread and driver behaviour – also influence the magnitude of these environmental impacts. These factors are constantly changing with developments in technology and society including modifications to pavement and tyre design and materials to optimise specific parameters such as skid resistance, tyre noise emissions and rolling resistance. For example recent developments in tyre material additives have produced tyres with lower rolling resistance and the increased use of quieter pavement surfacings has reduced tyre noise. Harmonisation of skid resistance policy could also result in changes, such as increasing the use of high quality aggregates.

When evaluating the environmental impacts of tyre/road surface interaction it is important to take a holistic approach, as an action to reduce one environmental impact can increase another. For example using softer tyre tread compounds can reduce noise, but increase particulate emissions. Furthermore, the whole life cycle of tyres and pavements need to be considered, not just their use; optimising tyre/road surface interaction plays an important part in their design and the constituent materials used. Life Cycle Assessments (LCAs) show that during the use phase rolling resistance has the largest potential environmental impact but the impacts of producing constituent materials and the manufacturing/construction processes are not insignificant. For example, raising skid resistance requirements could increase the amount of polishing-resistant aggregate consumed. Suitable aggregates can only be obtained from a limited number of quarries, so not only does this have a local impact on landscape and populations near the quarries, it has the potential to increase the transport emissions from the construction phase as aggregates from further away are transported to road sites where, previously, more local materials might have been used.

Identifying information gaps

Identifying the environmental impacts of harmonisation and optimisation activities can be complicated as there are numerous cascading implications of actions. To aid in identifying the environmental implications and corresponding information gaps, each potential impact was categorised into one of three levels:

- Level 1: Aspects that result directly from the action
- Level 2: Side effects of the action
- Level 3: Behavioural or market changes that could result from the action

A similar categorisation was used for categorising the impacts of climate change:

- Level 1: Direct effects on the tyre/road surface interaction
- Level 2: Side effects which could impact on tyre/road surface interaction
- Level 3: Behavioural or market changes as a result of climate change which impact tyre/road surface interaction

Research areas

Categorisation of the impacts in this manner has helped to identify a number of potential areas for further research, including:

- The extent of use of polish-resistant aggregates across Europe and the environmental effects associated with an increase in their use, for example transport emissions
- How to make the best use of polish-resistant aggregates and alternative methods of increasing skid resistance
- Particulates from tyre and road wear and their impact on skid resistance through build up during drought conditions, viscous aquaplaning and summer polishing
- Tyre noise in the wet
- Rolling resistance in the wet
- Electric vehicles and skid resistance requirements
- Weather thresholds for seasonal skid resistance variation
- The implications for skid resistance of longer heavier vehicles

- The implications of less winter maintenance (as a result of milder winters) on skid resistance
- Climate change effects on surface durability

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 (which is still in progress at the time of writing this report) 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].

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 the harmonisation of skid resistance policy and 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 changed weather conditions arising from climate change
- 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

This report, which is the first written deliverable for WP4, aims to summarise existing knowledge of environmental impacts, identifying the important factors and establishing the gaps in knowledge in order to suggest the important areas for future research. A further deliverable, D16, will cover the possible impacts of climate change. The contribution that tyre/road surface interaction makes to climate change, i.e. its influence on the amount of greenhouse gas emissions released into the atmosphere, has been classified as an environmental effect and therefore included in this report. The impact climate change has on tyre/road surface interaction is a related but separate issue which will be discussed in D16. Research gaps identified as a consequence of climate change are however included here.

The report is laid out as follows:

- Chapter 2 provides a general introduction to the environmental impacts related to the tyre/road surface interaction
- Chapter 3 describes the environmental impacts of the “in-use” phase of tyres and road surfaces
- Chapter 4 briefly explores the environmental impacts of tyre manufacture and disposal
- Chapter 5 summarises the environmental impacts of pavement construction and maintenance
- Chapter 6 moves on to discuss the possible environmental impacts of future optimisation activities
- Chapter 7 identifies some of the potential direct and indirect influences of climate change
- Chapter 8 identifies the potential level of the impacts
- Chapter 9 identifies the gaps in current knowledge relating to both environmental impacts and climate change
- Chapter 10 identifies areas for future research

- Chapter 11 summarises the findings and makes specific recommendations for research

2 General introduction to environmental impacts related to tyre/road surface interaction

2.1 The main influences

Tyre/ road surface interaction plays a key part in determining road transport's impact on the environment, contributing to:

- Noise pollution – tyre/road noise is a major source of vehicle noise, particularly at higher speeds
- Local air pollution – rolling resistance contributes to vehicle fuel consumption and the level of fuel consumption dictates the amount of exhaust pollutants, such as NO_X and SO_2 released. Tyre and road wear also produce airborne particulates
- Climate change – the rate of vehicle fuel consumption determines the amount of greenhouse gas emissions produced
- Water and soil pollution – tyre and road wear are a source of pollutants which impact on nearby water courses and soil

Factors which affect the interaction of the road surface and tyre have been identified in WP3. These include characteristics of the:

- Vehicle – speed, weight
- Road surface – texture, aggregate type (mineralogy, shape and size)
- Tyre – tread depth and pattern, materials
- Driver behaviour – aggressive acceleration, braking and cornering
- Environmental conditions – icy or wet conditions, contaminants on the pavement surface
- Road – geometry and topography

These factors determine not only the road/tyre friction available, but also the magnitude of the environmental impacts. For example the durability of the tyre material will affect the amount of particulates produced through tyre wear and the texture of the road surface affects the tyre noise emissions. Consequently, modifying one of these factors, e.g. aggregate type to improve skid resistance might alter the environmental impact.

Actions to improve skid resistance (by mechanical retexturing, for example) or to increase grip in winter conditions (such as applying de-icer or using studded tyres) also have environmental impacts.

2.2 Socio-economic developments

Road and tyre characteristics and their environmental impact change over time as a result both of technological developments and of changes in society. For example, new tyre materials and pavement designs may be developed and travel patterns may change, influencing the way in which traffic interacts with roads.

2.2.1 Technology developments

The design and constituent materials of tyres, pavement and vehicles are continuously being revised to improve desired characteristics. Some of these changes will affect tyre/road surface interactions and the associated environmental impacts. Changes might be made to directly reduce the environmental impact of tyre/road surface interaction, such as changes to the tyre design to reduce noise. Alternatively, changes could have an environmental side effect, such as reduced particulates from tyre wear resulting from improved durability of the materials used.

2.2.2 Societal changes, legislation and policy

Changes in society have potential impacts through changes in the ways in which people travel, the modes they use, destinations and travel patterns for both business and leisure. There are a number of possible future changes that could impact on transport, such as more people working from home, changes in the most popular tourist attractions, shopping on the internet and movement of freight from road to rail.

Economic conditions also affect travel demand and patterns: people travel less in a recession and choose cheaper modes. A report [7] looking at UK traffic flows in the recent recession found a significant drop in traffic flow.

The introduction of new legislation can also be a strong driver for change, for example, the EU Directive on tyre labelling and phasing out the use of Polycyclic Aromatic Hydrocarbons (PAHs) in tyre manufacture. Other environmental legislation and policy could have effects on tyre/road surface interaction, e.g. policies to encourage lighter cars or heavier Large Goods Vehicles (LGV).

2.3 Studying the whole life cycle

When looking at the environmental impact of the interactions between tyres and road surfaces it is important to consider the wider picture. The design and materials of tyres and pavements are often selected for their contribution to tyre/road friction, therefore tyre/road surface interaction is associated not just with their use, but with their whole life cycle. A systematic approach considering the tyre and pavement constituent materials, manufacturing/construction processes and end of life disposal in addition to use is required.

2.3.1 Tyre life cycle

Tyres affect the environment throughout their lifecycle, i.e. during their manufacture, use and disposal. For example, their manufacture consumes resources and energy and can generate pollutants such as Volatile Organic Compounds (VOC). During use their wear produces particulates; they emit noise pollution and influence fuel consumption. At the end of their life they need to be disposed of. The magnitude and nature of these environmental impacts depends on the characteristics of the tyre, the vehicle on which they are being used, the road it is used on and environment to which it is exposed. The main environmental impacts associated with each stage of a tyre's life are summarised below:

Manufacture

- Consumption of raw materials; for the tyre constituents, e.g. rubber, steel, textiles, carbon black and also the water and energy required for the manufacture of the tyre
- Pollutants emitted by manufacturing process such as Volatile Organic Compounds in particular Poly Aromatic Hydrocarbons, odour, noise and waste

Transportation

- Vehicle emissions, e.g. green house gases, CO, PM_{10}
- Noise associated with transporting the constituent materials and finished products

Use

- Contribution to fuel consumption and therefore vehicle exhaust emissions
- Particulates from wear that pollute air, water and soil
- Noise emissions

Disposal

The environmental impacts of disposal depend on whether a tyre is recycled, retreaded or burnt for energy. (Landfill European Directive (1999/31/EC) prohibits the disposal in landfills of both whole and shredded tyres).

