Unclassified **COM/ENV/DSTI(2013)1/FINAL**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development

30-Jul-2014

English - Or. English

ENVIRONMENT DIRECTORATE
DIRECTORATE FOR SCIENCE, TECHNOLOGY AND INDUSTRY

Cancels & replaces the same document of 03 July 2014

Nanotechnology and Tyres: Greening Industry and Transport

JT03360806

NANOTECHNOLOGY AND TYRES: GREENING INDUSTRY AND TRANSPORT

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FOREWORD

The rapidly advancing field of nanotechnology has the potential to impact industrial and economic development, the environment and society at a global level. The benefits are expected to be significant, with potential applications that could help to address major global challenges, such as sustainable energy production, water provision, healthcare and climate change.

However, the field of nanotechnology spans a range of different technological developments at the nanoscale and a plethora of potential applications across many industrial sectors and fields of activity. This makes it difficult to categorise and, indeed, to analyse and refine policies for science and technology, investment, commercialisation and regulation. Through this study on *Nanotechnology and Tyres: Greening Industry and Transport*, the OECD Working Party on Nanotechnology (WPN) and the OECD Working Party on Manufactured Nanomaterials (WPMN) hope to advance the policy debate by considering a wide range of issues regarding sustainable growth and the responsible development of nanotechnology from the perspective of a single application of nanotechnology in a mass market consumer product: tyres.

Encouraging the green growth of industry is a key policy goal in many countries. In addition, governments are confronted with the need to reduce dependence on oil imports, improve air quality, reduce CO_2 emissions and encourage greater competitiveness. Nanotechnologies in tyres can contribute to all of these objectives. However, while the potential benefits could be enormous on a global scale, there is still a need to develop a better understanding of the socio-economic impacts as well as possible risks to human health and environmental safety over the tyre life cycle.

The project on *Nanotechnology and Tyres: Greening Industry and Transport*, the conclusions of which are presented in this volume, was conducted by the OECD Working Parties mentioned above: the WPMN and WPN. The project was originally proposed and supported by the Business and Industry Advisory Committee to the OECD (BIAC) through the Tyre Industry Project (TIP) of the World Business Council for Sustainable Development (WBCSD). At the OECD Secretariat, the project was managed by Peter Kearns and Marie-Ange Baucher. The background project analysis and drafting of the report were conducted by the consultancy Ricardo-AEA, in collaboration with Eastern Research Group, Inc (ERG). The leading authors of the report were Gena Gibson and Sujith Kollamthodi (Ricardo-AEA) and Kurt Rindfusz, Anthony Gaglione and Rebe Feraldi (ERG). Jennifer Allain prepared the manuscript fot the publication.

The Committee for Scientific and Technological Policy and the Joint Meeting of the Chemicals Committee and the Working Party on Chemicals, Pesticides and Biotechnology agreed to the declassification of this report in March 2014.

This document "cancels and replaces" an earlier version, modifying one word of the text (**emboldened**) in the Executive Summary on page 14, second paragraph, fifth line.

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ACRONYMS AND ABBREVIATIONS

ATSDR	Agency for Toxic Substances & Disease Registry (United States)
CBA	Cost-benefit analysis
CEC	Cation exchange capacity
CED	Cumulative energy demand
CHN	China, People's Republic of
COD	Chemical oxygen demand
Defra	Department for Environment, Food and Rural Affairs (United Kingdom)
DIY	Do-it-yourself
EASAC	European Academies Science Advisory Council
EB	Exposure band
EC	European Commission
ECETC	European Centre for Ecotoxicology and Toxicology of Chemicals
ECIC	European Chemical Industry Council
EHS	Environmental, health and safety
ELT	End-of-life tyre
EOL	End-of-life
EP	Eutrophication potential
EPA	Environmental Protection Agency (United States)
ETRMA	European Tyre and Rubber Manufacturers' Association
EU	European Union

FIBC	Flexible intermediate bulk containers
GTR	Granulated tyre rubber
GWP	Global warming potential
HD silica	Highly dispersible silica
HD-HS silica	Highly dispersable high surface area silica
ICCT	International Council on Clean Transportation
ICN	International Council on Nanotechnology
IEA	International Energy Agency
IEA MoMo	International Energy Agency Mobility Model
ISO	International Organization for Standardization
JRC	Joint Research Center (European Commission)
LCA	Life-cycle analysis
LCI	Life-cycle inventory
MJ	MegaJoules
MMT	Montmorillonite
MSDS	Material safety data sheet
NHTSA	National Highway Traffic Safety Administration (United States)
NIOSH	National Institute for Occupational Safety and Health (United States)
NMVOC	Non-methane volatile organic carbons
NOx	Nitrogen oxides
ODP	Ozone depletion
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturers
PJ	PetaJoules
PM	Particle matter

PPE	Personal protective equipment
RMA	Rubber Manufacturers Association
SASSI	Synthetic Amorphous Silica and Silicate Industry Association
SOx	Sulphur dioxides
TDF	Tyre-derived fuel
TIP	Tyre Industry Project
TPMS	Tyre pressure monitoring system
TRB	Transportation Research Board
UN NGLS	United Nations Non-Governmental Liaison Service
USA	United States
USDOT	United States Department of Transportation
VOC	Volatile organic compounds
WBCSD	World Business Council for Sustainable Development
WPMN	OECD Working Party on Manufactured Nanomaterials
WPN	OECD Working Party on Nanotechnology

EXECUTIVE SUMMARY

The demand for vehicles is expected to double by 2030, putting enormous pressure on the sustainability of the transport sector. A number of measures should be taken to manage this increase and prevent its massive impact on the environment, society and the economy. These measures include, for example: reducing the use of personal vehicles by increasing the availability of public transport services, developing greener vehicles, and providing more sustainable tyres. Indeed, tyres significantly contribute to the overall environmental impact of the transport sector due to the high levels of natural resources used in their production (for example, natural rubber and synthetic rubber derived from fossil fuels) and the effect of the rolling resistance of tyres on vehicle fuel consumption.

New technological solutions are now being researched to improve the sustainability of tyres and nanotechnology is at the frontline of technologies that could help contribute to this goal. The use of new nanomaterials in tyre production is expected to help improve the sustainability of tyres throughout the life cycle of the product. New nanomaterials have the potential to decrease rolling resistance (improving fuel consumption) and **improve** wear resistance (increasing tyre lifetime) while maintaining wet grip and existing safety levels. Yet many of the policy implications of the use of nanotechnology in tyres are still unclear. In particular, uncertainty over environmental, health and safety (EHS) risks remains and specific risk assessment frameworks for the use of nanotechnology in tyre production are missing to assess those risks efficiently.

Key findings and messages

Industry-specific guidance is missing for assessing the environmental, health and safety risks in the development of new nanomaterials in tyre production: this study provides guidance for risk assessment for the use of nanotechnology in tyre production.

New nanomaterials offer promising avenues for future innovation, which could contribute towards the sustainability and resource efficiency of the tyre industry. However, uncertainty over the EHS risks appears to be a main and continuous concern for the development of new nanomaterials in tyre production, even for some of the new nanomaterials that are close to market. The difficulties in characterising the EHS risks lead to uncertainty in the way nanotechnologies are being regulated, which seems to affect innovation at all stages of development.

While generic EHS good practice guidance can serve as a starting point for the tyre industry when addressing the EHS risks, the lack of industry-specific guidance for assessing the risks associated with the use of nanomaterials in tyre production constitutes an important gap. To address this gap, a risk management framework was developed as part of this study that can be used specifically to develop site- or company-specific risk assessments or risk management strategies for using nanomaterials as additives in tyres. This gap in industry-specific guidance also seems to affect other industry sectors using nanotechnology. A possible next step could be the development of further industry-specific guidelines to help improve the effectiveness of the implementation of new nanomaterials in other sectors.

Policies to support research in the environmental, health and safety risks, as well as those to support the commercialisation of nanotechnology research results, are *critical to foster responsible innovation in the tyre sector.*

Many policies have an impact on the uptake of new nanomaterials in tyre production, in particular those policy instruments aiming to bring clarity to the assessment of the EHS risks. This study demonstrates that policies to foster knowledge sharing and co-operation concerning the responsible development of nanotechnologies play a critical role in managing uncertainty and act as a clear driver of innovation in the tyre industry. Public investment more generally was seen as a critical lever to address issues linked to the commercialisation of research results and the development of research into the societal and environmental issues associated with the development of nanotechnology.

Policy instruments aimed at greening transport and increasing consumer awareness are important drivers of sustainable innovation in the tyre industry, including research into new nanomaterials.

Innovation in the tyre industry is driven by three main market factors that are affecting different steps of the supply chain: the demand for better performance and “greener” tyres; the competition between tyre manufacturers; and major economic and environmental issues directly affecting tyre production, such as resource scarcity and the rising costs of raw material and oils.

The growing use of policy instruments for fostering fuel economy and reduction of CO_2 emissions for new vehicles, such as vehicle fuel efficiency standards, are driving demand for low resistance tyres. Specific legislation to reduce the impacts that tyres have on vehicle fuel efficiency is relatively recent, with minimum standards for rolling resistance being a key example. In order to influence demand and steer innovation toward more sustainable and cost-efficient tyres, improvements in tyre performances should be made clearly visible to consumers. Tyre labelling and rating systems are key instruments to that end. Increasing consumer awareness is an important enabling factor that allows the actual benefits to be perceived and understood. All of these instruments act as drivers for technological innovation in the tyre industry.

A range of analytical tools should be used to gain better insight into the socio-economic and environmental impacts of nanotechnology applications.

Estimates concerning the range of potential future impacts associated with the uptake of new nanomaterials in tyres are important inputs into the design and management of the various policy instruments that directly or indirectly affect innovation in tyres. A number of analytical tools were used in this study to explore the socio-economic and environmental impacts of nanotechnology when used in tyre production: a cost-benefit analysis, a multi-criteria analysis and a life-cycle analysis.

The study concluded that highly dispersible high surface area (HD-HS) silica and nanoclays, the nanomaterials explored in detail in the study, could generate significant net benefits for consumers whilst also reducing environmental impacts. However, accurate impact assessments are often difficult to attain because of uncertainty over the EHS risks. Quantitative cost-benefit analysis functions best when impacts can be accurately assessed, and uncertainty over the EHS risks means this is not currently practical. Benefits must then be weighed against the possibility of introducing a new and uncertain costs related to the potential EHS risks of nanotechnology use.

The life-cycle analysis (LCA) used in the study showed that environmental improvements over the lifecycle of the product, e.g. in tyre production and use, could be achieved over a range of environmental impact categories by using HD-HS silica and nanoclay. Although the savings in the production stage are relatively high in percentage terms, the magnitude of the savings is much greater during the in-use stage. However, data availability and accessibility issues affected the use of LCA, either because quantitative data had not been gathered or because the information and data needed to complete the analysis were considered to be confidential. Because of this lack of primary data, this study makes no claim to provide definitive results for HD-HS silica and nanoclay, or to make comparative statements for these products. Recommendations to improve the LCA framework for assessing the relative impacts of baseline and nano-enabled tyres, however, are included in the study.

Collaboration between governments and industry is critical to address the specific challenges raised by the introduction of new nanomaterials in different industry sectors.

Using the analytical tools mentioned above requires access to good quality data at the policy level and at the corporate level; this study benefited greatly from joint efforts between governments and industry stakeholders to provide such access. Without such collaboration, addressing the specific challenges raised by the introduction of new nanomaterials in different industry sectors would have been impossible. Similar collaborative approaches may therefore be beneficial for other industry studies confronted by data collection difficulties.

READER'S GUIDE

Definition of nanotechnology used in this study

Nanotechnology can cover a wide range of concepts. This study uses the widespread definition of: "technologies that enable the manipulation, study or exploitation of very small (typically less than 100 nanometres) structures and systems." Within the field of nanotechnology, two subgroups are defined (ChemRisk, 2011):

- Nano-objects: materials that exist in defined singular form that have at least one dimension in the nanoscale (<100nm). These include nanoparticles (three dimensions in nanoscale), nanofibres (two dimensions) and nanoplates (one dimension).
- Nanostructured materials: materials that have structural features on the nanoscale but whose particle size is typically greater than 100nm, such as materials that primarily exist in aggregated and/or agglomerated form.

Tyres sectors and geographical scope covered in the study

The market for tyres is very varied, so this study focuses on sectors that together constitute by far the largest share, namely:

- passenger car and light truck tyres
- commercial truck tyres.

Together, passenger car, light truck and commercial truck tyres account for almost 90% of the total tyre market both by volume and value. Although motorcycles and scooters constitute a large proportion of the road fleet in certain regions (such as Asia), they account for only a small proportion (~3%) of global transport energy consumption. Buses and coaches also account for a relatively minor portion of global transport energy use (~6% compared to 44% for light duty vehicles and 23% for road freight; International Energy Agency, 2010). Other types, such as those for agricultural vehicles and aircraft, account for a small proportion of the total market and are not included in this study.

The geographical scope of the quantitative cost-benefit analysis is restricted to the three largest vehicle markets in the world as predicted by 2035, namely: Europe, the People's Republic of China and the United States.

Nanomaterials analysed in detail in this study

Four specific nanomaterials are studied in detail and used as case studies in the different sections of this volume. They meet the following screening criteria:

- Those with sufficient data availability to allow a meaningful analysis. For example, options at an early stage of development with low expected impacts over the next decades were excluded.

- Those that are being investigated by a large number of companies (that is, are less likely to be proprietary to a single manufacturer).
- Those that could have significant uptake within the next 20 years.
- Those that result in the greatest improvements in performance.

Two of the nanomaterials investigated involve technologies that have been in use in the tyre industry for some time and two involve emerging new technologies. The four nanomaterials selected are set out below; they will be referred to as "case study nanomaterials" in the different sections of this report:

- Incumbent nanomaterials:
  - carbon black
  - conventional "highly dispersible" (HD) silica.
- Emerging new nanomaterials:
  - new generation "highly dispersible high surface area" (HD-HS) silica.
  - nanoclays.

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CHAPTER 1

NANOTECHNOLOGY IN TYRES: STATUS OF THE TECHNOLOGY

This opening chapter provides an introduction to the use of nanotechnology for improving tyre performance, and in particular tyre sustainability. It provides an overview of some of the main nanotechnology solutions currently in use and emerging, as they apply in tyre production. Four nanomaterials are being investigated in more detail in this chapter: two that are currently in use – carbon black and conventional "highly dispersible" (HD) silica, and two emerging ones – new generation "highly dispersible high surface area" (HD-HS) silica and nanoclays. It also gives a first insight into the main technical barriers to commercialisation and uptake of new nanomaterials in the tyre industry.

Modern tyres have used nanoscale materials (carbon black and silica) for decades to achieve performance levels far higher than would be possible otherwise. Rubber tyres are currently the biggest commercial market for nanomaterials (European Commission, 2012). However, the technical limits of these current options are being reached. New technological opportunities for improving tyre sustainability and performances are being investigated. In particular, many new nanotechnologies are being researched for use in tyre production. Even if barriers to their development remain, they offer very promising avenues for future innovation. One of the main advantages of nanotechnologies is that they may allow improvements in one or more tyre properties without sacrificing performance in other areas (as would be the case with conventional compounds).

This chapter explores the impact of currently in use and emerging nanomaterials on tyre performance. It gives an overview of the main and emerging applications of nanotechnology in tyres and their effect on different performance attributes. The technical barriers to commercialisation and uptake are also discussed.