A Life Cycle Assessment (LCA) on tyres [8] suggest that 75.2% of a tyre's environmental impact is from fuel consumption when in use, 10.8% is from particulates generated by tyre wear, 11.7% is from raw material use and production, 0.3% is from transportation and 2% is from disposal. This indicates that the use stage, and fuel consumption in particular, plays the major role in this cycle, but raw material use, manufacture and the particulates produced are also significant.

2.3.2 Pavement life cycle

Similarly, the whole life cycle for pavements needs to be considered as the design and component materials are influenced by the required skid resistance. For example, the required skid resistance helps to determine the type of aggregate used, and therefore its source and how far it is transported. Figure 2-1 illustrates the main stages for an asphalt surface: there will be equivalent stages for a cement concrete pavement.

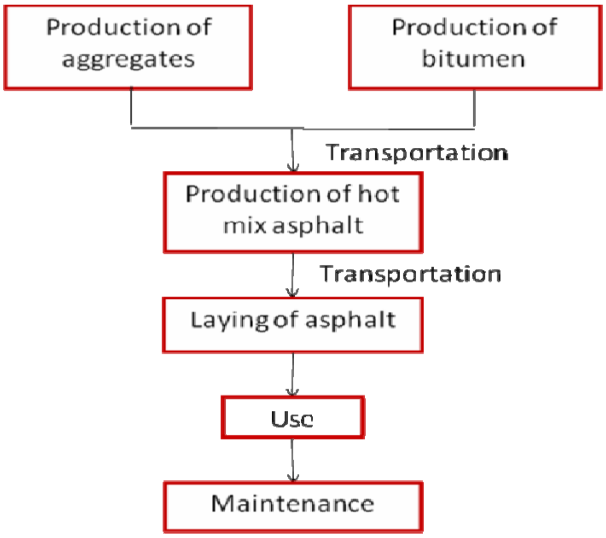

Figure 2-1 Life cycle of an asphalt pavement

The main environmental impacts associated with each stage of a surfacing's life are summarised below:

Production of constituent materials

- Environmental impacts associated with quarrying and crushing aggregates (or producing recycled/secondary aggregates), with obtaining crude oil and its refinement to produce bitumen, lime and silica for cement and the production of additives
- Consumption of raw materials – aggregates, bitumen or cement, polymers, wax additives
- Energy used for extracting and processing constituent materials

Transportation

Emissions associated with the transportation of constituent materials to the mixing plant and of the mixed materials to the construction location, e.g. greenhouse gas emissions, noise and air pollutants

Production of mix

- Energy to heat the mix and drive the batching and mixing plant
- Emissions, e.g. particulates and Volatile Organic Compounds (VOC), SO_2 CO, NOx
- Noise emissions from industrial plant

Laying

- Dust
- Waste
- Noise
- Energy to keep mix at laying temperature
- Fuel of plant used

- Leaching

Use

- Fuel consumption
- Particulates from wear
- Tyre/road noise

Maintenance

- There is usually no “end of life” with a pavement. Instead various forms of maintenance from patching to reconstruction are carried out throughout a pavement’s life. The environmental impacts are similar to those associated with the initial construction. Waste material may be recycled, for example Reclaimed Asphalt Plannings (RAP) may be incorporated back into the new surfacing.
- Winter treatments such as application of de-icer and sand for traction.

Production and maintenance are of similar high importance, although these stages are not as significant as use. Depending on traffic levels, construction, maintenance and operation of a road is thought to be 2 to 5% of the energy expended by the traffic [9].

3 Environmental impacts in the use stage of tyres and road surfaces

As demonstrated by LCA, the use stage of the tyre and pavement life cycle, i.e. when tyres and road surfaces interact, is where the largest environmental impact is exerted. This is mostly in the form of fuel consumption, but particulates from tyre and pavement wear and the generation of tyre noise also have a significant impact.

The following sections describe the factors, which influence the magnitude of the major environmental impacts due to tyre/road surface interaction.

3.1 Noise emissions

At higher speeds (over 15-25km/h for cars made since 1996 and 30-35km/h for LGVs) the major source of traffic noise is from the tyre/road surface interaction not the engine [10]. The sources of tyre/ road surface noise are indicated in Figure 3-1.

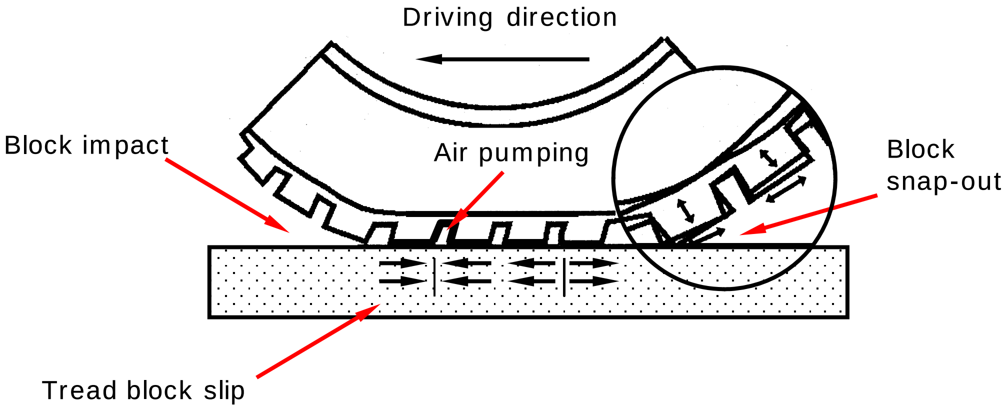

Figure 3-1 Road/tyre noise generation

Tyre/road noise is generated by a combination of a number of different mechanisms [10]:

- Impact mechanism
- Adhesion mechanism
- Air displacement mechanisms
- The horn effect
- The acoustical impedance effect
- The mechanical impedance effect
- Tyre resonance

These mechanisms are influenced by various factors relating to the tyre, pavement, vehicle and environmental characteristics. These are described in more detail in TYROSAFE D10 [6] and the magnitude of their impact [10] is summarised below:

- Vehicle speed – Tyre noise can increase by around 25 dB from 30 to 130 km/h
- Road surface – A difference of around 9 dB can be generated from different conventional road surfaces. This increases to 17 dB if non-conventional surfaces ranging from new porous surfaces to old paving stone surfaces are included
- Truck and car tyre type – Tyre types can vary by 8 to 10 dB
- Studs in tyre – Studded tyres generate around 8 dB more noise than tyres with no studs
- Load and tyre inflation - A variation of 25% can produce a difference of approximately 5 dB
- Road condition – Heavy rain can increase tyre noise by around 5 dB
- Temperature – There can be around a 4 dB increase in tyre noise measurements taken at 0°C compared to those taken at 40°C (depending on the type of tyre)
- Torque on the wheel – The torque acting on a tyre can increase tyre/road noise. Acceleration between 0 and 3 m/s^2 can increase tyre noise by around 3 dB

The main pavement characteristics that influence noise are [10]:

- Macrotexture has a very high influence
- Megatexture has a high influence
- Microtexture has a low to moderate influence
- Uneveness has a minor influence
- Porosity has a very high influence
- Thickness of the layer has a high influence for porous surfaces
- Adhesion (normal) has a low to moderate influence
- Friction (tangential) has a low to moderate influence
- Stiffness has an uncertain, possibly moderate influence

The EU project SILENCE (Quieter Surface Transport in Urban Areas) [11] involved producing an improved rolling model and suggestions on tyre design with regard to noise. It concluded that low noise tyres must have a soft tread compound and a heavy and soft belt construction. It has been found that a combination of softer rubber and lower air/rubber ratio may influence tyre/road noise emission on an ISO surface by about 6 dB (A).