Nanomaterials and tyres performance

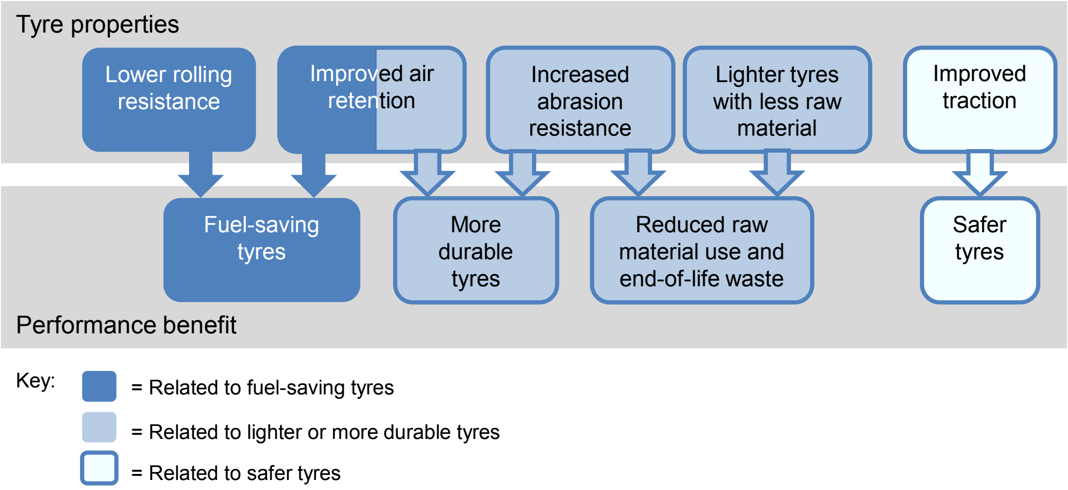
Tyres are designed to meet customer needs by carefully balancing three key properties, which are commonly referred to as the “magic triangle” because there are typically trade-offs between them:

- Rolling resistance: the amount of energy a tyre absorbs as it rotates under the weight of the vehicle. The average fuel savings due to a 10% reduction in rolling resistance are between 1.5% and 2% for a passenger car (International Council on Clean Transportation, 2012).
- Abrasion resistance: the speed of tread wear, which gives an indication of the durability of the tyre. More durable tyres last longer before they need to be replaced, reducing the frequency (and potentially the cost) of tyre replacement as well as reducing overall raw material consumption.
- Wet grip (traction, braking distance): the ability of a tyre to keep in contact with the road in the presence of a water layer. This is very important for safety. Improvements in traction can lead to safer tyres, for example by decreasing the vehicle stopping distance.

These tyre properties translate into performance benefits for the consumer as shown in Figure 1.1. Consumers are unlikely to directly demand nanotechnologies. Rather, they demand certain performance attributes, derived from the different tyre properties, which in turn can be influenced by different nanomaterials.

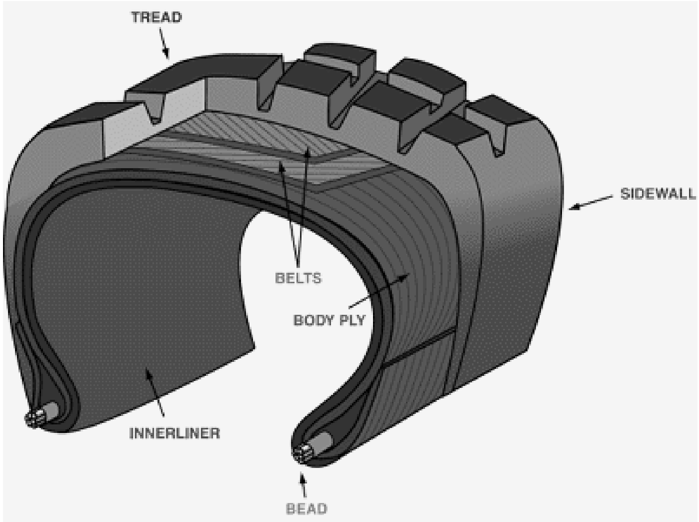
The key advantage of nanotechnologies is that they may allow improvements in one or more tyre properties without sacrificing performance in other areas. Conventional compound development involves trade-offs between the different performance parameters. Typically, modifying a composition to improve one property makes it difficult to maintain performance in at least one other area. For example, reducing rolling resistance through conventional means (such as changing the tread design) could result in decreased wet grip (safety). Simultaneous improvement in all of the key attributes requires innovation and step changes in technology. While there are many other aspects of tyre performance that are not captured in these metrics (such as vehicle handling, appearance, ride comfort), the three “magic triangle” parameters represent the most important factors determining external costs and societal impacts.

Figure 1.1. **Tyre properties and related performance improvements**



Different parts of the tyre have different functions. A schematic of the basic tyre construction is shown in Figure 1.2. Nanomaterials are used, depending of their specific properties, in some of these parts (see following section). The various components are essential to road mobility, since tyres provide the only contact point between the vehicle and the ground. The tread provides traction and cornering grip, and has the biggest effect of all components on rolling resistance. The inner liner is designed to keep air inside the tyre, which is also important to ensure safety, optimise fuel consumption and prevent oxidation of the internal components of the tyre. The body plies provide strength and flexibility to the tyre and ensure that the tread is held flat on the road. Finally, the beads ensure the tyre is properly seated on the rim and help maintain an airtight fit.

Figure 1.2. **Basic tyre construction**



Source: Rubber Manufacturers Association, see www.rma.org/tire-safety/tire-basics.

Examples of nanomaterial developments in the tyre industry

This section provides an overview of current (carbon black and HD silica) and emerging uses of nanotechnologies in tyre production and their impact on different performance parameters. In particular, it describes in detail the four nanomaterials that will be used as case study nanomaterials in the different parts of this study: carbon black and conventional "highly dispersible" (HD) silica; and the new generation "highly dispersible high surface area" (HD-HS) Silica and nanoclays.

Nanomaterials currently in use: Carbon black and HD silica

Carbon black is widely used as a filler to improve tread wear and traction. The particle size, structure and surface area of carbon black play a significant role in the material properties of rubber. In general, finer grades allow for better performance due to their higher surface area, and provide good traction and abrasion resistance. The main drawback is that a relatively high filler content is needed to achieve good reinforcement – typically around 30-40% – which increases rolling resistance and weight (Thomas and Stephen, 2010).

The market for carbon black is mature, and it is currently the main reinforcing agent for tyres. Globally, the market for carbon black is worth around EUR 10 billion, the majority (73%) of which is used in tyres (European Commission, 2012). Other applications of carbon black include reinforcement of other rubber goods and as a pigment in inks.

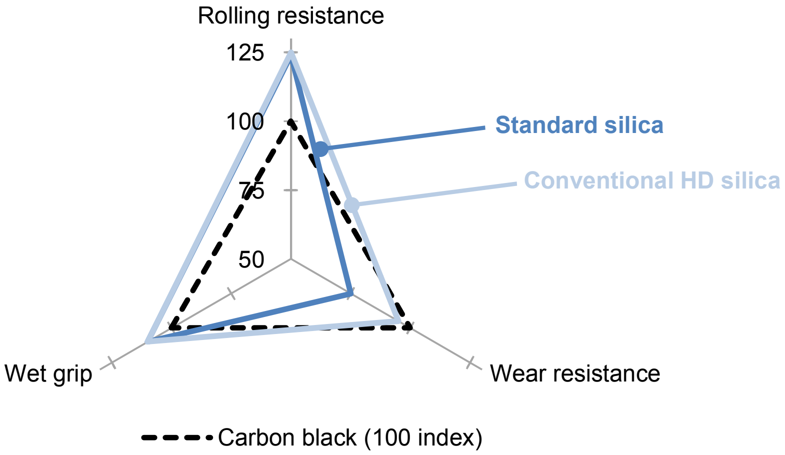
Environment, health and safety issues are thought to be less of a concern for carbon black than for some of the newer nanomaterials. Carbon black is available with primary particle sizes of 5-100nm, but these particles self-aggregate and agglomerate into larger particles during the manufacturing process. Since this results in particles larger than the nanoscale, carbon black is considered a nanostructured material but not a nano-object.

The addition of silica to tyres has made it possible to achieve a reduction in rolling resistance compared to tyres containing only carbon black,[1] without compromising traction and safety. Conventional tread compound development involves a trade-off between rolling resistance and wet grip (safety) performance. Silica reinforced rubber has higher hysteresis at high frequencies, but lower hysteresis at low frequencies compared to conventional carbon black. This results in lower rolling resistance and higher levels of traction. Current tyres use conventional HD silica rather than the "standard" silica used in the early days of the technology's development. HD silica is thought to result in significantly superior wear resistance compared to standard silica, as well as smaller improvements in wet grip and rolling resistance (Figure 1.3).

The average fuel savings due to a 10% reduction in rolling resistance are between 1.5% and 2%. There is good agreement on the ranges quoted in the literature, although actual fuel savings depend on the vehicle baseline fuel economy, the rolling resistance of the original tyre, the number of miles driven, among other factors (International Council on Clean Transportation, 2012). HD silica can reduce tyre rolling resistance by 20% or more, and can also improve grip by up to 12% and reduce braking distance by 10% (European Parliament, 2008).

The market is mature in the passenger car segment and silica is currently the second-biggest application of nanotechnology in tyres after carbon black. Examples of commercially available HD silicas include Zeosil 1165 MP and 1115 MP from Rhodia (Solvay), Ultrasil 7000GR from Evonik, and Zeopol 8741 or 8745 from Huber.

Figure 1.3. **Comparison of tyre performance when using different fillers**



Note: Silica systems to modulate the compromise reinforcement/hysteresis for the silica filled elastomers.

Source: Adapted from Rhodia (2011), "Product data sheet. Zeosil Premium", www.rhodia.com/en/binaries/rhodia_tire_solutions_leaflets_en.pdf.

In a similar manner to carbon black, silica forms primary particles on the nanoscale (approximately 2-40nm) that aggregate and agglomerate to form particles that are larger than the nanoscale and are therefore considered to be a nanostructured material, but not a nano-object (Chemrisk, 2011).

Emerging nanomaterials: New generation HD-HS silica and nanoclays

The demands placed on tyres are quite different depending on their application and this affects the choice of fillers to be used. Broadly speaking, the differences between passenger car tyres and truck tyres can be summarised as shown in Table 1.1.

Table 1.1. **Summary of performance requirements for different tyres**

	Passenger car	Truck
Main tread component	E and L-SBR/BR blends	Natural rubber, in some cases as a BR blend
Possibility of retreading	Usually not available	Up to five times
Filling pressure	2.2 bar	8.5 bar
Load bearing capacity per axle	1 000 kg	6 300 kg
Heat build-up	Low	Very important
Rolling resistance	Very important	Important
Tensile strength	Low	Important

Notes: SBR = strene-butadiene rubber; BR = butadiene rubber.

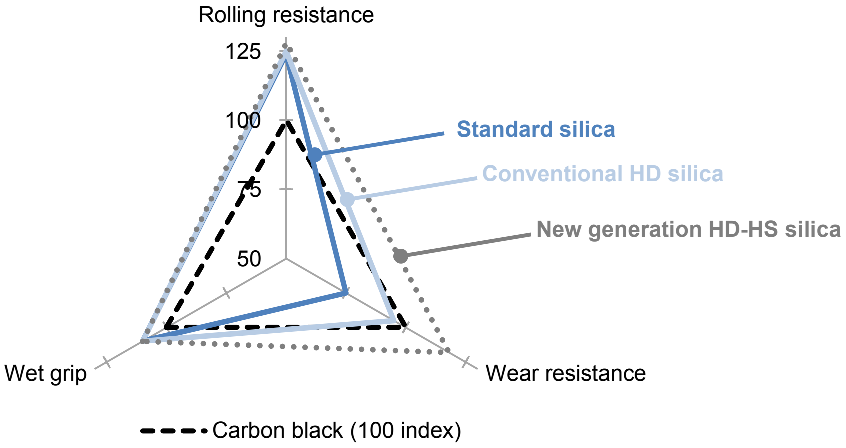
Source: Degussa Ag (2008), Patent Application Publication US 2008293871 A1, Highly dispersible precipitated silica having a high surface area, www.google.nl/patents/US20080293871; and interviews with industry experts.

The conventional HD silica used in passenger vehicle tyres is unsuitable for use in truck tyres and some high-speed tyres for passenger vehicles due to the different requirement profiles, whereas the new generation of HD-HS silica can be used in these applications. The standard HD silica used in passenger car tyres tends to agglomerate, which limits the reinforcing properties, and it is not compatible with emulsion-based polymers such as natural rubber (primarily used in truck tyres) and emulsion styrene-butadiene rubber (E-SBR). The new generation of HD-HS silica can achieve better dispersion and can be used for these more demanding requirement profiles. It can result in better wear resistance without sacrificing rolling resistance or wet grip (Figure 1.4).

HD-HS silica has only been commercially available since 2009 from a few major chemical companies and tyres containing this new material are only just entering the market. Examples include Zeosil Premium by Rhodia/Solvay, Ultrasil 9000 by Evonik and Hi-Sil EZ200G by PPG.

The loss of tyre inflation pressure strongly affects other tyre properties, such as rolling resistance, sidewall deflection, spring rate, heat build-up and service life. Since the introduction of halobutyl rubber, there have been very few significant changes to the composition of the tyre inner liner. However, nanoclays could be used to enable permeability reductions that are not possible with conventional systems using halobutyl rubber. There are many clay minerals, but the most widely used are montmorillonites, which have a plate-like structure. This structure makes them ideal as barriers to reduce air loss through the tyre inner liner. This is thought to be due to the increase in path tortuosity, thus lengthening the diffusion path and reducing the concentration gradient. Due to limitations on tyre manufacturing process capability, it is unlikely that liner thickness reductions can be further achieved to take advantage of the improved air retention. Therefore, the improvement in air retention performance and resultant improvement in tyre casing durability will likely be passed along to consumers.

Figure 1.4. **Performance improvements achieved using different generations of silica fillers**



Source: Adapted from Rhodia (2011), “Product data sheet. Zeosil Premium”, www.rhodia.com/en/binaries/rhodia_tire_solutions_leaflets_en.pdf.

Several estimates of the improvement in permeability from montmorillonite (MMT) nanocomposites were available from the literature (Table 1.2). In general, reductions of up to around 50% in gas permeability compared to natural and synthetic rubber were found, with higher nanoclay content contributing to better performance. Only a few specific examples of nanoclay inner liners could be found. Krishanmoorti (2010) reports a 50% reduction in air permeability for nanoclay inner liners compared to traditional inner liners, but only limited further detail was provided in this study. ExxonMobil has produced a nanocomposite blend with MMT and brominated isobutyl methylstyrene (BIMS) which reduces air permeation by 38% compared to a formulation without clay (Thomas and Stephen, 2010).

Table 1.2. **Comparison of reduction in gas permeability due to nanoclay from various sources**

Source	Alipour (2011)	TNO (2013)	Suchiva and Siririttikrai (2013)	Krishnamoorti (2010)	Thomas and Stephen (2010)
% reduction in permeability	12-56%	15-50%	22-53%	50%	47-54%
MMT content	1-5wt%	1-5.2%	0-15 phr	Not specified	20phr
Comparator	NR/BR	NR	NR	Traditional inner liners	NR/BR
Gas used in testing	Nitrogen	Oxygen	Oxygen	Air	Oxygen

Notes: NR = natural rubber; BR = butadiene (synthetic) rubber; phr = parts per hundred rubber.

Based on the literature review and interviews with tyre industry representatives, a conservative estimate of a 30% reduction in air permeability was assumed for nanoclay inner liners (compared to conventional inner liners).

Individual nanoclay platelet thicknesses are around 1nm, but surface dimensions are typically 300-600nm, resulting in an unusually high aspect ratio (Kang, 2010). Nanoclays normally exist as agglomerated bundles consisting of thousands of platelets held together by van der Waals force.

In order to achieve good gas barrier properties, the clay must be exfoliated (separation of the individual clay platelets). A key difficulty has been to develop suitable processing techniques, as well-exfoliated polymer-clay nanocomposites are notoriously difficult to obtain. Limited success has been achieved by modification of the clay, modification of the rubber polymers, the use of dispersion aids and the use of various blending processes.

Table 1.3 summarises the key properties of the nanomaterials discussed above, indexed against carbon black – currently the main reinforcing agent used in tyres. More in-depth consideration of the impacts over the tyre lifecycle and an assessment of environmental, health and safety issues for the four nanomaterials described above will be provided in Chapters 4 and 5 respectively.

Table 1.3. **Key properties of nanomaterials on tyre performance**

Nanomaterial	Tyre performance benefits			Key issues
	Rolling resistance (fuel use)	Wear resistance (tyre life)	Wet grip (safety)	
Carbon black (mature)	Index	Index	Index	High filler content needed, which increases rolling resistance and weight
HD silica (mature)	✓✓ (up to 25% improvement)	–	✓ (up to 10% improvement)	Slightly higher cost of HD silica Slight reduction in wear resistance
HD-HS silica (market entry)	✓✓ (up to 30% improvement)	✓✓ (up to 20% improvement)	✓ (up to 10% improvement)	Significantly higher cost of HD-HS silica
Nanoclay (market entry)	✓ (a few percent improvement)	✓ (a few percent improvement)	–	Higher cost of nanoclay Improvements may not be visible to consumer Difficulty in achieving good dispersion in rubber

Notes: – : indicates negligible improvement relative to carbon black; ✓ : indicates some improvement (<10%); ✓✓ : indicates significant improvement (>10%).

Overview of other new nanomaterials for tyre production

While the four nanomaterials described above are the most widely researched applications, there are many other new nanomaterials that could also be used to improve various aspects of tyre performance. Table 1.4 provides details of some cases, along with an indication of the technology readiness level. The technology readiness level is based on a simplified version of the NASA nine-point scheme,[2] as adopted in ObservatoryNano (2011). According to this modified scale, technologies develop as they move through the five stages: basic research, applied research, prototype (demonstration), early market (commercialisation) and mature market (diffusion).

These nanomaterials are at an earlier stage of development compared to the case study nanomaterials.

Main barriers to entry of new nanomaterials

There are a number of barriers to entry for new nanomaterials, which are also common to applications in different areas, including:

- high cost of the nanotechnology
- unreliable production techniques
- uncertainty over environment, health and safety (EHS) risks.

High costs are a key barrier to the incorporation of many nanomaterials. Most new nanomaterials are significantly more expensive than traditional tyre materials. In the longer term, these costs may decrease due to increased production capacities and improved processes. For example, the price for (multi-walled) carbon nanotubes has declined by a factor of over 100 in recent years. Major producers (including Bayer, Arkema and Hyperion) currently use catalytic chemical vapour deposition for large-scale carbon nanotube production. While currently still quite expensive, at around EUR 100-150/kg, the cost is expected to decrease to EUR 40/kg in the medium term due to volume production and more efficient manufacturing processes (ObservatoryNano, 2010).

Reliable and scalable production techniques have not yet been developed for some of the newer nanomaterials. This challenge applies particularly to nanomaterials in the earlier stages of development (basic and applied research). In order to reach commercialisation, the nano-enabled products must be able to be safely and profitably mass-produced, and to have consistent properties and quality. Enabling technologies, such as improved fabrication tools and monitoring processes, are expected to help to achieve more consistent production.

There is also a need for a better understanding of the potential EHS risks, particularly concerning the issue of tyre wear particles and end-of-life stages. Several industry stakeholders highlighted in interviews the need for sector-specific guidance for dealing with new nanomaterials (further discussion of these aspects is provided in Chapters 4 and 5).

Table 1.4. **New nanotechnologies and their potential applications in tyre production**

Technology	Description	Technology readiness
Rubber nanoparticles: "Nanopreme"	These are "traditional" tyre rubber raw materials, but produced at the nanoscale. The additive significantly reduces wear of the tyre tread and improves dry road grip by between 10% and 15%.	Market entry
Silica carbide: "Purenano"	Can improve skid resistance, as well as potentially reducing abrasion by nearly 50%.	
Core/shell polymer nanoparticles "NanoPro Tech"	Can improve cornering and steering response and reduce heat generation (lower rolling resistance). Weight reductions can also be achieved since the core-shell particles are significantly less dense than carbon black or silica fillers.	Prototype/ market entry
Poly(alkylbenzene)-poly(diene) (PAB-PDM) nanoparticles: "nanostrings"	Can be used to improve the mouldability of rubbers. However, current production techniques are not completely reliable.	Applied research/ prototype/market entry
Polyhedral oligomeric silsesquioxanes (POSS)	A member of the silanol chemical family. POSS could improve wet traction without sacrificing rolling resistance compared to silica.	Applied research
Carbon nanotubes	May be able to reduce rolling resistance through reduced heat generation. Could improve durability – possibly even past the life of the car itself. Improved tensile strength (600%), tear strength (250%) and hardness (70%) of the composites compared to pure styrene-butadiene rubber.	Basic research/ applied research
Graphene	Graphene can be produced at a much lower cost than carbon nanotubes but offers similar characteristics to carbon nanotube composites. However, applications are at an early stage of research.	
Aerogels	Extremely lightweight materials (0.0011 to ~0.5 g/cm^3) made up of billions of air bubbles trapped in a matrix of nano-sized particles of silica and plastic. Their usefulness was initially limited because they were brittle and absorbed moisture. Reliable and cheap production at volume remains an issue. However, more recent research envisions their use to create lighter, longer lasting tyres.	
Nanodiamond	Improves rolling resistance while maintaining reinforcing properties. Could help to ensure excellent abrasion resistance, braking ability and fuel efficiency. Nanodiamond applications in tyres are at an early stage of research although mature elsewhere (such as coatings). Key barriers include the ability to control the size and composition during production. The production process itself is relatively slow and expensive.	
Fullerenes: "Buckyballs"	An allotrope of carbon that could potentially provide good reinforcement and a low rolling resistance; however, there are concerns over their toxicity and they are currently very expensive.	Basic research

Sources: NGLS (2008), *Downsizing Development: An Introduction to Nano-scale Technologies and the Implications for the Global South*, Development Dossier, United Nations Non-Governmental Liaison Service, New York and Geneva, www.un-ngls.org/IMG/pdf/0850177_UNCTAD_NGLS_FINAL3.pdf; ObservatoryNano (2010), "CNT and nanodiamond", European Commission, www.observatory-nano.eu; ObservatoryNano (2011), "Briefing No. 23: Transport – Nanotechnology in automotive tyres", European Commission, www.nanopinion.eu/sites/default/files/briefing_no.23_nanotechnology_in_automotive_tyres.pdf; Lanxess (2008), “New nano additive from LANXESS extends tire service life”, News Release, http://lanxess.fr/fr/lanxess-in-france/news-france/global-news/new-nano-additive-from-lanxess-extends-tire-service-life; European Commission (2006), “Nano road SME (Development of Advanced Technology Roadmaps in Nanomaterial Sciences and Industrial Adaptation to Small and Medium sized Enterprises): Roadmap report”, European Commission, Brussels, http://cordis.europa.eu/publication/rcn/12246_en.html; Flanigan, C.M., et al. (2012), “Comparative study of silica, carbon black and novel fillers in tread compounds”, *Rubber World*, Vol. 245, No. 5, pp. 18, http://d27vj430nutdmd.cloudfront.net/9911/101311/101311.27.pdf.

In addition, there are barriers that are more specific to the tyre industry and that result in long lead times to reach the market. Indeed, several nanomaterials are at more advanced stages in other fields of application, including nanodiamond (used in coatings), nanoclays (used in plastic film packaging) and carbon nanotubes (light-weight composites). Further barriers that are more specific to the tyre industry include:

- difficulty of achieving uniform dispersion in the rubber
- high levels of safety required in the tyre industry.

A common challenge relates to achieving good (uniform, homogenous) dispersion of the nanomaterial in the rubber, as the nanomaterials tend to aggregate. Compared with thermoplastics, the dispersion of nanomaterials in rubber is more difficult due to the high viscosity, amorphous nature and low surface energy of the rubber polymers. Various techniques to achieve optimum dispersion have been proposed, but it appears that chemical modification (functionalisation) is necessary in many cases (Thomas and Stephen, 2010). Enabling technologies such as improved computer modelling simulations are expected to help to improve understanding of dispersion and rubber-filler interaction.

Time to market is further lengthened due to the high levels of safety required in the tyre industry. Testing the performance of the nanotechnology in the tyre product leads to many iterations between suppliers and tyre manufacturers. Estimates provided by tyre industry experts suggest that commercialisation of a new nanomaterial can take ten years or more.

Finally, several respondents to a stakeholder survey carried out for this project (see Annex A for full details) mentioned regulatory complexity (particularly differing regulatory frameworks across countries) as a barrier to the development of new nanotechnology applications in the tyre industry.

Concluding remarks

Nanotechnology is one of the most promising avenues for future innovation in the tyre industry. New nanomaterials are in research or just entering the market, with the potential to significantly improve rolling resistance (fuel consumption) and wear resistance (tyre lifetime) while maintaining wet grip (safety). A large number of different nanomaterials are currently being researched and are at different stages of development.

For new nanotechnologies at an early stage of development, there are a number of barriers to entry, which are also common to applications in different areas, including:

- increased cost of materials
- lack of reliable and scalable production techniques
- uncertainty over the EHS risks.

In addition, there are barriers that are more specific to the tyre industry and result in long time to market, including:

- difficulty of achieving uniform dispersion in the rubber due to high viscosity, amorphous nature and low surface energy of the rubber polymers
- high levels of safety required in the tyre industry: therefore testing the performance of the nanotechnology in the tyre product leads to many iterations between suppliers and tyre manufacturers.

Progress in overcoming some of the technical and economic issues is likely to be accelerated by key enabling technologies, including improved fabrication tools and monitoring processes as well as recent advances in computer simulation.

NOTES

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[1]. Note that the term "silica tyres" refers to tyres containing a mixture of silica and carbon black.

[2]. For more information, see: www.acq.osd.mil/chieftechnologist/publications/docs/TRA2011.pdf. The simplified scale is obtained by combining stages 2-5 and 6-7 of the standard nine-point scale.

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CHAPTER 2

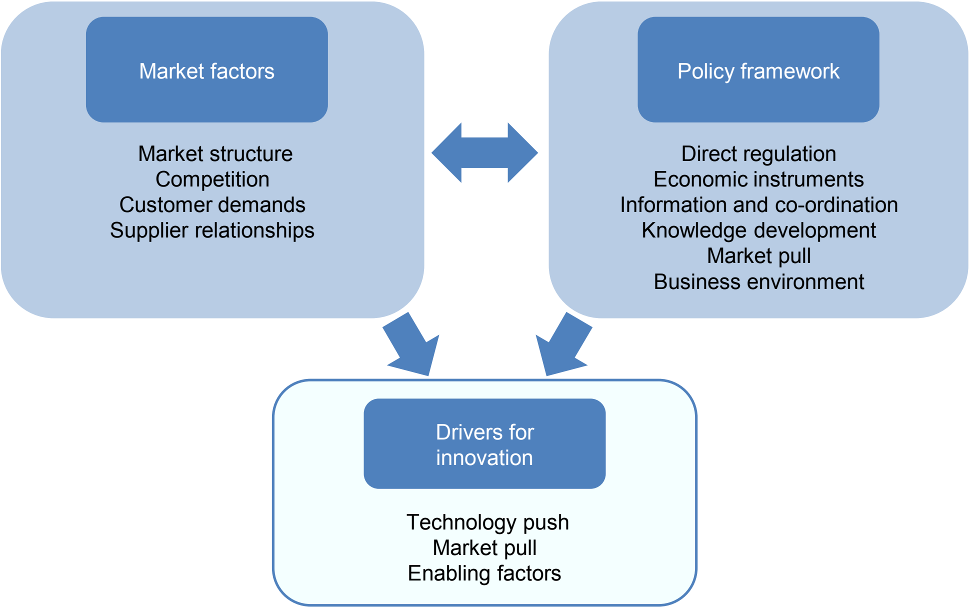
KEY DRIVERS OF INNOVATION IN THE TYRE INDUSTRY

This chapter considers the drivers of innovation that can influence the uptake and diffusion of new nanomaterials in the tyre production process. It discusses the main market drivers that can affect the innovation process and the policy levers that could drive the uptake of different technologies. It discusses the nature of innovation and the likely future direction of the tyre industry regarding the development of new nanomaterials in tyre production.

A number of factors are affecting research into new nanomaterials in the tyre industry. Those are primary market and policy drivers and build on current needs of consumers and societies for more cost-efficient and sustainable products, responding to today's major concerns over economic constraints and main environmental issues. These drivers can be categorised into three broad types (see Figure 2.1):

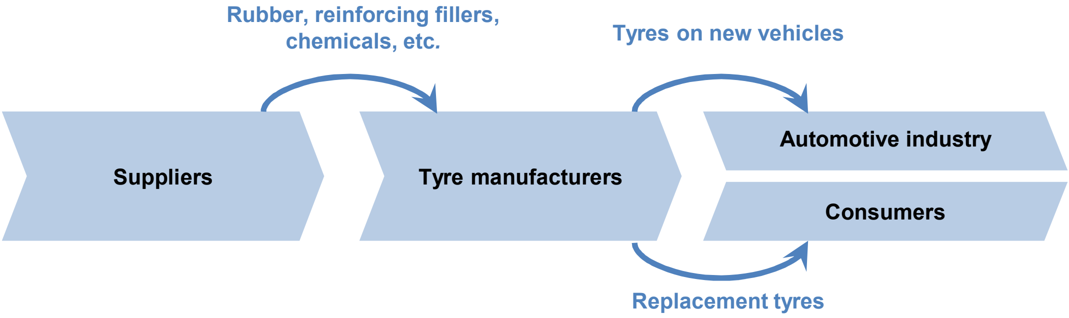
- Technology push: where advances in scientific understanding and technological opportunities determine the rate and direction of innovation.
- Market pull: where identified market demands (and therefore profitability) incentivise firms to work on certain problems. Demand signals can trigger innovation and thus "pull" new technologies into the market.
- Enabling factors: reinforce market demands or allow them to be realised. For example, if consumers cannot differentiate between products, it is more difficult for their demands to create market pull. Labelling products may therefore be an enabling factor.

Figure 2.1. **Market and regulation factors in creating drivers for innovation**



The drivers of innovation can be analysed at each step of the supply chain, which is illustrated in Figure 2.2. On the supplier side, the main raw materials provided to the tyre manufacturers are natural rubber, synthetic rubber, reinforcing fillers (carbon black and silica), other compounding chemicals and tyre cords. On the customer side, there are two main markets: tyres on new vehicles and replacement tyres. Demand for tyres on new vehicles is directly correlated to levels of automotive production whereas demand in the replacement market depends on vehicle usage. Around 75% of tyre production is for the replacement market and the remaining 25% for original equipment manufacturers (the automotive industry).

Figure 2.2. **Tyre industry supply chain**



This chapter considers drivers of innovation that can influence the uptake and diffusion of new nanomaterials in the tyre production process. It presents an analysis of the situation in different regions and the possible policy levers that could affect the uptake of different technologies. It discusses the nature of innovation and the likely future direction of the tyre industry regarding the development of new nanomaterial in tyre production.