3.2 Greenhouse gas emissions

A major environmental impact resulting from tyre/road surface interaction is the contribution to climate change through rolling resistance, which is an important factor in a vehicle's fuel consumption. Resistance to the forward movement of a vehicle is a combination of aerodynamic resistance, mechanical friction and tyre rolling resistance. All of these factors combine to influence fuel consumption, which is directly related to the emission of greenhouse gases. Studies have found that 5 to 15% of the energy consumed by a passenger car is due to rolling resistance; for LGVs the proportion is 15 to 30% [12], [15]. The greater the fuel consumption the more greenhouse gas emissions are emitted. This is mainly in the form of carbon dioxide, but also small amounts of nitrous oxide and methane. The average CO_2 emissions of the passenger car fleet in the EU were 153.5 g/km in 2008; under EU legislation a CO_2 emissions limit of 130 g/km is being phased in. Decreasing rolling resistance has a part to play in meeting this target. Tyres designed to have low rolling resistance can generate fuel savings of around 1.5% to 4.5% during their lifetime [13]. A 10% decrease in rolling resistance can decrease fuel consumption by up to 2% [13]. Differences in rolling resistance of up to 60% have been found between different roads corresponding to around 15% fuel consumption [14]. The factors which affect rolling resistance are described in D10 [6].

3.3 Air quality

Through its influence on fuel consumption, rolling resistance affects the amount of other pollutants generated by burning fossil fuel as well as greenhouse gases. These include primary pollutants such as carbon monoxide, hydrocarbons, benzene, nitric oxide, particulates (see Section 3.4) and sulphur dioxide. Secondary pollutants such as ozone and nitrogen dioxide form when the emissions generated react.

These pollutants impact on local air quality and therefore the health of people, crops, vegetation and wildlife. Respiratory diseases such as asthma and bronchitis are known to be aggravated by vehicle emissions and the immune system is thought to be affected by benzene, nitrogen dioxide and particulates. EU directives set limits on the concentration of a range of air pollutants, but many countries struggle to maintain these in urban areas, mainly due to vehicle emissions.

3.4 Particulates

The terms “particulates” or “particulate matter” refer to small solid particles of different compositions suspended or dissolved in a gas or liquid. Road transport is a significant source of anthropogenic particulates and, as previously discussed, airborne particulates from road transport contribute towards poor air quality. Of greatest concern are those particles small enough to enter into the lung (below 10µm in diameter (PM_{10})), these can be carcinogenic or contribute to cardiovascular problems. Smaller particles (e.g. $PM_{2.5}$ and $PM_{0.1}$) are even more damaging.

Particulates also pollute nearby watercourses and soil when washed off the road surface during rainfall. Material deposited on the road surface can be re-suspended by turbulence from traffic and wind. The road surface affects both the source and propagation of particulates. The source through rolling resistance (exhaust emissions), tyre and road wear and the propagation as deposition and re-suspension depends on the porosity and the adhesiveness of the road surface.

3.4.1 Exhaust particulates

Particulates from exhaust emissions are a particular problem for diesel fuelled vehicles. The particulates are composed mostly (80%) of organic and elemental carbon, with the remainder comprising sulphates and a small quantity of inorganic additives and components of fuel and motor oil. Approximately 98% of the particles are less than 10 microns in diameter (PM_{10}). Modern diesel vehicles of Euro IV and above are fitted with filters, which reduce the emissions of particulates. The maximum allowed PM_{10} emissions of a diesel Euro IV car is 25 mg per vehicle km, the Euro V limit decreases this to 5 mg per km.

3.4.2 Particulates from tyre and road wear

Around 25% of PM_{10} road emissions come from sources other than exhaust emissions and, as vehicle emissions become more regulated, this proportion is increasing. The most important sources of non-exhaust emissions are tyre wear, brake wear and road surface wear [16]. Around 20% of non-exhaust roadside PM_{10} emissions originate from tyre wear. Tyres lose 10 to 20% of their total weight before they are disposed of; this is 30 to 40% of the tread weight at a rate of approximately 100 mg per vehicle km. Around 5% of this material loss is emitted as PM_{10} [16], most of the tyre debris is too course to remain airborne. Airborne tyre wear particulates are normally found in two groups; ultrafine particles of less than 1µm and particles of around 7µm. The ultrafine particles are thought to originate from the volatilisation of extender oils and thermal degradation of polymer, which then condenses, whilst the larger particles are from mechanical wear.

Approximately half of tyre wear particulates consist of organic compounds [17] including styrene and butadiene polymers, and also a quantity of polycyclic aromatic hydrocarbons. Around 17% of the material is elemental carbon. Heavy metals are also generated, particularly zinc, lead and cadmium. Around 20% of the total zinc concentrations of airborne particulates in inner cities are thought to originate from tyre particles [18]. The full health effects of particulates generated from tyre rubber wear are unknown.

The exact amount of tyre wear depends on the characteristics of the tyre, road and vehicle and the operation of the vehicle (e.g. amount of braking). Factors which have found to influence the amount and type of particulates generated by tyre wear include:

- **Tyre type –** Wear of studded tyres produces more ultra-fine particles; this is thought to be generated from the thermal degradation of the carbon reinforcing filler and volatilisation of softening oils [19]
- **Tyre material –** The durability and abrasion resistance of the tyre material determines the amount of particulates released by tyre wear and the type of constituent materials determines the composition of the particulates
- **Tyre tread** – The sipes (small slits) in the tread of winter tyres produce more particulates due to increased tyre surface area and also act as a sink for particles [19]
- **Tyre pressure –** The incorrect tyre pressure will affect tyre wear as it changes the contact area. Under inflation increases wear on the outer edges of the tyre and over

inflation increases the wear in the centre. A 138 kPa (20 psi) increase in tyre pressure in LGVs can increase the surface damage of flexible pavements by 200 to 300%

- **Pavement type –** A study in the USA [20] found that emission rates of tyre wear per km driven on Portland cement concrete road surfaces were 1.4 to 2 times higher than emission rates on asphalt rubber friction course road surfaces. A Dutch study [21] found that ModieSlab (a two-layer modular concrete slab pavement) produces half the tyre wear of porous asphalt concrete (although the authors noted that the difference in particulate emissions is small compared to the background level). Tyre wear increases with increasing microtexture [22]
- **Vehicle speed –** The amount of particulates produced from tyre wear of studded tyres increases with speed whereas for summer tyres it decreases due to dilution from turbulence
- **Vehicle load –** Overloaded vehicles increase the pressure on the tyres [17]
- **Temperature –** The impact of temperature depends on the type of tyre rubber, for example winter tyres remain soft in cold weather whereas summer tyres harden. Softer tyres wear more quickly generating more particulates
- **Precipitation –** Tyre wear decreases in the wet, so fewer particulates are generated

Some studies suggest that road surface wear contributes less PM_{10} than tyre wear (0.11 mg/km-vehicle compared to 4.9 mg/km-vehicle respectively [23]), but other research suggests it contributes more particles [19]. It is difficult to separate the different sources of non-exhaust vehicle emissions, which could be why the information on the relative contributions of tyre and road wear is contradictory.

Asphalt pavements are approximately 95% aggregate and 5% bitumen binder. Therefore the majority of road wear particulates are mineral particles (aluminosilicates) originating from the aggregate. Aggregate contains metal pollutants and bitumen small amounts of polycyclic aromatic hydrocarbons. There can be quite a large difference in wear from different road surfaces, affecting the amount of particulates produced, their size and their potential to harm human health and the environment. For example it was found that particulates produced from SMA have less potential to cause lung inflammation than asphalt concrete [23] and that a granite pavement has a significantly higher capacity to induce the release of cytokines (an immune response) than an asphalt/quartzite pavement [25]. Asphalt concrete generates more particulates than SMA and the use of anti-skid aggregate substantially increases the amount of PM_{10} emitted. SMA produces a greater proportion of smaller particulates ($PM_{1.0}$) than asphalt concrete pavements [26].

Scandinavian countries have a particular problem with particulates in dry periods during winter and spring. The application of sand for traction and the use of studded tyres greatly increase PM_{10} emissions. Particulates generated by road wear are increased 40 to 50 times by the use of studded tyres. Countries that use studded tyres use larger aggregates to cope with the higher wear rate. Porous pavements become clogged more quickly when studded tyres are used. Applying aggregates (sand) for traction with high fragmentation resistance and coarse grain size distribution generates the least PM_{10} emissions. Unwashed natural sand generated more particulates than washed crushed stone [24]. Sand also increases pavement wear due to the abrasive action of the sand on the pavement surface when trafficked.

3.5 Water and soil quality

Tyre and pavement wear produces pollutants such as heavy metals and organic compounds which pollute nearby water courses and soil when washed off the road during rainfall. Pollutants can be soluble or suspended particulates and exert varying degrees of damage. For example zinc from tyre wear is toxic to aquatic microorganisms and can build up in fish. The quantity of zinc released by tyre wear in the USA in 1999 was estimated to be 10,000 to 11,000 metric tons [27]. A significant amount of the PAHs in waterways is also thought to be due to tyre dust. The use of PAHs in tyre manufacture is being phased out according to EC Directive 2005/69/EC.

De-icers, mainly sodium chloride, are applied during winter to prevent the formation of ice. Salt can both damage roadside vegetation and pollute nearby water courses. Road salt also contains anti-caking agents such as iron cyanide compounds, which can enter water courses.

Pollutants may leach into soil and water courses from pavement materials as they are subjected to wet and dry cycles from precipitation and groundwater.

4 Environmental impacts of tyre manufacture and disposal

A tyre is manufactured from between 10 to 30 different components. The main raw materials are natural rubber, synthetic rubber, carbon black and oil, of which more than 80% are the rubber components. Vulcanising agents, booster chemicals and protective agents are used in the rubber compounds and various kinds of reinforcement are used. The various components are heated together at temperatures of around 120°C [28]. The rubber or rubber blend, the amount of extender oil and the type of carbon black/silica etc. are selected to produce the desired tyre characteristics. The rubber component, for example, differs for summer and winter tyres.

4.1 Raw material, water and energy use

The manufacture of tyres consumes raw materials, water and energy all of which have environmental implications. Raw materials include rubber, carbon black, oil, chemicals, textiles and steel. A large amount of water is used for cooling and washing during production and energy is consumed through electricity use (45%), steam (32%) and use of water (23%) [8]. The environmental impacts of manufacture and disposal are dependent on the constituent materials and design and these are influenced by the desired tyre/road surface interaction. For example incorporating a novel additive to improve wet grip can change the environmental impacts of manufacture or disposal. Examples of different fillers and their impacts on tyre characteristics are given on manufacturer websites [29], [30].

Tyre manufacturers are researching methods of decreasing the environmental impact of producing tyres. This includes the incorporation of derivatives from vegetation such as rice, rape-seed and maize. Pirelli has reported that by the end of 2009 it expected to be able to use rice bran (a by-product of rice processing) as a component in tyre production, claiming that this will reduce the use of synthetic substances, so decreasing pollution [31]. Goodyear has developed a tyre called BioTRED in which traditional chemical compounds are replaced by an organic derivative from maize plants. The company states that this tyre also has a 20% reduction in rolling resistance and 50% reduction in noise. Other manufacturers are looking at using vegetable oils instead of crude oil in tyres. Yokohama is selling a tyre made with 80% non-petroleum materials, substituting oil made from orange peel as the primary ingredient to make vulcanized rubber. They have manufactured racing car tyres using this technique and are now selling passenger car made in this way. Sumitomo Rubber Industries is planning to manufacture a tyre containing no petroleum products by 2013.

Rice bran is used to enrich breads, breakfast cereals, and rabbit food, as a supplement for horses and to make cooking oil. Orange peel pulp is used as a pelleted animal feed and as cat litter. A life-cycle assessment is required to establish whether using rice bran and orange peel in tyres is more sustainable than using them for these other applications.

Silica is used as filler in place of some of the carbon black to improve rolling resistance. A LCA comparing tyres including silica with those containing only carbon black found the environmental impact of those containing silica was less [32]. A LCA by Continental [33], found a similar result and also that using polyester instead of rayon as the fibre cord reduced the environmental impact, as the manufacture of cellulose for the production of rayon consumes a large quantity of water and produces more waste.

Other developments in tyre composition include [34]:

- RockTron are developing a material called MinTron7 produced from water-pulverised fuel ash (waste obtained from coal fired power stations) which can be used in place of a proportion of the silica filler. It is less likely to agglomerate than silica, reducing the energy required in the mixing process as well as reusing an industrial by-product. Tyres manufactured with MinTron 7 are said to have increased wet grip and decreased rolling resistance; however, hardness, durability and modulus need improvement
- Organosilanes can be used to couple rubber and silica molecules with the aid of silicon compounds. This is said to reduce rolling resistance by 40% and also reduce VOC emissions during manufacture by 80% [35]
- A rubber additive called Nanoprene has been developed by Lanxess AG [36]. This additive links to the silanes and silicas in the tyre allowing grip and durability (reducing particulate emission) to be improved. There have been reports that dry grip is improved by up to 20%, tyre abrasion by 15% and that rolling resistance is not affected

4.2 Air emissions

The most significant emissions from tyre manufacture are volatile organic compounds (VOCs), which can harm human health by increasing lower atmosphere ozone and also contribute to climate change. The production of tyres involves the use of solvents to increase rubber “tack[1]” at certain stages of the manufacturing process and to offset natural drying. Solvents are also used in the cleaning process. These solvents emit VOCs. European Directive 1999/13/EC aims to reduce Non-Methane VOC (NMVOC) emissions from the use of solvents in some industrial activities. The amount of VOCs emitted depends on the method of tyre production and varies by country. However on average for an activity level of 3,552 kt of tyres produced, the average emission factor is about 6.2 kg NMVOC per tonne of tyres. Emissions from this sector are already partly treated in the EU25 (unabated emission factor is about 10 kg/t of tyre). The compliance date for the directive was 30th October 2007. Actions taken to reduce emissions of VOCs include reducing the amount of solvent used and using a thermal oxidiser [37]. Modifying the manufacturing process, so that instead of a rubber solution in a solvent being used underneath the tyre tread, a layer of bonding rubber is used, can reduce VOC emissions by 75%. Changes can also be made to the tyre constituents to reduce emissions, for example the addition of organosilanes is reported to reduce the VOCs emitted during manufacture by 80%.

Dust and odour are also generated by rubber compound mixing and tyre curing.

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[1] Tack is the ability of two similar materials to resist separation when brought under contact with a light pressure. Sufficient tack is necessary to enable the tyre compounds to hold together until moulding.

4.3 Waste

The production of tyres generates both non-hazardous waste, such as non-vulcanised rubber, and hazardous waste such as oil and solvent. Some of the non-hazardous waste can be recycled, but the hazardous waste needs to be carefully disposed of. The cooling water can be returned to rivers but the washing water is disposed of as industrial effluent. Tyre manufacturers aim to reduce waste by reusing as much material as possible.

4.4 Noise emissions

Noise is generated at tyre manufacturing plant and recycling/shredding centres. These are point sources of noise affecting the surrounding area. The machinery is often very noisy, but measures are usually put in place to mitigate the noise. Planning applications often set limits on the noise level allowed and the times of operation.

4.5 Climate change implications of tyre manufacture

The manufacture of tyres also has climate change implications. This is through the production and transportation of the constituent materials, particularly those manufactured from fossil fuels. The water and energy consumed also has an impact.

4.6 Tyre disposal

Approximately 250 million car and truck tyres are disposed of each year in Europe [38]. In the past, the majority of tyres were sent to landfill, but the EU Directive 1999/31/EC came into force in 2006 banning the disposal of whole and shredded tyres to landfill. At the end of their lives tyres can be retreaded, recycled, for example into surfacing for children’s playgrounds, or incinerated for energy.

Manufacturing a retread tyre for an average car takes around 20.5 litres (4.5 gallons) less oil than the equivalent new tyre; for commercial vehicle tyres the saving is estimated to be about 68 litres (15 gallons) per tyre. Car tyres can only be retreaded once but truck tyres can be retreaded up to three times if the carcase is in a good condition [39]. There has been some debate on whether low rolling resistance tyres can be retreaded and also whether the rolling resistance of retreaded tyres is greater than new tyres and if this offsets the benefits of retreading [40].

There are GHG emissions associated with the disposal of tyres, for example burning tyres for energy, retreading or shredding. Studies comparing the environmental impact of different uses of waste tyres have been conducted, for example the study by Corti and Lombardi [41] and Schmidt et al. [42].

5 Environmental impacts of pavement construction and maintenance

5.1 Depletion of natural resources

Pavement construction involves the consumption of natural resources, particularly aggregates which are the largest component of pavements.

5.1.1 Asphalt pavements

Around 95% of an asphalt pavement is made up of aggregate. The type of aggregate depends on the pavement layer and design. Aggregates in the surface layer are required to have a minimum PSV depending on the location of the pavement, for example motorway, junction etc. Aggregates for lower layers are selected to provide certain standards of strength and PSV is not specified. In the UK the amount of high PSV aggregate has increased by 220% over the last 10 years [43]. This is mainly due to the increased use of thin surfacing which uses high PSV aggregates throughout the layer and not just at the surface. Research is being undertaken to investigate methods of reducing the consumption of high PSV aggregates. The growth in this type of surfacing in other European countries may result in a similar increase in consumption. There is a limited permitted source of this type of aggregate and often the material has to be transported long distances. To reduce emissions it is therefore desirable to reduce the use of high PSV aggregate, for example through recycling surfacing and not over specifying. The use of recycled and secondary aggregates in pavement construction is growing, mainly in the lower pavement areas. This conserves natural resources and reduces the amount of waste sent to landfill. It can also decrease transport emissions if there are local sources of recycled and secondary aggregates available.