Overview of market factors affecting innovation trends in the tyre industry

A number of market factors can affect the innovation process; these factors interact closely with policy drivers. A better understanding of the market interactions will also show where interventions could be beneficial in encouraging innovation. Market factors include:

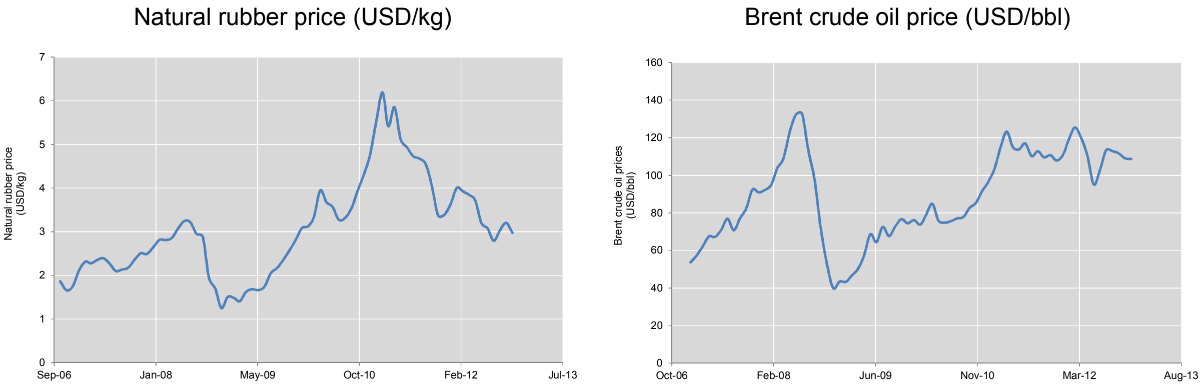
- Market structure: this can influence where innovation occurs, for example in terms of market segment, region or location in the supply chain.
- Competition: the nature of competition could lead firms to innovate as a way to differentiate themselves from rivals. Competition within the industry can change over time depending on sector development, diversity and the existence of barriers to entry.
- Customer demands: manufacturers may not gain any direct benefits from innovative products (for example, it is the customer who would benefit from the fuel savings due to low rolling resistance tyres). In theory, this should lead consumers to "demand" product innovation – i.e. be willing to pay a premium for innovative products from which they will benefit.
- Supplier relationships: collaboration between suppliers and customers (such as between rubber suppliers and tyre manufactures, and between tyre manufacturers and vehicle manufacturers) is an important means of fostering innovation.

Suppliers: Market factors

Tyre manufacturers often source nanotechnology materials from suppliers, while they develop new tyre applications in-house (ObservatoryNano, 2011). Innovation in the supplier industry is therefore important because it can generate a technology push effect, encouraging uptake in the tyre industry.

Increasing and/or volatile raw material costs may also create incentives for tyre manufacturers to investigate new materials. The cost of raw materials accounts for the largest component of total tyre production cost, representing around 50% on average (Xerfi Global, 2010). A number of these raw material inputs have very volatile costs, which makes it difficult to predict the impact on profitability. In addition, there is a long-term trend of increasing prices for many material inputs. Natural rubber mainly comes from rubber plantations located in Indonesia, Malaysia and Thailand. Issues in availability of natural rubber have arisen mainly due to production cuts in Malaysia and shifting plantations more towards palm oil, the growing usage of natural rubber in global tyre production and an increasing demand in the People's Republic of China. These global shortages in recent years have led to large price spikes, which have led directly to tyre raw material price increases. Both synthetic rubber and carbon black are derived from fossil fuels, hence their costs have increased in line with oil prices. Although there has been a recent dip in prices, they are expected to increase again in the long term (Figure 2.3).

Figure 2.3. **Costs of key raw materials**



Source: Based on data from Index Mundi (brent crude oil spot price and rubber monthly price); for more information see, http://ycharts.com/indicators/brent_crude_oil_spot_price_and www.indexmundi.com/commodities/?commodity=rubber&months=120 .

One strategy to mitigate risks of access to raw material supply is to reduce raw material consumption by making lighter, longer lasting tyres. Nanotechnologies that can extend tyre lifetimes (and thus reduce raw material input) are known to be an area of active research. Currently, the additional expense of some nanomaterials is a key barrier to uptake and further technology development is needed to reduce costs if commercialisation is to be successful.

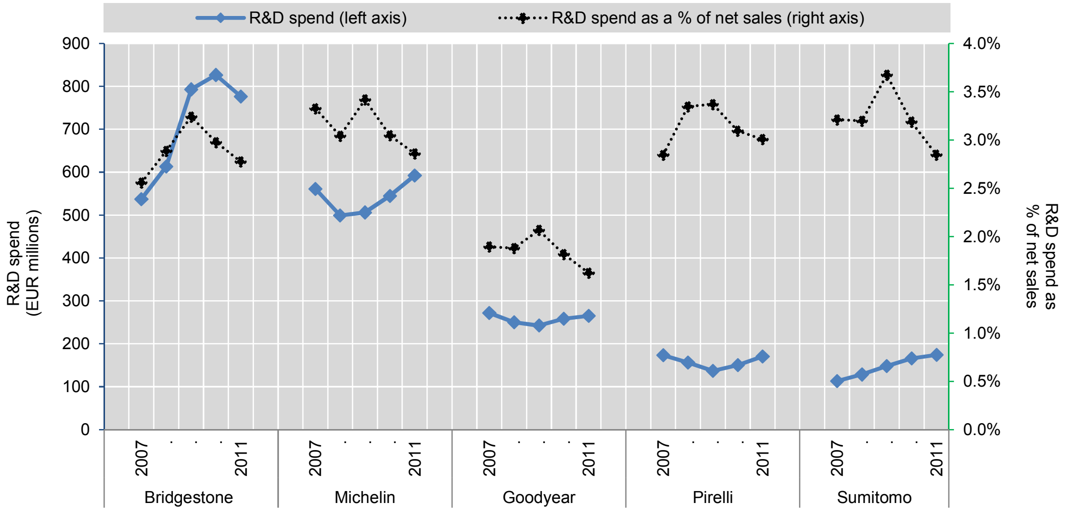
Tyre manufacturer: Market factors

There is increasing competition from low-cost manufacturers, which appears to be leading larger firms to adopt strategies to differentiate their products through technical innovation**.** The tyre industry is highly concentrated, with the three largest players (the "big three": Bridgestone, Michelin and Goodyear) holding a major share of global market sales. This is in part due to the capital-intensive nature of the industry and the long payback periods, which make barriers to entry relatively high. However, smaller players are increasingly gaining market share, leading to increasing competition in the industry. The big three accounted for 42% of global sales in 2010 (in terms of value), down from 57% in 2002 (Rubber Market News, 2012). Growth is particularly strong in Asian companies, which represented over 12% of the global market in 2010, up from 7% in 2005.

In order to compete in the market, there are two main strategies: product technical innovation or low-cost pricing strategies. Innovation occurs when firms compete through differentiating their product offerings. This is particularly apparent in the larger tyre manufacturers. On the other hand, the large majority of low-cost tyres come from Chinese or Chinese Taipei manufacturers, which compete on low-pricing and volume strategies and are therefore unlikely to become large producers of nanotechnology tyres until the technology is commoditised.

Research and development investments in the tyre industry are generally large as a percentage of revenues, although in absolute terms the spending is concentrated in the biggest firms. On average, over the past five years, the six largest tyre manufacturers have invested 2.7% of their net sales revenue in research and development (R&D), although this proportion varies between companies. The biggest firms (particularly Bridgestone and Michelin) make the largest R&D investments in absolute terms, although their investment as a percentage of net sales is in line with the rest of the industry. While there is no disaggregated data on the share of this R&D spend that is directed to nanotechnologies, it could be expected that companies with larger research resources would be better able to develop promising new technologies in general. It is clear that smaller companies may invest a larger share of their net sales in R&D, but it is difficult for them to match larger companies in absolute terms (Figure 2.4).

Figure 2.4. **R&D investments and R&D investments over net sales ratio for five of the largest tyre manufacturers**



Notes: Data are used from five of the largest tyre manufacturer's annual reports from the period 2007-11. The R&D spend and net sales includes only the proportion related to tyres and not for the whole company in cases where companies are involved in several industries.

Automotive industry: Market factors

Demand from vehicle manufacturers for specific performance attributes can lead to product innovation to meet these needs. Vehicle manufacturers (also known as original equipment manufacturers, OEMs) purchase large volumes for new vehicles on long-term contracts. This gives them influence over tyre prices and specifications. The upside for tyre manufacturers is that the OEM sales keep their production plants operating at efficient volumes, while also helping to generate future sales in the replacement market. The passenger car market is the largest market for tyre manufacturers. It is also the most demanding in terms of R&D, and tyre manufacturers must innovate in order to keep their market share (Krammer, 2009). The ability for vehicle manufacturers to influence the specifications of the tyres allows them to directly influence the nature of innovation.

The potential market uptake of electric and hybrid vehicles, which are typically fitted with custom tyres, could drive demand for low rolling resistance tyres. Electric and hybrid vehicles represent a growing market segment with requirements for high-performance tyres. Electric and hybrid cars are typically fitted with low rolling resistance tyres as standard, because this helps to increase the battery range. Therefore, tyre manufacturers have recently started to produce a range of tyres specifically for these vehicles. Silica and other nanotechnologies that are capable of reducing rolling resistance without sacrificing other performance parameters are likely to benefit.

Replacement market: Market factors

Consumers in the passenger car market are thought to be placing more importance on fuel savings (and thus lower rolling resistance tyres). Although older surveys of consumer preferences usually show that fuel efficiency was not an important consideration, more recent surveys show that fuel efficiency is now a key concern. For example, consumers in the United States surveyed in 2005 felt that tyre lifetime was the most important factor (72% ranked tyre life as among the top three most important factors), compared to 60% for traction and 31% for fuel efficiency (Rubber Manufacturers Association, 2005). Similarly, in 2006 a survey in Europe found that the most important attributes for consumers were tyre wear (considered very important by 72% of respondents), good grip (69%) and braking properties (66%), though fuel savings were a very important attribute for 55% of consumers (European Policy Evaluation Consortium, 2008). In contrast, more recent surveys suggest that high fuel prices are increasing the importance of fuel economy considerations when making purchases. Consumer Reports (2012) found that consumers in the United States rated fuel economy as the most important consideration (37%), compared to quality (17%) and safety (16%). Goodyear reported that fuel efficiency was the most important factor in 2011 (Barclays Capital, 2011). An online survey found that 60% of voters would be willing to pay more for tyres that make their fuel go further (Tyrepress, 2011).

Consumers in the premium market typically demand higher technology tyres and are increasingly attracted to performance products offering tread durability, reduced rolling resistance and improved handling. The requirements for high performance and lower price sensitivity in the premium market make it a particularly attractive area for nanotechnology tyres, which use relatively expensive nanomaterials to achieve superior performance. Premium tyres make up an estimated 20% of the market in mature economies (Xerfi Global, 2010). In emerging economies, consumers tend to be most interested in price; therefore mass-market products are dominant. However, emerging economies are seen as a promising growth market in the future.

Consumer demand for low rolling resistance tyres can be further stimulated by two factors: rising fuel prices and greater environmental awareness:

- Rising oil prices are leading directly to fuel price increases in most countries, but fuel taxation policies can reinforce this effect (or negate it through subsidising fuel). High fuel prices mean that the potential savings from fuel-saving tyres are greater and the payback time is reduced. However, in order to effectively stimulate innovation, consumers must be able to identify which tyres are indeed fuel-saving. Thus, a key enabling policy factor is to provide information that allows consumers to compare different tyres in terms of the performance characteristics that are most important to them – particularly through tyre labelling, but also through having well-informed sales assistants at retail outlets or running awareness-raising programmes.
- Greater environmental awareness among some consumer groups is leading to more interest in efficient vehicles, which could translate into demand for fuel-saving tyres. Fuel-efficient vehicle models (including electric and hybrid vehicles) tend to come equipped with low rolling resistance tyres as standard, which will further boost demand if consumers decide to replace them with the same type of tyres. For instance, around 20% of consumers in Europe are thought

to replace tyres like-for-like (European Policy Evaluation Consortium, 2008) and 27% in the United States (Rubber Manufacturers Association, 2005).

However, evidence suggests that customers are concerned that low rolling resistance tyres may compromise traction and wear performance in exchange for better fuel consumption. While consumers may understand that low rolling resistance tyres can improve fuel efficiency, there may be confusion and concern about the potential sacrifices in other performance areas (JD Power, 2013).

In the truck market, fuel consumption accounts for a major portion of road freight operating costs, making fuel saving a priority where it can enhance profits. Recent analysis of truck operating costs in Europe show that fuel operating costs are the second largest cost component after the drivers' wages, and are much larger than the costs of replacing tyres. On average, replacement tyres account for 2-8% of total truck operating costs in Europe, whereas fuel costs account for 20-37% (World Bank, 2008; Bayliss BT, 2012). When using a range of fuel price projections, low rolling resistance tyres are consistently found to be one of the most cost-effective technical options to reduce fuel consumption (CE Delft, 2012).

However, the extent of the freight operator's exposure to increases in fuel prices depends on the contract structure, which can wholly or partially shield operators from increases in fuel prices. For example, by adding fuel surcharges or using open book contracts (in which buyers and transport providers agree on a fixed operational margin). This can reduce the incentive for freight operators to invest in low rolling resistance tyres to reduce their fuel consumption. It is not clear what the share of different contract types is in the market, so the effect of this is not certain (CE Delft, 2012).

Other barriers to uptake despite the cost-effectiveness of low rolling resistance tyres in the truck market include:

- Uncertainties about performance (including real-world fuel savings and trade-offs with tyre lifetimes). Since worn tyres have lower rolling resistance (due to decreased tread depth), this can mask any fuel economy benefit when they are replaced with a set of new low rolling resistance tyres – that is, the benefits must be measured over the lifetime of the tyre (Ricardo-AEA, 2012).
- Information barriers: although freight operators are thought to be much more aware of the impact of tyre performance compared to consumers in the passenger car segment, market data suggests that there may be information barriers to uptake (CE Delft, 2012). More than half of heavy duty truck tyres fitted in Europe are re-treads, which are not covered by the requirements for tyre information labels (Ricardo-AEA, 2012).

Summary of market factors affecting innovation in the tyre industry

Table 2.1 shows a summary of the market factors driving innovation in the tyre industry. The drivers can be classified into three broad types:

1. Close relationships between stakeholders: the demand for better performance stimulates innovation in the supply chain. The tyre industry is characterised by particularly strong links and collaboration between the automotive industry, tyre manufacturers and suppliers.
2. Competition between manufacturers: greater competition from low-cost manufacturers is leading to a greater need to differentiate premium products through technical innovation and high levels of R&D.

3. Resource scarcity/environmental issues: including rising costs of raw materials and oil, as well as increasing awareness and concern over environmental impact.

Table 2.1. **Main market drivers for innovation in the tyre industry**

Stakeholder	Market driver for innovation	Driver type	Innovation in which tyre performance parameters?		
			Rolling resistance (fuel use)	Wear resistance (lifetimes)	Wet grip (safety)
Supplier	R&D investment and innovation	Stakeholder relationships	✓	✓	✓
	Raw material cost increases or volatility	Resource scarcity/ environmental		✓ (and reducing material use)	
Tyre manufacturers	Increasing competition	Competition between manufacturers	✓	✓	✓
	Research-intensive nature of industry	Competition between manufacturers	✓	✓	✓
	Relationship between tyre manufacturers and original equipment manufacturers	Stakeholder relationships	✓		✓
Automotive industry	Increasing sales of efficient vehicles	Stakeholder relationships	✓		
	Premium market requirements for high performance	Stakeholder relationships	✓	✓	✓
Replacement market	Consumer sensitivity to high or rising fuel prices	Resource scarcity/ environmental	✓		
	Consumer increased environmental awareness	Resource scarcity/ environmental	✓		

The structure of the tyre market suggests that innovation in new nanotechnologies is more dependent on the size of the firm and its position in the market rather than its geographical location. That is, innovation is likely to occur in the larger premium brand firms, which invest significant sums in R&D and have close links to the OEM markets. These large premium brand firms have access to all of the global markets and will be able to transfer their innovative products between geographical locations to service new demands. Drivers such as increasing resource costs (raw materials, oil) and environmental issues (consumer awareness, uptake of cleaner vehicles) are likely to increase over time in all regions. The automotive industry is a very important market, and tyre manufacturers work to meet its needs. Even though it accounts for a minority of the tyre market (25%), sales to OEMs help tyre manufacturers to capture more of the replacement market (which accounts for the remaining 75%).