The bitumen binder is produced from the refinement of non-renewable crude oil. There has been work on developing bio-binders, binders produced from vegetable oils instead of fossil fuel to replace some or all of the bitumen binders. In France a process has been developed that incorporates vegetable oil in a 70 to 100 penetration grade bitumen, some of which has been modified. The first experimental section was built in 1997 and seven million square metres were laid in 2000. Shell Bitumen, which also has been experimenting with plant-based binders, conducted two highway trials in Norway in 2007. It concluded that there are no differences in the way the product holds up against initial traffic loads compared to asphalt binders, and in 2008 it released its version of a plant-based binder — Floraphalte — designed mainly for use on bicycle paths and footways [44]. A study looking at oils from oak flour, switchgrass, and corn stover found that further work was required [45].

Asphalt pavements can contain small amounts of other additives such as synthetic waxes and polymers which are also derived from crude oil.

5.1.2 Concrete pavements

Concrete pavements are made up of 60 to 75% aggregates (sand and crushed stone). The binder consists of cement (7-15%) and water (14-21%). The constituents of cement include limestone, clay, shale, iron ore, gypsum and additives such as calcium chloride to increase the rate of hydration or plasticisers. In reinforced concrete pavements steel is used to increase the pavement strength. Recycled and secondary materials can be used in concrete pavements such as Furnace Bottom Ash, foundry sand and waste glass.

5.2 Noise emissions

The construction and maintenance of pavements produces noise. Although a concern for local residents, this is a relatively short lived point source of noise. Quarries, refineries, cement plants and mixing plants are more permanent sources of noise.

5.3 Greenhouse gas emissions

Pavement construction and maintenance contributes to climate change, though obtaining, transporting and processing constituent materials. Energy is required to extract and crush aggregates, for the fractional distillation of crude oil and to produce cement. Cement is particularly energy intensive to produce (around 1 tonne of CO_2 per tonne of cement) as it involves heating constituent materials to high temperatures. Similarly the energy required to produce the asphalt mix and maintain it at a suitable temperature for laying, and the fuel of the plant used in the laying and compacting of the pavement generate GHG emissions. CO_2 is also produced during the distillation of crude oil to produce bitumen. A LCA study ([46]) showed that the largest proportion of energy consumed in the production of Continuously Reinforced Concrete Pavement (CRCP) is due to the manufacture of cement and reinforcing steel (94%). The largest proportion of energy consumed for asphalt pavement is due to the asphalt mixing and drying of aggregates (48%) and the production of bitumen (40%).

Warm and cold asphalt mixes have been developed which can be produced at lower temperatures reducing GHG emissions from energy consumption. However, these mixes can contain additives with high embodied energy; therefore a LCA is required to ascertain if emissions are reduced overall [45].

5.4 Particulates

Aggregate production and processing (e.g. crushing) produces large amounts of particulates. Mitigation actions are often taken at quarries to reduce dust. Actions are also taken at cement plants to capture cement kiln dust, reducing the amount emitted to the atmosphere.

Highway maintenance especially the impact techniques of in situ retexturing to improve skid resistance also produce particulates.

5.5 Local air pollutants

Depending on the source of the energy used to produce the constituent materials (e.g. coal power stations or wind turbines) air pollutants may be produced. Transportation also produces air pollutants from fuel consumption. NO_X, SO_2 and CO are produced during cement manufacture and a range of VOCs, NO_X, H_2S and SO_2 are produced during the distillation of bitumen from crude oil.

5.6 Skid resistance monitoring

An important aspect of the maintenance of the pavement surface, of particular relevance to the TYROSAFE project, is the monitoring of skid resistance condition. The measurement process itself has an impact on the environment, albeit relatively small compared with that of other traffic. Network level skid resistance measurement techniques consume fuel through the propulsion of the survey vehicle and use a great deal of water. Water consumption is of particular concern during drought conditions, and skid resistance is predominantly measured during summer when such conditions are more likely. Any harmonising of skid resistance measurement techniques should consider the level of water consumption and other environmental impacts including indirect effects such as the impact surveying has on traffic flow and resulting fuel emissions.

6 Effects of harmonisation and optimisation activities on the environment

As described in D06 the policies and approaches to skid resistance and skid resistance measurement vary considerably across the EU. Harmonisation has the potential to generate benefits in safety and consistency, but needs to be implemented in a manner which considers the wider implications including the environmental impacts. This section discusses some of the possible environmental implications of harmonisation, and of optimising specific parameters such as skid resistance, rolling resistance or noise emissions through pavement and tyre design and materials. These relate to the recommendations on how to implement a common approach to skid resistance policy given in D08 and the roadmap for the harmonisation of skid resistance measurement methods described in D09.

6.1 Higher skid resistance requirements

Harmonisation of skid resistance policies could lead to an increase in skid resistance requirements in some countries. The use of higher skid resistance pavements could result in the consumption of more polishing-resistant aggregates, identified by their high Polished Stone Value (PSV). This could generate greater transport emissions as suitable aggregates can only be obtained from a limited number of quarries and as a result may be transported over greater distances rather than using local aggregates with lower PSV. Particle emissions may be increased on higher-PSV aggregates because of the mechanisms by which they wear and/or influence tyre wear.

There could be less maintenance required as skid resistance should remain higher for longer. This will reduce the environmental impacts associated with maintenance.

Other actions can be used to create greater skid resistance such as increasing texture depth.

6.2 Policy changes

Harmonisation of skid resistance may result in changes in policy in relation to the specification or procurement of surfacing materials. For example, highway authorities might introduce certificates of production and quality schemes, which are often based on a material or system’s performance rather than its constituents. These may allow greater innovation but a question remains as to whether all materials used would be fully tested for their environmental impact.

Conversely, policies may be introduced with specific environmental constraints. For example, in some countries, suppliers are not allowed to sell a tyre unless they collect the one it replaces and send it to be recycled.

6.3 Optimising tyre/ road surface noise through surface design and materials

Low noise surfacings (such as porous asphalt and thin surfacings) are normally more porous and have a smaller aggregate size than many asphalt concrete or cement concrete surfaces. Possible side effects with environmental implications are increased maintenance (repaving and cleaning), additional winter maintenance and decreased rolling resistance.

The improved drainage with porous surfacing means that run-off is released more slowly, reducing soil erosion. Less spray also means that fewer pollutants are distributed by this mechanism, which is advantageous as spray-borne pollutants bypass any run-off treatment systems. The draining of rainwater though the pores in the road surface produces an infiltration effect that removes the majority of particulates suspended in the rainwater. Road pollutants such as heavy metals and PAHs attach to particles of dirt and so are quite effectively removed by this filtration process. Porous asphalt for example, has been found to remove around 90% of the PAHs and heavy metals present in road runoff. Dissolved pollutants such as chlorides and nitrates are not affected.

The incorporation of 15 to 20% of rubber crumb from recycled tyres in pavements has been reported to reduce tyre noise significantly (>6dB). The more flexible pavement was also found to be less prone to cracking. In the past, rubber pavement has been prone to ravelling particularly at intersections, but durability is improving. It is also thought to be less temperature susceptible and less maintenance is required as skid resistance is retained for longer and there is less cracking.

The mixing temperature requirement for mixtures incorporating rubber is higher than conventional asphalt (180°C compared to 160°C) increasing energy use during manufacture and laying. Rolling resistance is increased slightly, but the particulates emitted due to road and tyre wear are reduced [47].

6.4 Optimising rolling resistance through surface design and materials

Reducing rolling resistance has become an important issue for tyres but it has not yet become a primary driver for pavement design. It is possible this could change in the future. A low rolling resistance road would be harder and less deformable than a conventional road. For passenger cars less texture and a lower aggregate size may be beneficial. The benefits for LGVs are unknown. Under laboratory test conditions texture was found to have around a 15% effect on passenger car rolling resistance. In addition to reducing fuel consumption and therefore GHG and other exhaust emissions, low rolling resistance roads could also reduce tyre wear and the generation of particulates. The generation of fewer particulates means less clogging of porous surfacing, so the surfacing requires less cleaning and retains its noise reducing properties for longer.

6.5 Optimising tyre design

There are several radical new tyre designs being prototyped, e.g. the Tweel. This non-pneumatic deformable tyre/wheel is composed of a solid hub with flexible polyurethane spokes supporting a thin rubber band to which the tread is attached. The Tweel [49] is said to have reduced noise emissions compared to conventional tyres and similar rolling resistance. It is unknown how other environmental impacts compare with conventional tyres, although it is said to be more durable. To find out more information on these prototypes consultation with tyre manufacturers is necessary.