Consumers in the replacement market must be able to tell the difference between tyres that meet their demands and those that do not. Tyre labelling of performance characteristics should allow this driver to be more effective in the market. Suppliers and tyre manufacturers already invest heavily in

R&D. Policy measures can support these efforts with complementary research on societal issues and by providing guidance on responsible use of new nanomaterials.

Policy instruments can be considered with all these market factors in mind. For example, policy makers can influence OEMs' demands through fuel economy regulations, which can stimulate innovation and uptake of low rolling resistance tyres. These policies and other potential policy instruments are discussed in more detail in the next section.

Overview of policies affecting innovation in the tyre industry

Policy interventions can play an important role in driving all stages of the innovation process and can target different parts of the supply chain. The different types of policy instrument include:

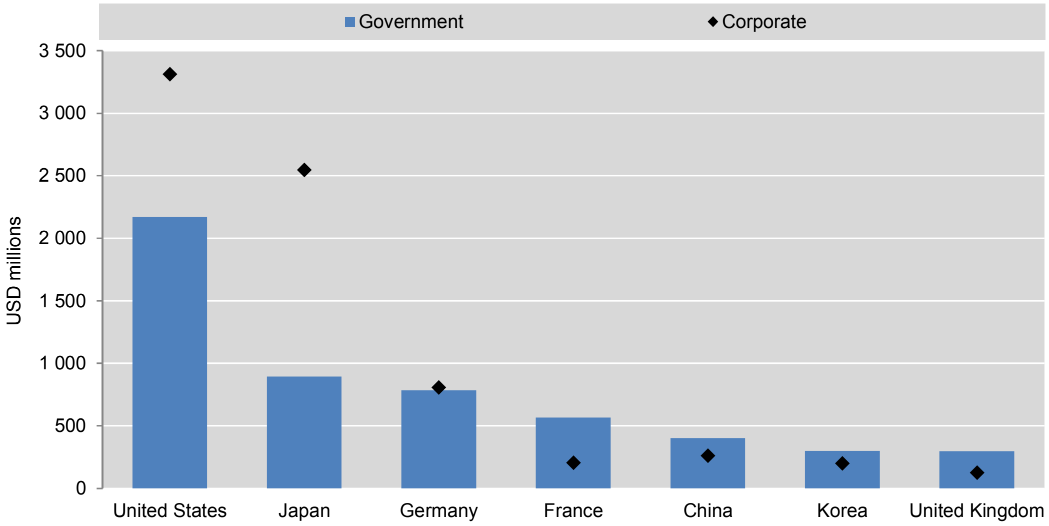
- Direct regulation or standards development: this can be specifically targeted to support innovation, e.g. through regulatory standards for tyre safety, noise, rolling resistance, longevity. Direct regulation of other industries can also indirectly stimulate innovation in the tyre industry, for example, stricter fuel economy requirements could drive demand for low rolling resistance tyres.
- Economic instruments: providing fiscal incentives or access to finance to enterprises to support one or more elements of the innovation process. For example, government funding for nanotechnology research is by far the largest in the United States and Europe, which is reflected in the higher concentration of nanotechnology firms in these regions.
- Information and co-ordination: creating or supporting networks and partnerships to provide information to consumers (for example, through tyre labelling).
- Knowledge development: through R&D investment and investment in skills and education needed in the labour force.
- Stimulating the market: creating demand in the early market, e.g. by public procurement or purchase subsidies.
- Business environment: broader factors such as providing supportive frameworks for intellectual property (IP) management, safety regulation and guidance on development of new materials.

Suppliers: Policy factors

The strong link between suppliers and tyre manufacturers means that the technology push effect is important for the development of new nanomaterial applications in the tyre industry. Public funding can further encourage the technology push effect. Investment in basic and long-term research provides the foundation for future innovation. The United States federal government invested more in nanotechnology R&D than any other single country from 2008 to 2010 (Figure 2.5); to date, more than USD 16 billion has been invested (President's Council of Advisors on Science and Technology, 2012). In 2011, China invested USD 1.36 billion in nanotechnology R&D, compared to over USD 1.9 billion in the United States and Europe (ObservatoryNano, 2012). Companies have also increased their investment, indicating a transition from public to commercial R&D; the United States is the world leader in corporate and venture capital investments in nanotechnology (President's Council of Advisors on Science and Technology, 2012).

Figure 2.5. **Average annual nanotechnology spend, 2008-10**

USD millions



Source: Based on President's Council of Advisors on Science and Technology (PCAST) (2012), "Report to the President and Congress on the fourth assessment of the National Nanotechnology Initiative", Executive Office of the President, PCAST, Washington, DC, April, http://nano.gov/sites/default/files/pub_resource/pcast_2012_nanotechnology_final.pdf.

Public funding may also be used to explore wider areas of interest around the commercialisation and uptake of new nanotechnologies. There are two increasingly common areas of research funded by governments across the world: the commercialisation of research results and the emphasis on societal and green values within the application areas of nanotechnology.

- Various models to improve commercialisation are being pursued. For example, France has invested EUR 450 million (USD 585 million) in the Nano2012 industry/research partnership, which is being matched with a funding commitment from the companies involved. The Inno.CNT programme in Germany is focused on developing the whole value chain, with 18 projects each targeted at a specific application (e.g. CarboDis aims to better understand and control the intentional integration of CNT into a variety of polymeric structures) (ObservatoryNano, 2012).
- Societal and environmental issues are receiving greater attention. For example, the Netherlands directed EUR 5 million (USD 6.5 million) to a technology analysis project which studied the intersections between technology and society. In the United States, the National Nanotechnology Initiative directs considerable funds towards environmental, health and safety (EHS) research, which received USD 76.4 billion from 2001 to 2009, and education and societal issues, which received USD 40.7 billion in the same period (ObservatoryNano, 2012).

Policies to foster knowledge sharing and co-operation can help to better understand challenges – particularly around the EHS concerns and ethical, societal and legal issues. Responsible development of nanotechnology requires co-operation between many stakeholders. Proven co-operation strategies that foster innovation in general include: joint investment in basic research; mapping of R&D needs; collaborative research in international networks; technology transfer initiatives; and scholarships and fellowships for the international mobility of researchers (OECD, 2011). A large number of knowledge-sharing initiatives exist, both at the national and international level; the most significant initiatives with respect to nanotechnology in tyres will be examined in further detail in Chapter 6.

Finally, it should be noted that other policies affecting the academic and business environments can also indirectly influence innovation in nanotechnology materials**.** Important aspects span a wide range of issues, such as investment in universities and skills training, good infrastructure and support for private sector R&D (e.g. through tax rebates). However, the scope of these general policy factors is too broad to be considered in detail in terms of their impact on nanotechnology in tyre production.

Tyre manufacturers: Policy factors

Policy factors that potentially affect innovation in the tyre manufacturing industry mainly relate to direct regulation rather than the other types of policy instruments listed above. Minimum standards for tyre performance (such as for rolling resistance) eliminate the worst-performing products and reduce the size of the feasible technology space. A number of regions have introduced direct regulations that specify minimum standards for various aspects of tyre performance, such as the following examples:

- Europe: mandatory standards from November 2012 for efficiency, wet grip and noise. Separate standards apply to tyres for passenger cars, light trucks and heavy duty vehicles.
- Korea: proposed standards for efficiency and wet grip were to take effect in 2013. The standards for passenger car tyres and light truck tyres are similar to those proposed in Europe, as Korea exports a major portion of its tyre production to the European market. Standards for heavy duty vehicle tyres are being considered. (International Council on Clean Transportation, 2011).
- United States: the state of California has been investigating the possibility of minimum fuel efficiency standards for tyres (CEC, 2009).

The stringency of minimum standards has an impact on the level of the incentive for innovation. For example, in Europe, the first phase of the tyre-fuel efficiency standards (2012-14) aims to eliminate the lowest efficiency tyres on the market (a relatively small share). However, the second phase (2016-18) will tighten the standards considerably. Projections of the tyre market out to 2015 indicate that without the tyre efficiency standards, just under half of tyres would have failed to meet the now required minimum standards (International Council on Clean Transportation, 2011).

In some regions, companies have been made responsible for their products from cradle to grave, creating incentives to reduce waste by improving tyre lifetimes. This type of legislation is not widespread, but can have significant financial implications for tyre manufacturers where they are included:

- In Europe, the End-of-Life Vehicles Directive mandates that by 2015, 85% of a car’s materials (by weight) must be reused and recycled. In many European member countries, governments have also mandated that tyre manufacturers must collect the equivalent number of tyres that they produce annually. The cost of this regulation in France is thought to be almost USD 100 million per year (Bekefi and Epstein, 2008).
- Japan has also mandated that 70% of automobile materials must be reused by 2015 (Bekefi and Epstein, 2008).

There are a number of ways in which tyres can be recycled, and the impacts of nanomaterials on each of these pathways will be discussed in Chapter 4.

Many of the same technology push factors remain relevant for the tyre industry as for the suppliers. These include R&D support from government, knowledge sharing and co-operation. Note that tyre labelling and other consumer information policies are important in order to allow consumers to make better choices.

Automotive industry: Policy factors

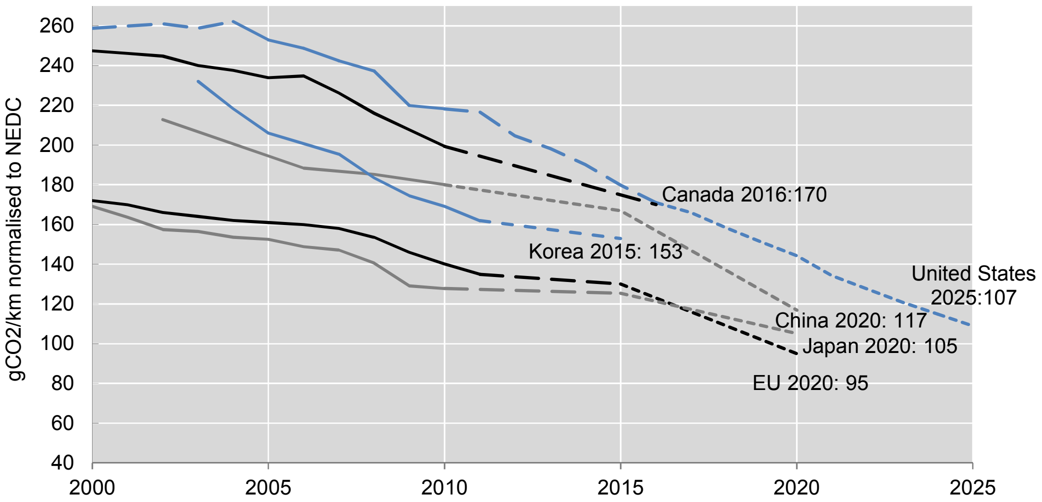
Stricter regulations for fuel economy and CO_2 emissions from new vehicles are driving demand for low rolling resistance tyres. A key nanotechnology that has benefited from this growing market is silica. In many regions, the fuel efficiency of new vehicles is improving, which stems in part from consumer demand for more environmentally friendly transport, but is primarily the result of increasingly stringent regulations on vehicle fuel efficiency. These regulations have stimulated greater demand for low rolling resistance tyres to enable new vehicles to comply. Silica is now incorporated into low rolling resistance tyres by many manufacturers.

Demand for silica tyres is particularly high in regions with stricter standards. For example, Europe currently has the strictest standards, and in 2011, silica tyres made up an estimated 80% of OEM passenger car tyres. Figure 2.6 shows the enacted and proposed standards for passenger vehicles out to 2025. The difference between regional standards is forecast to diminish over time. Since compliance is measured based on testing of the whole vehicle, including tyres, low rolling resistance tyres can help car manufacturers meet the target.

In the United States, new passenger cars have the same tyres when they are tested for fuel economy and when they are sold. In China and Europe, the tyres used for fuel economy testing may not be the same as those on new vehicles sold to consumers (International Council on Clean Transportation, 2011).

Mandatory requirements to fit low rolling resistance tyres directly drive uptake of the technology. The United States Environmental Protection Agency runs a voluntary “SmartWay” programme that can verify the performance of low rolling resistance tyres for heavy duty line haul tractor trailers. The California Air Resources Board has adopted a regulation that requires SmartWay certified tyres to be fitted to new heavy duty vehicles, with such tyres to be phased in for existing fleets (International Council on Clean Transportation, 2011), and other US states are considering legislation. Although different technologies can meet the SmartWay standard, nanotechnologies such as silica are particularly well-placed as they can achieve better performance without trade-offs in safety (wet grip).

Figure 2.6. **Comparison of global passenger vehicle standards**



Notes: NEDC = "New European Driving Cycle". Solid lines: historical performance and enacted targets; dotted lines: proposed targets. China's target reflects gasoline vehicles only. The target may be lower after new energy vehicles are considered. Canada and United States light duty vehicles include light-commercial vehicles.

Source: Based on International Council on Clean Transportation (ICCT) (2013), "Global comparison of light-duty vehicle fuel economy/GHG emissions standards", ICCT, Washington, DC, www.theicct.org/info-tools/global-passenger-vehicle-standards.

Replacement market: Policy factors

The (perceived) net benefit of an innovative tyre technology can be increased by reducing the cost to the consumer, increasing the value of the benefits or by increasing consumer awareness. These three options are explored in more detail below. Increasing consumer awareness is an important enabling factor that allows the actual net benefits to be perceived and understood.

Consumers exposed to higher fuel prices are more likely to demand technologies that will improve the fuel efficiency of their vehicles in order to reduce their costs. The relatively high fuel price in Europe was thought to be a key factor in the market success of silica (low rolling resistance) tyres, whereas uptake was much slower in the United States where fuel prices are much lower. The difference in fuel prices between regions is, in part, due to the policies on fuel taxation or subsidies. For example, in Europe, the average tax on one litre of gasoline was USD 1.17 in 2012 (Bolton, 2012), whereas in the United States tax was considerably lower at USD 0.11/litre in the same year (American Petroleum Institute, 2012). For some time, China subsidised and administratively set fuel prices. In December 2008, China began to apply a formula-based approach, although its application has not been consistent. The price differentials for diesel fuel follow a similar pattern. Although many European countries tax diesel at a lower rate than gasoline and there is significant variation between European Union member countries, the rates are still substantially higher than diesel taxation rates in most of the world, including Australia, Canada, China, the Russian Federation and the United States (GIZ, 2011).

Tyre labelling and rating/grading is a key enabling factor to allow consumers to identify higher performance tyres. Until recently, consumers in the replacement market have had limited ability to differentiate between tyre performance. Voluntary tyre labelling was first introduced in Japan in 2010 and in Korea in 2011. Table 2.2 summarises the mandatory labelling systems in place or planned in major global markets. No rating systems are in place in Brazil, China or Mexico, but regulatory action is expected in two to three years (Barclays Capital, 2011).