6.6 Optimising tyre manufacture

There have been a number of changes in the composition of tyre materials, driven by health issues (e.g. reducing the amount of PAHs) or environmental issues (the addition of silica to reduce rolling resistance and the use of vegetable oils in place of fossil fuel oils).

The impacts that these composition changes have on other environmental aspects is unclear. A full LCA is required to ascertain all impacts.

6.7 Optimising pavement construction

The environmental impacts of using secondary materials in pavements need to be examined. For example, issues of leaching need to be considered, so that soil and water courses are not contaminated with metals or harmful organic compounds. It is important that the weathering conditions the materials are exposed to do not produce materials which are harmful to the local environment or which can reach drinking water sources. Also, surface interaction characteristics may be changed if different materials or warm/cold mixes are used. There have been some indications that the incorporation of some waste materials such as rubber crumb can substantially reduce noise emissions.

7 Potential influences of climate change

Europe's climate is projected to become hotter with an increase in average temperature of up to 5.5°C in some locations by 2080 under a medium emissions scenario [50]. 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. The material properties of pavements and tyres vary with temperature; tyre hysteresis and inflation pressure are affected by temperature and bitumen binder softens in high temperatures. Precipitation affects skid resistance, rolling resistance and tyre noise. There are reports of climate changes already affecting tyre/road surface interaction; therefore the impacts of climate change will have a bearing on harmonisation and optimisation actions. When optimising pavement and tyre design and materials for parameters such as skid resistance the future climate it will be exposed to should be considered. It should also be remembered that climate change impacts will vary for different regions.

In addition to the direct impacts brought about by changes in climate variables such as temperature and precipitation, there are also indirect effects from actions taken as a result of climate change. This can be to reduce carbon emissions (mitigation) e.g. increased use of electric vehicles or to adapt to the changing climate, e.g. using stiffer binders in asphalt pavements. These actions can also have an impact on tyre/road surface interaction.

Both the direct and indirect potential impacts of climate change on skid resistance, rolling resistance and noise emissions will be described in detail in D16. Sections 7.1 to 7.4 below provide a summary of some issues that could arise as a consequence of these impacts.

7.1 Increased temperature

Increased temperatures could result in changes in the binder used in asphalt pavements. Highway engineers are already accustomed to tailoring binders to the climate and the projected increase in temperature was not thought to be a major problem by the experts consulted. In some situations extreme high temperatures in summer may result in decreased skid resistance from fatting up of the binder and embedment of aggregate.

Milder winters will result in less ice and snow, improving winter friction and rolling resistance. Less snowfall and fewer cycles of freeze-thaw could increase the durability of pavements. However, fewer freeze-thaw cycles and a decrease in weathering could mean less restoration of microtexture during winter and a change in the pattern of seasonal skid resistance variation. Changes of this nature are already being reported by some countries. Countries which use studded tyres are likely to require them less, reducing the retexturing effect that they have. Milder winters may also cause problems for the Scandinavian forestry industry as the ice roads become unreliable, and the ice road season becomes shorter. If the thaw is no longer predictable, their use becomes dangerous.

Normally skid resistance is measured in summer when skid resistance is at its lowest, this window for measurement could extend into spring and autumn.

7.2 Changes in precipitation

Climate models have projected that southern Europe will experience drier summers. This is likely to result in increased polishing and a greater build-up of road contaminants. There will also be more long dry spells followed by intense rainfall, which could result in greater skid resistance problems during the first flush (viscous aquaplaning). This could also have implications for water quality and the Water Framework Directive as contaminants are flushed from the surface into the local environment. In addition water consumption during skid resistance measurement may become more of an issue in drought conditions.

Northern Europe is projected to experience wetter winters. This may mean increased surface water and incidents of aquaplaning in winter. If, as thought by Meyer and Reichert [51], the most important factor in the restoration of skid resistance by weather is the length of time the surface is wet, this may be beneficial for reversing the impact of summer polishing. However, the temperature is expected to be higher, so it is unknown if increased evaporation will counteract any impact increased rainfall could have. It should also be noted that different surfaces take longer to dry out; surfaces with higher porosity retain moisture for longer than dense surfacings. Also the noise benefits of using more porous pavements are negated by surface water. This could have implications for the types of surfacing used in the future.

7.3 Issues due to other climate change impacts

Rising sea levels will impact on coastal roads and increases in groundwater level could erode road foundations and result in subsidence. While confidence in predictions related to both the frequency and intensity of storms is low, there could be an increase in storms, increasing the amount of debris deposited on the road surface. This could decrease skid resistance and clog porous surfacing reducing the noise benefits.

7.4 Issues due to indirect impacts

It is likely that the need to reduce greenhouse gas emissions will increase the number of alternatively powered vehicles. The use of electric vehicles in particular is expected to grow significantly. Currently it is unclear if this change in propulsion will impact on the tyre/road surface interaction. The two factors that were suggested could have an impact are vehicle weight (the battery can increase weight although research is being carried out on methods to reduce this) and the difference in the torque characteristics compared to a vehicle with a conventional internal combustion engine.

The need to reduce transport GHG emissions is also a strong driver for reducing the weight of passenger cars. However, there are proposals to use LHVs (longer heavier vehicles) to reduce emissions by reducing the number of LGVs on the roads. It is unclear what impact this polarisation of vehicle weight would have on pavement construction and tyre/road surface interaction.

8 Potential levels of impacts

This chapter describes the relative importance of the factors discussed earlier, helping to identify priorities for research. Examining the environmental impacts of optimisation activities can become quite involved as there are numerous cascading implications of actions. Therefore, to assess the environmental implications of the potential activities the TYROSAFE team categorised the impacts into three levels:

- Level 1: Aspects directly affected by the action
- Level 2: Side effects of the action
- Level 3: Behavioural or market changes that could result from the action

A similar categorisation was used for categorising the direct and indirect impacts of climate change:

- Level 1: Direct effects on the tyre/road surface interaction
- Level 2: Side effects which could impact on tyre/road surface interaction
- Level 3: Behavioural or market changes as a result of climate change which could impact on tyre/road surface interaction

Categorisation of impacts in this manner aids in capturing all the implications of an event and identifying information gaps. The results of the categorisation of environmental impacts of optimisation activities are given in Table 8-1 and the categorisation of the climate change impacts on tyre/road surface interaction are given in Table 8-2.

Table 8-1 Environmental impacts of optimisation activities

Optimisation Activities (issues)		**Level 1** **Direct effect**		**Level 3** **Market or behavioural change**
Low noise surfaces	Surface texture	Noise emissions	Drainage	Repaving frequency
	Aggregate (type)		Particle emissions	Aggregate production – changes in type and location of source
	Construction (mix design)			Difference in maintenance regimes
	Maintenance			
Higher skidding resistance requirements	High PSV aggregate requirements	Aggregate transportation emissions	Particle emissions	Increased imports of high PSV aggregate Less maintenance
	Procurement			
Low rolling resistance surfaces		Decrease in fuel consumption	Reduced tyre wear	Less frequent replacement of tyres
		Less CO_2 emissions	Reduced particulates	
		Improved air quality		
EU Regulations	Removal of the use of PAH's in tyre production	Not known yet	Not known yet	Not known yet
Technology changes	Tyre design	Not known yet	Not known yet	Not known yet
	Tyre composition	Not known yet	Not known yet	Not known yet
	Recycled and secondary Materials in pavements	Not known yet	Not known yet	Not known yet
Policy	Certificate of production	Not known yet	Not known yet	Not known yet
	Product approval	Not known yet	Not known yet	Not known yet

Table 8-2 Implications of climate change

Climate change impacts		Level 1 Direct effect		Level 3 Market or behavioural change
Temperature	Extreme summer temperatures	Potential for rutting and fatting up with asphalt pavements	Decrease in safety	Shift to other surface construction materials such as concrete or different binders
	Milder winters	Changes to the seasonal variation in skid resistance		Change in time and duration of skid resistance measurement window
	Freeze / thaw cycles		Surface durability	
	Less snow	Improved winter skid resistance	Fewer accidents, but more severe accidents due to increased speed	Less use of studded tyres – less particulates and less surface wear
Precipitation	Intense precipitation periods	More surface water - Aquaplaning	Increase in tyre/road noise	Drainage and pavement construction considerations More use of porous surfaces
	Longer drier periods	Increased summer polishing Increased contaminates Reduction in tyre/road noise Dust clogging porous surfaces	Change in skid resistance policy Tyre wear/ particulates more of a concern	Pollutants in highway runoff more of a concern
Changes to seasonal weather patterns	Warmer wetter winters, drier hotter summers	Change to the seasonal variation in skid resistance	Changes to the aging process	Changes in pavement standards
Rising sea levels		Damage to coastal roads	Debris on road surface	Not known yet
Changes in travel behaviour		Traffic volumes and destinations may change		