Table 2.2. **Introduction of mandatory tyre rating and labelling schemes**

	European Union	Japan	Korea	United States
Traction (wet grip)	Mandatory A-G rating from November 2012	Voluntary since 2010, with rating from A-D. Plans for mandatory labelling.	Voluntary since 2011. Mandatory following EU legislation.	Pending label based on 0-100 scale (earliest 2013). Existing Uniform Tyre Quality Grading (UTQG) from AA-C.
Fuel economy	Mandatory A-G rating from November 2012	Voluntary since 2010, with rating from AAA-C. Plans for mandatory labelling.	Voluntary since 2011. Mandatory following EU legislation.	Pending label based on 0-100 scale (earliest 2013).
Tread wear	2020 (estimated)	None expected.	None expected.	Pending label based on 0-100 scale (earliest 2013). Existing Uniform Tyre Quality Grading based on comparative grade.

Source: Based on information from Barclays Capital (2011), "European autos & auto parts, tyre makers – focus on cost and mix", Barclays Bank PLC for the EU, Japan, Korea and planned US labels; and from Safecar.gov, www.safercar.gov/Vehicle+Shoppers/Tires/Tires+Rating for the existing US rating scheme (UTQGS).

Labelling schemes can incentivise improvements in performance as manufacturers strive to gain the highest ratings. The European Commission predicts that labelling programmes will raise the efficiency of most tyres above the minimum standards. The bands specified for each grade, and the provisions to revise the bands over time as the market changes, may influence the effectiveness in this respect. For example, relatively few tyres qualify for the highest A-grade rating for fuel efficiency in Europe, which leaves room for further improvements. In the current US Uniform Tyre Quality Grading system, 75% of tyres obtain an A grade for traction, making differentiation between tyre performance more difficult.

Many other potential demand-side policy instruments exist, although they are applied to a much lesser degree worldwide compared to tyre labelling. Examples include:

- Certification, demonstration and information programmes can raise consumer awareness and provide credibility to manufacturers' claims about performance. For example, the voluntary SmartWay project in the United States certifies low rolling resistance tyres and retreads for heavy duty vehicles; most manufacturers now offer a SmartWay certified line. In Canada, the ecoENERGY Efficiency for Vehicles programme is developing a consumer awareness programme for energy efficient light duty vehicle tyres, and is also adopting a Canadian version of the United States' SmartWay certification.
- Economic incentives, e.g. tax discounts or purchase subsidies, can provide technology-specific incentives for uptake. These instruments are suitable for stimulating the early market and are typically phased out in the medium or long term. Subsidies and tax incentives for electric and/or low-carbon vehicles are very

common globally; these provide an indirect incentive for low rolling resistance tyres (which are usually fitted to these vehicles).

- Government procurement provides the opportunity to accelerate market transformation towards low rolling resistance tyres by creating economies of scale for manufacturers and thereby reducing the costs of production. Criteria for environmental friendliness or fuel efficiency are increasingly being used in public procurement. For example, both the Danish Environmental Protection Agency and the Norwegian Agency for Public Management provide guides for environmentally responsible procurement. For passenger cars and transport services, the basic criteria include tyres with reduced rolling resistance (BRE, 2011).

Summary of policies affecting innovation in the tyre industry

Table 2.3 shows a summary of the policy factors driving innovation in the tyre market. It can be seen that different policy instruments apply to different stages of the supply chain and they can be designed to encourage improvement in different areas of tyre performance.

Table 2.3. **Main policy drivers for innovation in the tyre industry**

Stakeholder	Policy instrument	Effects on tyre industry	Encourage innovation in which tyre performance parameters?		
			Rolling resistance (fuel use)	Wear resistance (lifetime)	Wet grip (safety)
Suppliers	R&D investment from governments	Technology push	✓	✓	✓
	Fostering knowledge sharing	Technology push	✓	✓	✓
Tyre manufacturers	Minimum standards for tyre performance	Establishes minimum performance standards for everyone in the tire industry	✓	✓	✓
	End-of-life treatment regulation for tyres	Leads to higher costs for recycling		✓	
Automotive industry	Vehicle fuel efficiency standards	Stimulates original equipment manufacturers' demand for efficient tyres	✓		
	Mandatory fitment of efficient tyres	Forces market uptake	✓		
Replacement market	Tyre labelling	Innovation to reach the higher ratings	✓	✓	✓
	Fuel taxation	Increase the benefit of fuel-saving tyres	✓		

Overview of current policy frameworks in relation to innovation in the tyre industry

The review of policy drivers in the previous section showed that different instruments affect different parts of the supply chain. Table 2.4 compares the policy drivers encouraging innovation in nanotechnologies in China, the European Union and the United States. The "policy index" represents a simple scaling of the indicators as a percentage of the highest indicator for each policy driver (where possible). For non-numerical indicators (i.e. yes/no), a score of 100 is assigned if the indicator is found and a score of 0 is assigned if the indicator is not found.

Comparing the overall "policy index" scores shows that policies to encourage innovation in nanotechnology to reduce rolling resistance could be considered strongest overall in Europe and weakest in China. Development and historical uptake of low rolling resistance tyres (conventional HD silica) has been fastest in Europe and slowest in China. The key contributing factors behind the historical uptake of silica tyres in Europe are thought to have been the higher fuel prices in this region (driving replacement market sales) and the vehicle fuel efficiency standards (driving OEM market demand). Going forward, the minimum standards and tyre labelling policies are expected to result in significant improvements in average rolling resistance (see discussion of policy factors in the previous section).

Policies to encourage innovation in nanotechnologies to improve tyre lifetimes could be considered strongest in the United States (Table 2.4). Tyre market data indicates that tyres in the United States tend to have longer lifetimes; however, this is due to a combination of factors and cannot be attributed only to policy. Tyres in the United States are generally larger (due to the average passenger vehicle being larger compared to other regions) and consumers typically drive longer distances, which may mean they place greater importance on tyre lifetime compared to other regions.

There is some difficulty in defining standardised test procedures to enforce minimum standards for tyre lifetimes and to set labelling criteria. In the United States, tyre labelling of tyre lifetimes was introduced under the Uniform Tire Quality Grading Standards (UTQGS). The ratings are assigned relative to a control tyre. For example, a tyre grade of 200 should last twice as long as the control tyre. However, the results are not always consistent and there are some discrepancies between the grades. Tyre lifetime was considered for inclusion in the European tyre label, but excluded at the time (in 2008) due to a lack of reliable testing procedures.

It is not straightforward to compare policies in terms of their importance in affecting innovation, as it can be difficult to measure how important each policy factor is in practice. A survey was carried out as part of this study in which stakeholders were asked "How important do you feel each of the following policy factors are for driving innovation for nanotechnology in tyres?", with answers provided on a scale of 1 (not important at all) to 5 (very important). Individuals from most major tyre manufacturers participated, with respondents from companies representing the majority (almost two-thirds) of global tyre market sales; nevertheless, the survey was subject to limitations that are discussed further in Annex A. The responses are shown in Figure 2.7.

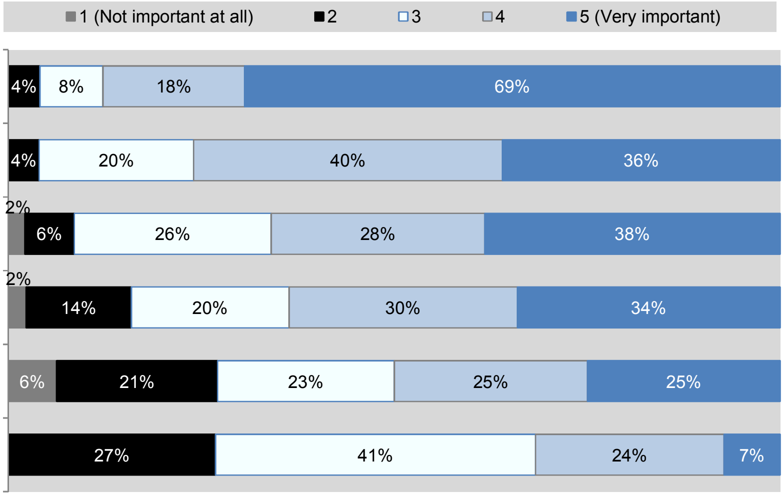
The responses indicate that minimum standards for tyre performance appear to be considered the strongest driver for innovation. Vehicle fuel economy standards, tyre labelling and R&D investment or incentives are also considered to be relatively strong drivers.

Table 2.4. **Comparison of policy framework encouraging development of nanotechnologies to improve rolling resistance and tyre lifetimes**

	Indicator	Source note	Indicator units			Policy index		
			European Union	United States	China	European Union	United States	China
Policy driver – rolling resistance								
Minimum standards for tyre performance create a push effect	Required minimum standard for rolling resistance	1	12kg/t from 2012	Only California	x	100	0	0
Fuel efficiency standards stimulate original equipment manufacturers' demand for low rolling resistance tyres	Fuel efficiency standard for cars (2020 target, gCO_2/km)	2	95	144	117	100	66	81
Tyre labelling to increase consumer awareness and ability to differentiate	Year of introduction for labelling of rolling resistance	3	2012	2013	x	100	100	0
R&D investment leading to innovation in nanomaterials	Government funded research on nanotechnology (USD billion)	4	1.92	1.96	1.36	98	100	69
Fuel taxation and subsidy – higher fuel prices increase benefit of fuel savings	Average fuel price (USD/litre)	5	1.66	0.76	1.11	100	46	67
			Simple average			100	62	44
Policy driver – tyre lifetime								
Minimum standards for tyre performance create a push effect	Required minimum standard for wear resistance	1	x	x	x	0	0	0
Tyre labelling to increase consumer awareness and ability to differentiate	Labelling of tyre lifetime (yes/no)	3	x	Yes	x	0	100	0
R&D investment leading to innovation in nanomaterials	Government funded research on nanotechnology (USD billion)	4	1.92	1.96	1.36	98	100	69
End-of-life tyre regulations	Restrictions on end-of-life treatment of tyres (yes/no)	6	Yes	Yes	No	100	100	0
			Simple average			50	75	17

Sources and notes: 1. International Council on Clean Transportation (ICCT) (2011), "Opportunities to improve tire energy efficiency", White Paper Number 13, ICCT, Washington, DC, www.theicct.org/sites/default/files/publications/ICCT_tireefficiency_jun2011.pdf. 2. International Council on Clean Transportation (ICCT) (2013), "Global comparison of light-duty vehicle fuel economy/GHG emissions standards", ICCT, Washington, DC, www.theicct.org/info-tools/global-passenger-vehicle-standards. 3. Barclays Capital (2011), "European autos & auto parts, tyre makers – focus on cost and mix", Barclays Bank PLC. 4. ObservatoryNano (2012), "Public funding of nanotechnologies", reflects mix of fuels used in the passenger car segment. 5. World Bank indicators for diesel/petrol pump prices. Average price, see more information at http://data.worldbank.org/indicator/EP.PMP.SGAS.CD. 6. End-of-life tyres are regulated at the state level in the United States.

Figure 2.7. **Responses to survey question "How important do you feel each of the following policy factors are for driving innovation in nanotechnology for tyres?"**



Note: Total of 50 responses to this question (respondents were allowed to skip any question in the survey).

Concluding remarks

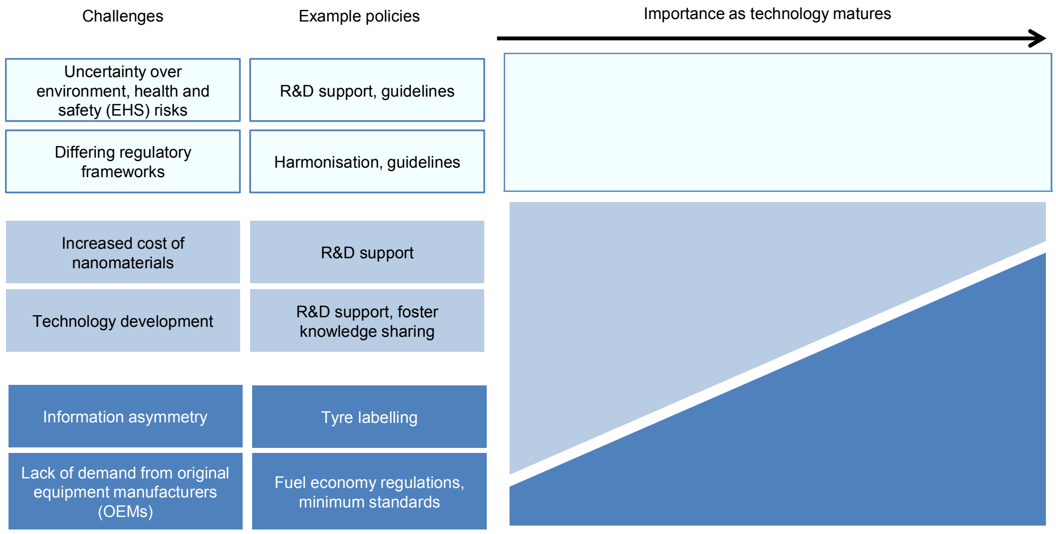
Innovation in the tyre industry is driven by a range of market and policy factors influencing different steps of the supply chain. Innovation in new nanotechnologies is most likely to occur in the larger premium brand firms, which invest significant sums in R&D and have close links to the OEM markets. Increasing competition from low-cost manufacturers is further encouraging premium brand firms to differentiate their products through technology innovation. However, new nanotechnology applications may gradually diffuse into the non-premium market in the longer term.

At the later stages of development, market pull factors become more important, with demand from the OEMs being a major driver. Development and uptake of fuel-efficient tyres has been fastest in Europe compared to other regions. The key contributing factors are thought to have been the higher fuel prices in this region (driving replacement market sales) and the ambitious vehicle fuel efficiency standards (driving the OEM market demand). Going forward, the minimum standards and tyre labelling policies are expected to result in significant improvements in average rolling resistance. Similar policies could also be used to encourage tyres with longer lifetimes, but difficulties in creating standardised test methods have hampered their introduction.

Uncertainties over the EHS risks remain a key issue for many nanomaterials, at both the early and later stages of development. Firms face a challenge in deciding whether and how to invest given the difficulties associated in measuring the risks and the fact that any risks to human health would be considered unacceptable. Public support helps to address the scientific challenges and encourage the responsible development of technologies; in particular, policies to foster knowledge sharing and co-operation play a critical role in advancing the EHS research. This is already a focus of government-funded research globally; however, a key gap highlighted by industry stakeholders was the lack of sector-specific guidance for dealing with new nanomaterials. Chapter 5 explores this further, and develops initial guidance for the tyre industry.

Policy drivers affect different stages of the innovation process. Public R&D funding has an impact on the innovation capacity of the suppliers of nanotechnology-enabled solutions. Public investment more generally was seen as a critical lever to address issues linked to the commercialisation of research results and the development of research into the societal and environmental issues linked to the development of nanotechnology. An indication of how the policy framework might evolve as the technology matures is provided in Figure 2.8. Good practice policies should include elements to ensure that high levels of safety are maintained, due to the potential trade-offs between different tyre performance parameters.

Figure 2.8. **Evolution of policy framework as technology matures**



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CHAPTER 3

SOCIO-ECONOMIC IMPACTS OF THE DEVELOPMENT OF NEW NANOMATERIALS IN TYRES PRODUCTION

This chapter provides an assessment of the socio-economic impacts that may result from the use of new nanomaterials in the tyre industry. The analysis focuses on two emerging nanomaterials – new generation “highly dispersible high surface area” (HD-HS) silica and nanoclays. A cost-benefit analysis is first used to compare impacts that are quantifiable in monetary terms considering three stakeholder groups: consumers (final consumers), producers (tyre manufacturers) and the society and the environment. An assessment and a discussion are then conducted about impacts that are relatively difficult to quantify and monetise, with a particular focus on societal impacts (public health and safety, impacts on developing countries, employment and road accidents) and on environmental impacts (resource consumption and use of energy). The chapter finally discusses this range of potential future impacts that could be expected from the uptake of nanotechnology in tyres.