Table 8.2 Implications of climate change (Continued)

Climate change impacts (Continued)		Level 1 Direct effect		Level 3 Market or behavioural change
Climate change policy	Changes to the minimum depth of tread on tyres		Tyres need to be changed more frequently	Increased consumption of tyres
Climate change policy	Maintenance	Introduction of minimum requirements	Increased measurements	
Technology changes to reduce CO_2 emissions	Electric vehicles	Vehicle weight Torque	Tyre noise more important at low speeds Less pavement wear due to regenerative braking	Increase in use of low rolling resistance tyres
	LHV's (25m /60t)	Not known yet	Not known yet	Not known yet

9 Gaps in current knowledge

After categorising the effects and discussions on the findings of the literature review, the TYROSAFE team has identified areas where the established knowledge is not as detailed as is necessary to fully understand the impacts. Addressing these information gaps requires prioritisation. Where the environmental impacts or climate change implications are small resources may be better spent elsewhere, but where there are large effects and additional information could help minimise these and aid in long term decision making it is important to address this. The general gaps in knowledge identified are outlined below, more specific research areas are described in Section 10.

9.1 Environmental effects

On Theme 1, the environmental effects of tyre/road surface interaction, there are some topics where a great deal of work has been done such as on the mechanisms of tyre/road surface noise in the dry and the measurement of vehicle exhaust emissions, but others where knowledge is less detailed. As shown in Table 8-1 information is particularly scarce where changes are introduced either as a result of harmonisation and optimisation of tyre/road interaction or occur as a result of more general developments in policy and technology. For example where new materials and designs for tyres and pavements are being introduced a holistic whole life approach would be beneficial in being able to compare all the environmental impacts of different materials.

Another important area where there is insufficient information is the source of different types of aggregates across Europe and how they are used in highway construction. Knowing the available sources of high PSV aggregate and where the aggregate is transported to, is necessary to evaluate the potential impact of harmonisation. More information is required on how increasing skid resistance standards through harmonisation could impact on aggregate use and the environmental implications of this.

9.2 Climate change impacts

Observations from highway authorities and contractors suggest that climate change is already having an impact on tyre/road surface interaction. However this is not an area that has been greatly researched and there are significant gaps in knowledge (as shown in Table 8-2). As understanding of the potential changes in climate is increased through greater awareness, more advanced climate models and projections, there are now the tools available to explore this area further. The construction of highway infrastructure and European skid resistance policy both have long lead times, so it is necessary to plan ahead and ensure European highways are suitable for the future climate.

The most important direct influences are the changes in rainfall and seasonal patterns. Increases in average temperatures have fewer effects and even extreme temperatures are easier to adapt to, for example by changing binders. However changes in rainfall patterns including increased flooding and drought are more difficult to deal with. Also the impacts of changes in seasonal patterns and the combination of changes in temperature and rainfall are less well understood.

Indirect influences (i.e. the actions we take to reduce carbon emissions or adapt to climate change) could be quite significant and are often more difficult to define than direct effects. Firstly as it is often more difficult to predict these changes and secondly they can be completely different to the current situation, e.g. different tyre additives. More is known about how temperature effects pavements and tyres than how new pavement and tyre materials and designs, or vehicle technology effects skid resistance.

10 Areas for future research

By examining the information gaps, as described in Sections 8 and 9, areas for future research were identified and discussed with the experts at the workshop in Cologne. The research areas described in this section are those in which it was felt vital information was missing and that it is a priority this is addressed. This section covers research that would contribute to the understanding of the environmental impacts of tyre/road surface interaction focusing on the potential changes as a result of harmonisation or optimisation of different parameters. It also includes research that would increase the understanding of the consequences of climate change on skid resistance, rolling resistance and tyre/road surface noise.

10.1 Understanding local aggregates

The production and transportation of aggregates produce some of the major environmental impacts of pavement construction. It was identified that a greater understanding of where different types of aggregates are located, how they are used and how this could change with harmonisation, is necessary to inform European skid resistance policy. In particular, concerns have been raised that increasing skid resistance requirements could lead to an increased consumption of high PSV aggregates. There are limited sources of this type of aggregate, so this could lead to depletion of natural resources and an increase in transport emissions as they need to be imported from further afield. Making better use of local aggregates could reduce the amount of high PSV aggregates required.

Preliminary findings from enquiries within the TYROSAFE team suggest that currently most European countries produce the majority of aggregates for all their highway requirements from within their own borders. Some countries such as Slovenia have to import almost all high PSV aggregates from neighbouring countries. Even when aggregates are produced domestically, the quarries may not be close to the area of most demand. It is considered that there needs to be a greater understanding of:

- The type and location of European aggregates and how they can be utilised more effectively
- Whether an increase in skid resistance standards would increase the consumption of high PSV aggregates and if so, by how much
- Which regions are likely to generate this increase in consumption
- Whether this would lead to a large increase in transport emissions
- If any increase in aggregate transport emissions would be offset by the need for less maintenance

10.2 Making better use of high quality aggregates

Related to the above topic it was felt that more work needs to be carried out on methods to make better use of high quality aggregates. It was considered that this could be through:

- Mixing them with lower PSV aggregates - preliminary work suggests that with some mixture types small sized lower PSV aggregates could be mixed with larger sized high PSV aggregates to produce a graded mix without decreasing skid resistance
- Use of alternative materials which have a high skid resistance (e.g. synthetic aggregates such as calcinated bauxite)
- Greater recycling of high PSV aggregates

10.3 Particulates and skid resistance

Although studies have been carried out on non-exhaust particulates and their sources, these have not focused on how this relates to skid resistance. It is considered that greater understanding is required of:

- How the type and concentration of particulates generated varies by tyre and surfacing type
- The particulate characteristics which produce a negative impact on skid resistance, through polishing or contamination build-up
- How particulates build up during periods of drought
- The impact of the “first flush” on skid resistance (viscous aquaplaning) and water quality
- How contamination build-up affects skid resistance measurement

10.4 Seasonal variation of skid resistance

It has been observed by several European partners that the pattern of seasonal skid resistance variation is changing. Historically skid resistance decreases in summer (due to polishing) and is restored in winter. One study by the UK Highways Agency [52] suggested that during recent autumns skid resistance did not start to recover until late in the season and then did not recover to its previous level. Further work is required to confirm this phenomenon and examine the impact of different types of pavement surfaces with different trafficking.

It would be useful to explore how this pattern differs in different countries and understand more about the weather thresholds below which no restoration takes place.

10.5 Tyre noise in the wet

It is considered that not enough is known about how tyre noise increases in the wet. Noise measurements are normally taken using dry surfaces. Wetter winters and greater use of more porous surfaces may mean pavement surfaces are wet much of the time during winter. More information is needed on:

- How tyre noise increases in the wet
- How this differs with different road surfaces and tyre types
- How long surfaces remain wet enough to effect noise after rainfall has ceased
- How the noise varies with depth of water and speed

Estimates suggest that the degree of moisture and speed affect the amount of noise increase and that the increase is at frequencies above 1 kHz [10]. It may be beneficial to carry out noise mapping in the wet as well as the dry, similar to the night and day mapping currently carried out. It should be noted that the impact of human behaviour also needs to be considered. For example, it has been observed that on surfaces with less spray drivers increase their speed as visibility improves [53]. This increases the noise emissions, despite the quieter surface.

The assumptions in the EU project Harmonoise [54] (2001- 2005) which involved modelling road and rail noise needs to be reviewed and clarified for wet conditions. The derived model correction only covered Category 1 vehicles, is very specific to water depth and only applicable for a limited time after rainfall. Therefore it should be used with care and further work is required to understand the full effects for all current surfaces and vehicle categories.

10.6 Rolling resistance in the wet

Rolling resistance increases in the wet, however the degree to which it increases at different depths of water is not well understood. A technique for effectively and consistently measuring rolling resistance in the wet needs to be developed so that different tyre and surfacing combinations can be examined at different depths of water. Rolling resistance can be measured in a laboratory or on the road using an ISO procedure (ISO 28580:2009); however some aspects of the test such as the period of warm up required and drum diameter are not well described in the specification [56].