Responsible innovation for the development and use of new nanomaterials in tyres aims to maximise the growth and competitiveness of the tyre industry while assuring that due consideration is given to societal, environmental and broader economic impacts. There is indeed a wide range of impacts that can be associated with the introduction of new nanomaterials in tyres. These impacts include costs and benefits to consumers and producers and environmental impacts. Other impacts are linked to public health and safety, employment and development (for example, impact on emerging economies).

Changes in the performance, manufacture and disposal of tyres will impact many stakeholders and industries overall and perceptions of the costs and benefits of these impacts will vary from one stakeholder group to another. Discussing this variety of possible effects allows for a better understanding of the environment in which the tyre industry is evolving, and in particular it gives an opportunity to discuss and inform policy makers of the range of potential future impacts that could be expected from uptake of nanotechnology in tyres. Identifying these impacts and their likely magnitude is an important step when making policy decisions about whether market development or uptake should be encouraged and whether any possible negative impacts could be mitigated.

This chapter examines the socio-economic impacts of different nano-enabled tyre technologies (HD-HS silica and nanoclays used in the tyre inner liner) over the lifecycle of the product. It is structured around two analytical approaches:

- A cost-benefit analysis has been used to compare the most important impacts in monetary terms where possible. This allows different impacts to be compared on a like-for-like basis.
- For the remaining impacts that cannot be monetised or easily quantified, multi-criteria analysis has been used to compare them. This ensures that important impacts that are difficult to quantify can still be considered.

Socio-economic impacts of the development of new nanomaterials in tyres production: Cost-benefit analysis

The approach used for the analysis of the socio-economic impacts of the development and use of new nanomaterials in the tyre industry is broadly based on the cost-benefit analysis (CBA) methodology for nanotechnology innovation developed by the United Kingdom's Department for Environment, Food and Rural Affairs (Defra) (Defra, 2010). The purpose of this study is to evaluate the potential impacts of different tyre technologies across several regions (Europe, the People's Republic of China and the United States), and over a long time-horizon (out to 2035). The impact of new nanomaterials, the new generation HD-HS silica and nanoclays, is being looked at in the analysis. They are compared with the incumbent technology (carbon black and conventional HD silica). Therefore the approach of the standard Defra methodology was modified to make it suitable for this purpose.

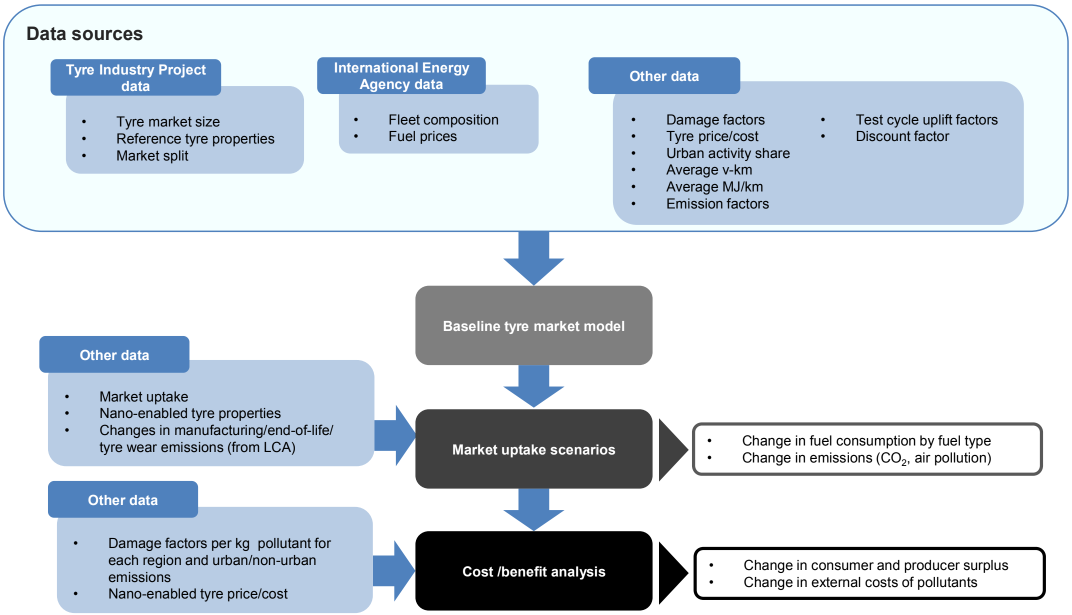
In the Defra methodology, there is assumed to be a reference product with a fixed market size, and a new nano-enabled product to be analysed, that has no or a positive effect on market size. If market size is assumed to increase, then market size of the nano-enabled product is a power decay function $\frac{k}{x}$ where x is price and k is the fixed initial market size. In reality, the size of the tyre market will evolve in the reference (i.e. no nanotechnology) scenario due to changes in demand (changes in vehicle sales and/or mileage) and changes in the baseline technology. Therefore, additional modelling is needed to more accurately represent the full tyre market effects in the CBA.

To address this limitation of the Defra methodology, a tyre stock model was created for each region. The tyre stock model was used to determine the market size and related technology uptake levels. It is assumed that the nano-enabled tyre will not affect new vehicle sales as they make up a very small percentage of the new vehicle price, and therefore the total market size for tyres will not be affected. However, if this technology increases the lifetime of the tyre, fewer replacement tyres will be needed and therefore the tyre market size is adjusted to account for this effect.

The full tyre nanotechnology model developed for this project thus consists of a CBA component and a tyre market component. The tyre market component consists of a baseline tyre market model, which forms the basis for the market uptake scenario runs. A simplified schematic of the model and its data inputs are shown in Figure 3.1. Part of the underlying data was supplied by the International Energy Agency (IEA) Mobility Model, including fleet composition and fuel prices. Further data was supplied by the Tyre Industry Project, including tyre market size, market split and reference tyre properties. All other information required was obtained from publically available sources (see Annex B for full details).

It is important to note that the scenarios explored here are not intended to act as forecasts; rather, they are intended to inform policy makers of the range of potential future impacts that could be expected from uptake of nanotechnology in tyres. The CBA identified the types of impact (positive or negative), the likely magnitude of these impacts and who is affected.

Figure 3.1. **Tyre market cost-benefit analysis model structure**



Notes: TIP (Tyre Industry Project) data was obtained through interviews with tyre industry representatives and cross-checked with available literatures. IEA data refers to the Mobility Model. Full references for other data are provided in Annex B.

The scope of the study includes the market for passenger cars only, reflecting its dominance (around 80% of the market) and since data for the truck market is very sparse.

The CBA considers three stakeholder groups, namely:

- consumers (final consumers)

- producers (tyre manufacturers)
- society/environment.

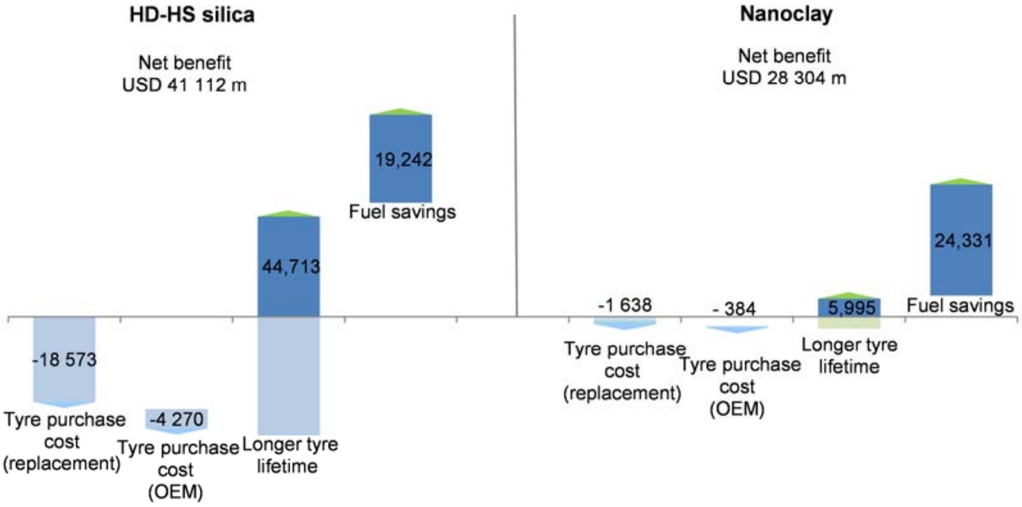
A summary of the quantitative analysis for each group of stakeholders is presented in the following sections. All calculations are expressed in terms of the changes due to purchases of new nano-enabled tyres[1] compared to the reference incumbent tyres. That is, the costs and benefits arise from the different impacts of the nanomaterial part of the tyre.

Costs and benefits to consumers

Costs to consumers arise from the higher upfront purchase costs of the new nano-enabled tyres, while savings come from reduced expenditure on fuel (due to greater fuel efficiency) and reduced expenditure on replacement tyres (due to longer tyre lifetimes). Figure 3.2 shows a breakdown of total costs and benefits to consumers due to each of these factors. The analysis carried out for each case study of new nanomaterial found that total discounted net consumer savings from 2015 to 2035 could be around USD 41.1 billion due to uptake of HD-HS silica, or USD 28.3 billion in the nanoclay scenario. By way of comparison, the United States invested USD 1.9 billion in nanotechnology R&D in 2011 (ObservatoryNano, 2012). The overall savings are higher for HD-HS silica tyres, mainly because it achieves a greater improvement in tyre lifetimes compared to nanoclay.

Figure 3.2. **Breakdown of total discounted costs and benefits to consumers, 2015-35**

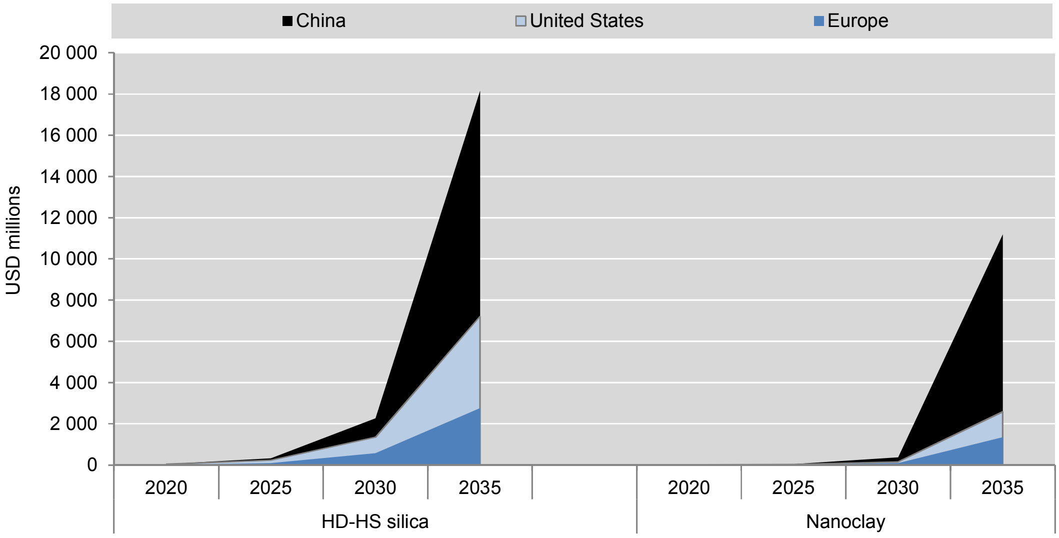
Sum of China, the European Union and the United States, USD millions



Notes: It is assumed that increased costs of tyres on new vehicles are fully passed through to consumers. A social discount factor of 3% is used to discount net benefits to the year of market entry (2015). Costs and benefits are expressed in terms of the difference between the emerging new nanotechnology (HD-HS silica or nanoclay) and the incumbent nanotechnology (carbon black and conventional HD silica).

Figure 3.3 shows the total consumer savings in each region due to new nano-enabled tyres purchased in each year compared to the baseline. The largest overall benefit is to consumers in China since the car market is expected to rapidly grow in coming years, and consequently this is the largest tyre market.

Figure 3.3. **Consumer savings due to tyres purchased in each year, 2020-35**



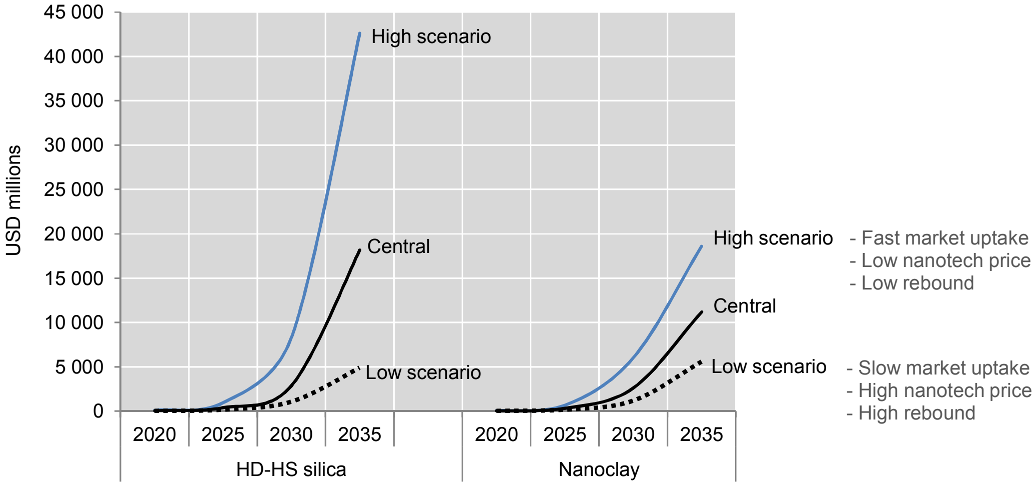
Assumptions on the development of the car market (i.e. powertrain mix and vehicle efficiency) and fuel prices are consistent with the IEA's Mobility Model (MoMo) baseline scenario. The result depends on several assumptions, including: tyre prices, technology uptake and the rebound effect (an increase in activity due to lower unit costs). Figure 3.4 shows a sensitivity analysis considering these key variables. The high scenario represents the best combination of assumptions – fast market uptake rate, low cost of the new nanotechnology and a low rebound effect. Consumer savings in the high scenario increase to USD 42.6 billion in 2035 for HD-HS silica and to USD 18.6 billion for nanoclay. Conversely, in the low scenario, the least favourable combination of assumptions was selected; this reduces benefits to USD 4.9 billion for HD-HS silica in 2035 and to USD 5.6 billion for nanoclay. All other combinations of assumptions would sit within this range. Nevertheless, consumers benefit in all scenarios.

Some potential consumer benefits have not been quantified, as they are likely to be small or uncertain. These include: changes in ride comfort, opportunity cost savings from reduced number of fuel tank refills (due to improved fuel efficiency) and opportunity cost savings of consumer's time from reduced frequency of tyre replacement (due to improved tyre life).

Costs and benefits to producers

Tyre manufacturers incur additional costs due to the higher input price of the new nanomaterials compared to traditional tyre materials. They also lose profit compared to the baseline scenario due to losses of replacement market sales if new nano-enabled tyres are longer lasting. In terms of benefits, manufacturers gain from a higher profit-per-tyre due to the higher mark-up on the nanotechnology. A breakdown of the total costs and benefits (discounted) to producers due to each of these factors in the period from 2015 to 2035 is shown in Figure 3.5. The benefit from HD-HS silica in 2035 is around USD 5.2 billion, compared to a benefit of USD 0.15 billion from nanoclay. Since nanoclay is used in the tyre inner liner, where only a very small amount of material is used, the impact on manufacturing costs and mark-up is much lower. The impact on replacement market sales is also much lower because of the relatively small effect of nanoclay on tyre lifetimes.