10.7 Skid resistance requirements of electric vehicles

The need to reduce transport GHG emissions is driving the advancement of vehicles powered by alternatives to fossil fuel. Foremost among these is the electric vehicle, powered by a battery, which is charged from the main electricity distribution system. There are a number of different prototypes currently being trialled and the use of electric vehicles could become wide spread in the future. Little is known about how, if at all, these vehicles' interaction with the pavement surface differs to conventional vehicles. Before these types of vehicles become more wide spread, it would be beneficial to understand how their skid resistance requirements compare with conventional vehicles and if any modifications to the pavement need to be made. Topics include:

- How do the torque characteristics produced by electric propulsion affect friction?
- How does regenerative braking impact on tyre/road surface interaction?
- What other vehicle technologies being developed will impact on skid resistance?

10.8 The implications of longer heavier vehicles for skid resistance

Trials of longer heavier vehicles are taking place in some European countries. It has been suggested that the use of larger freight vehicles will enable fewer vehicles to be used, reducing vehicle emissions. Little is known about how this will impact on road construction [55]. If the widespread use of LHVs requires a change in the way roads are constructed or the types of aggregate used there may be changes to the surface characteristics that could affect skid resistance. It is unknown at this time if there are other side effects or behaviour/market changes that will result from LHVs that could impact on skid resistance. For example, changes to the way freight is transported, perhaps through distribution centres and the routes used. If the use of LHVs is to increase it is important that these questions are addressed.

10.9 Changes in surface durability as a result of climate change and the implications on skid resistance

Surface durability is pertinent to the tyre/road surface interaction, e.g. ravelling can cause a skid hazard and ruts can fill with water with the potential for causing aquaplaning. It is unclear if changes brought about by climate change will have an impact on surface durability and thus skid resistance. For example, will a decrease in freeze/thaw action improve durability or will higher temperatures increasing oxidation and binder hardening have a greater impact? Research is required to investigate the climate variables which produce different surface defects and relate these defects to changes in skid resistance. Climate projections can then be used to evaluate the potential for these defects to increase significantly in the future.

10.10 Influence of winter service on skid resistance

The change in climate is likely to result in less winter service being required, i.e. less application of de-icers and less use of studded tyres in countries which currently use them. This has ramifications for skid resistance. Although studded tyres damage pavements, they also restore skid resistance to surfaces that have undergone summer polishing by retexturing the surface. The application of salt can also increase weathering restoring skid resistance. It is unknown if one of the impacts of less winter maintenance will be less restoration of skid resistance or if less winter maintenance will improve surface durability.

10.11 Prioritisation of research areas

Table 10-1 lists the research areas described above and provides an indication of their priority.

Table 10-1 Prioritisation of research areas

Research Area	Priority	Comments
Understanding local aggregates	High	The production and transportation of aggregates exerts a large environmental impact. It is important that the implications of harmonisation on this is understood, so harmonisation can be implemented to minimise this impact.
Making better use of high quality aggregates	High	This is an important area for long term research as reduction in the use of high quality aggregates has the potential to reduce significant amounts of ghg

		emissions.
Particulates and skid resistance	Medium	Changes to contaminant build-up and viscous aquaplaning could be significant in areas that are projected to become substantially drier in the future. This is a long term issue.
Seasonal variation of skid resistance	High	Impacts are already being seen and to gain a view of the long term trend it is important to start this work as soon as possible.
Tyre noise in the wet	Low/Medium	This is an important gap in the understanding of tyre noise. An increase in intense rainfall events and wetter winters in some locations will make it increasingly important.
Rolling resistance in the wet	Low	Water and snow can increase rolling resistance by 10-20%. Understanding this better could help decrease GHG emissions.
Skid resistance requirements of electric vehicles	Medium	EVs are already being used and the EU is encouraging their use. It is important the any implications for skid resistance are understood quickly.
The implications of LHVs on skid resistance	High	LHVs are being trialled in some EU countries. If they are to be introduced more widely the implications for skid resistance needs to be known.
Changes in surface durability and the implications on skid resistance	Low	Climate has a large influence on surface defects therefore the surface durability is likely to be affected by climate change. However, it is likely the impact will most significant on local roads which are more vulnerable than the better maintained main roads.
Influence of winter service on skid resistance	Medium	Changes in the amount of salt applied are already being seen, but this is likely to be a long term effect. It will be most relevant to those regions where there is a large increase in winter temperature projected.

11 Conclusions

Work Package 4 of TYROSAFE is focused on two themes: the environmental implications of optimisation of specific parameters of tyre/road surface interaction and the impact of climate change on skid resistance, rolling resistance and noise emissions. This report focuses mainly on the first of these themes; the second report D16 will cover the impacts of climate change.

A literature review was carried out on the environmental impacts of tyre/road surface interaction. The findings and their implications for harmonisation and optimisation of skid resistance, rolling resistance and tyre noise were discussed at an expert workshop held in Cologne on the 2nd December 2009. The gaps in information and areas of future research were also discussed.

11.1 Relevant factors influencing the environmental impacts of tyre/road surface interaction

The literature review and workshop helped to consolidate the current state of knowledge on the environmental impacts of tyre/road surface interaction and the optimisation of specific parameters such as skid resistance and tyre/surface noise could change these impacts. The key findings were:

- The whole life cycle of tyres and pavements needs to be considered as the optimisation of skid resistance involves modifying the design and materials used which effects the environmental impacts of manufacture and disposal
- The ‘in use’ stage produces the majority of the environmental impacts for both tyres and pavements although the environmental impacts from manufacture and disposal are still important
- The key environmental impacts in the use stage are tyre/road noise, greenhouse gas emissions (through the contribution of rolling resistance to fuel consumption) and particulate emissions from tyre and pavement wear
- The factors identified in WP3 as impacting on the tyre/surface interaction such as aggregate type, tyre material and texture also affect the environmental impacts
- Modifications to tyre and pavement design and materials can have a significant influence on environmental impacts. An LCA is required to ascertain the changes in different environmental impacts

11.2 Recommendations for future research areas

The information gathered was used to categorise the environmental impacts and climate change effects as follows:

Level 1: Direct effect
Level 2: Side effect
Level 3: Behavioural/market driver

The categorisation is shown in Table 8-1 Environmental impacts of optimisation activities and Table 8-2 Implications of climate change. Categorising the impacts in this way helped to identify and prioritise the gaps in knowledge in order that future research areas could be identified.

An important gap identified was a lack of information on the sources of different types of aggregates across Europe and an understanding of how they are used in highway construction. This information together with a study on how an increase in skid resistance requirements could change consumption particularly of high quality aggregates is required. There is a concern that harmonisation could generate an increase in the consumption of high quality aggregates potentially increasing the GHG emissions from aggregate transportation as sources of high quality are limited and may need to be transported longer distances. Without this additional information it is not possible to ascertain if this is the case.

Another area where more information is needed is where the design and constituent materials of tyres and pavements are modified to optimise different characteristics such as skid resistance. A full LCA is required looking at the environmental impacts of manufacture, use and disposal.

In regard to the second theme of WP4, the effects of climate change on skid resistance, rolling resistance and tyre/ surface noise, there are a large number of unknowns. The impacts of temperature and precipitation on tyre and road characteristics are understood to some extent, but more research is required on for example tyre noise and rolling resistance in the wet. Additional research is also required on phenomena such as the seasonal variation of skid resistance and the build up of contaminants during drought to better understand the conditions which cause these and how this might change in the future. Information on the future climate needs to be combined with an understanding of the influence of climate variables such as temperature and precipitation patterns on skid resistance, rolling resistance and tyre/surface noise. More information is required on the impacts of actions taken as a result of climate change (e.g. use of electric vehicles, LHVs, more use of recycled materials in pavements) on skid resistance, rolling resistance and tyre/surface noise.

The specific areas where further research is recommended are in:

- Understanding the type, source and quantity of the aggregates used across Europe, particularly obtaining information on where high PSV aggregates are sourced from and how they are used in highway construction
- Investigating methods of making better use of high quality PSV aggregates to minimise levels of consumption
- The impact that particulates and contaminants have on tyre/road surface interaction, for example by polishing, build-up during drought conditions and viscous aquaplaning

- Monitoring the changes that are occurring with seasonal skid resistance variation due to climate change and increasing understanding of the climate parameters which cause this phenomenon
- How tyre/road surface noise changes in wet conditions, including looking at the impact of water depth and the duration of the noise increase after rainfall has ceased
- How rolling resistance changes in wet conditions, including how it varies with water depth
- The tyre/road surface interaction of electric vehicles to ascertain if the skid resistance requirements for electric vehicles are different to conventional internal combustion engine vehicles
- Identification of possible changes in tyre/road surface interaction and pavement construction as a result of allowing longer heavier vehicles
- The impact of climate change on surface durability and the implications for tyre/road surface interaction
- How changes to winter salting and studded tyre use as a result of climate change would influence tyre/road surface interaction

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