Figure 3.4. **Consumer savings sensitivity analysis, 2020-35**



Notes: Assumptions are derived in Annex B, and summarised below for ease of reference.

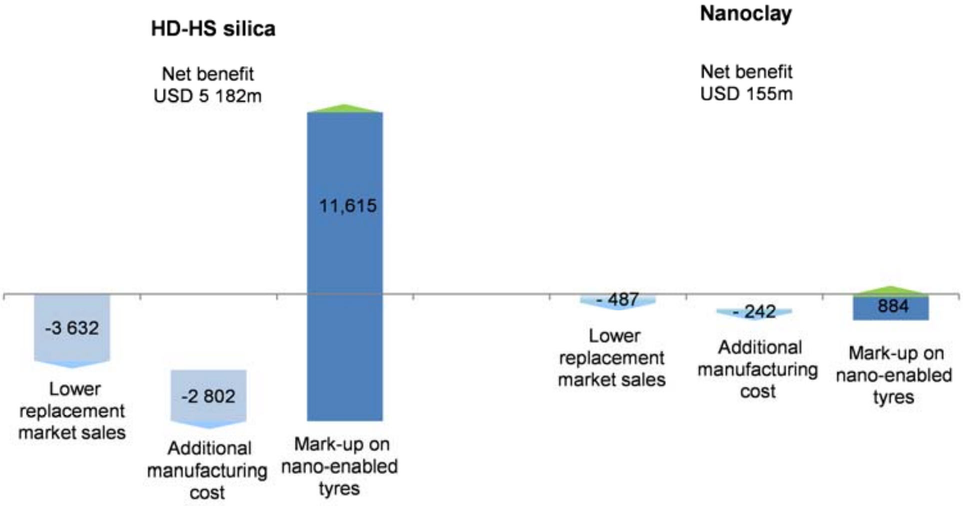
	HD-HS silica		Nanoclay	
	High scenario	Low scenario	High scenario	Low scenario
Market diffusion rate	16 years (OEM) 17 years (repl.)	21 years (OEM) 23 years (repl.)	16 years (OEM) 17 years (repl.)	21 years (OEM) 23 years (repl.)
Nanotechnology price	USD 17.8	USD 36.0	USD 0.59	USD 1.82
Rebound effect	10%	30%	10%	30%

As noted in Chapter 1, it seems likely that the largest brands established in Europe, Japan and the United States will develop nano-enabled tyres first, since these firms have the capacity to invest in R&D and will also benefit from public expenditure in nano-related areas. Therefore, it is likely that these firms will capture the profits from additional mark-up, which will help the larger firms to compete against a backdrop of strong growth in the low-cost tyre segment. The costs due to lower replacement market sales may not involve the same firms as the direct costs and benefits due to the sale of nano-enabled tyres.

The geographic attribution of producer surplus is more challenging, as tyres may be manufactured in one part of the world and sold in another. If manufacturing of nano-enabled tyres is concentrated to particular regions, benefits to producers will occur there. High-value tyres are typically exported from the United States (mainly to Canada and Mexico) and Europe (mainly to non-European Union, Europe, the United States and Canada), but volumes are small compared to local market size. Initially, nano-enabled tyres are likely to be introduced as premium products for consumers who are willing to pay for improved performance. In the longer term, wider consumer demand may be crucial to ensure investment and market development for the specific case study nanomaterials, and manufacturing may occur in more regions.

Figure 3.5. **Breakdown of total discounted costs and benefits to producers from tyres sold in 2015-35**

Sum of China, the European Union and the United States, USD millions



Notes: Costs from lower replacement market sales may not involve the same firms as the impacts from additional manufacturing costs and benefits from mark-up on nano-enabled tyres.

The value of the nano-enabled tyre market was calculated on the basis of the added value of the nanotechnology included in the products, rather than the total value of the tyres. Cost estimates were developed for the specific nanomaterials in each case study on the basis of material substitution. Production cost increases were not explicitly included, but are likely to be minor as the processing requirements are thought to be similar to the baseline technology. Annex B details all the assumptions made in developing the estimates, which were based on the best information available at the time of writing.

Environmental externalities

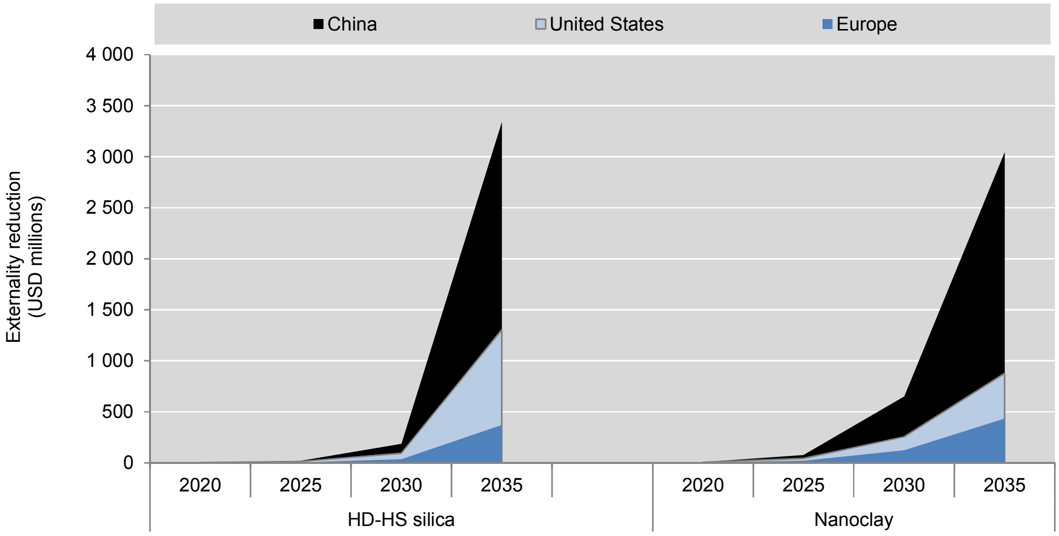
The main impact categories that have been monetised in the CBA relate to the impacts of environmental externalities (air pollution and CO_2). The selection of these impact categories was based on evidence that suggests these are the most important impacts over the vehicle lifecycle (mainly because they impact human health – directly and indirectly – and are therefore valued highly in monetary terms).

Nano-enabled tyres can contribute to reductions in emissions by reducing fuel consumption (lowering rolling resistance) and reducing lifecycle emissions (due to longer tyre lifetimes). The analysis of lifecycle impacts carried out in Chapter 4 considers that production of HD-HS silica and nanoclay are unlikely to have very significant impacts on total lifecycle emissions. The impact of emissions has been monetised by considering human health damage cost functions (marginal damage cost per tonne).

Figure 3.6 shows the quantified reductions in environmental external costs from CO_2 and air pollution. Total discounted costs reached USD 6.3 billion in the HD-HS silica scenario and USD 7.5 billion for nanoclay. Note that the external cost reduction is higher in the nanoclay scenario because the total reduction in fuel consumption is greater than for the HD-HS silica scenario. Reliable estimates of external costs of air pollution on a unit basis were not available for China and therefore were not quantified here. However, the reductions in air pollutants are by far the highest in China due to the higher emission factors associated with the vehicle fleet.

Figure 3.6. **Quantified reductions in external costs due to tyres purchased in each year, 2020-35**

Excludes air pollution in China



Notes: Includes external costs of CO_2 in all regions, and air pollution (NOx, SOx and PM) in Europe and the United States. Reliable estimates of external costs of air pollution in China were not available; therefore these were not quantified.

Other possible environmental effects include material damage through degradation from acidic air pollutants, damage to ecosystems through acidification and eutrophication and reduced visibility (a possible effect of PM). However, these impact categories are much smaller compared to the magnitude of human health effects and have therefore not been considered in detail.

Overall costs and benefits

The evolution of discounted costs and benefits for consumers, producers and society are shown in Figure 3.7, using a social discount rate of 3% (see Annex B). Total discounted benefits reach USD 52.6 billion (cumulative from 2015-35) for HD-HS silica and USD 35.9 billion for nanoclay compared to the baseline.

The sensitivity of the results to underlying assumptions in the model was also tested. Figure 3.8 shows the results for low, central and high scenarios. The high scenario represents the best combination of assumptions for consumers, as detailed earlier – fast market uptake rate, low cost of the new nanomaterials and a low rebound effect. Total discounted benefits (cumulative from 2015-35) could reach USD 111.7 billion for HD-HS silica or USD 65.0 billion for nanoclay in the high scenario. The low scenario represents the least favourable combination of assumptions. In this scenario, total benefits reduce to USD 21.1 billion for HD-HS silica and USD 18.0 billion for nanoclay; nevertheless, there are net benefits in all scenarios.

Figure 3.7. **Discounted costs and benefits, 2015-35**

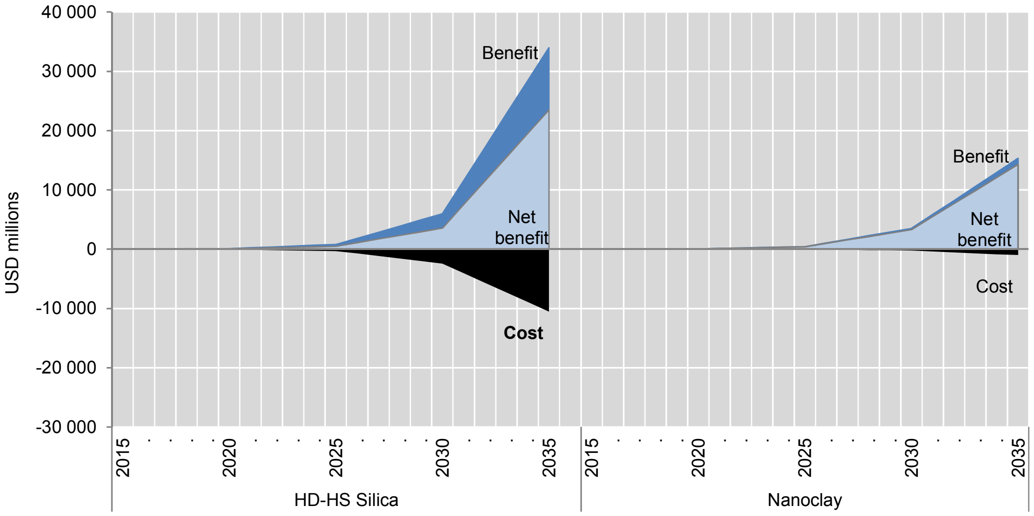
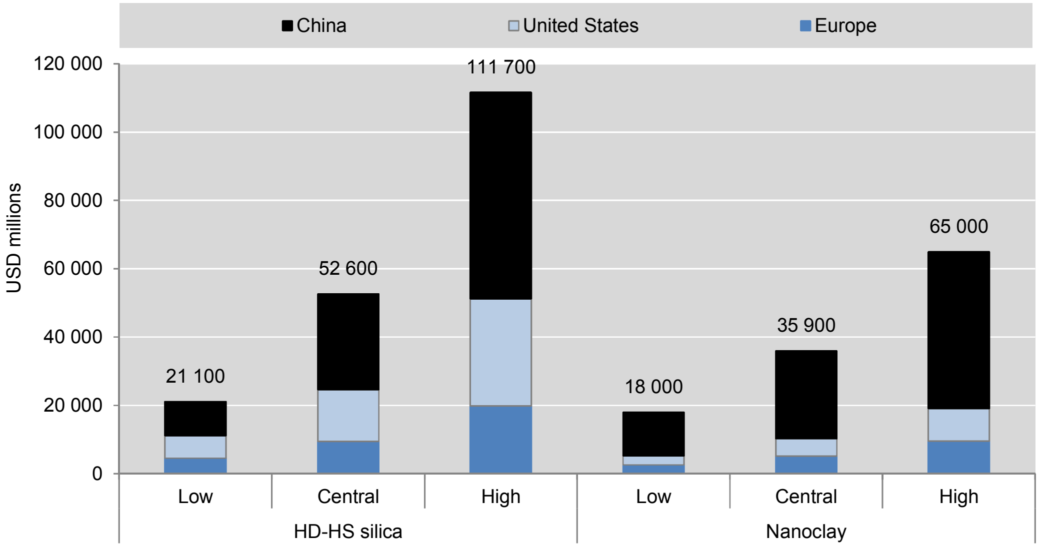


Figure 3.8. **Sensitivity analysis for net present value by region, 2015-35**

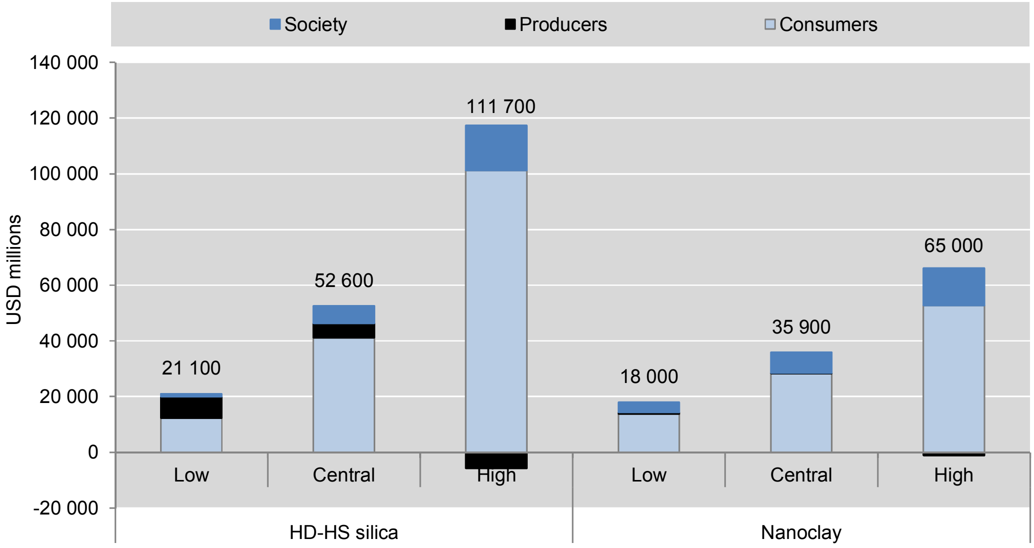


Note: A simplifying assumption is made that producers and consumers are in the same region.

Figure 3.9 shows that most of the benefits accrue to consumers due to the savings from reduced expenditure on fuel and replacement tyres. The benefit to producers in the nanoclay scenario is negligible due to the low changes in cost and price for this technology. Note that this represents the net impacts on the tyre industry as a whole, but does not capture the costs and benefits to different manufacturers (e.g. due to changing market share). The monetised benefits to society include reductions in CO_2 and air pollutants – in the traditional cost-benefit framework they appear relatively small, but there are many additional impacts that are not easily captured in monetary terms (see the next section).

In summary, the cost-benefit analysis shows that there are net benefits associated with both of the case study new nanomaterials; these benefits mostly accrue to consumers. The sensitivity analysis also found that even under the least favourable combination of assumptions, there were still net benefits to consumers. However, the cost-benefit framework is unsuitable for analysing many of the wider impacts of new nanotechnologies in tyres, particularly for societal impacts that are not easily monetised. Therefore, these are considered in the next section.

Figure 3.9. **Discounted net benefits split by stakeholder, 2015-35**



Socio-economic impacts of the development of new nanomaterials in tyre production: Qualitative multi-criteria analysis

This section includes an assessment and a discussion of impacts that are relatively difficult to quantify and monetise, with a particular focus on the following impact categories:

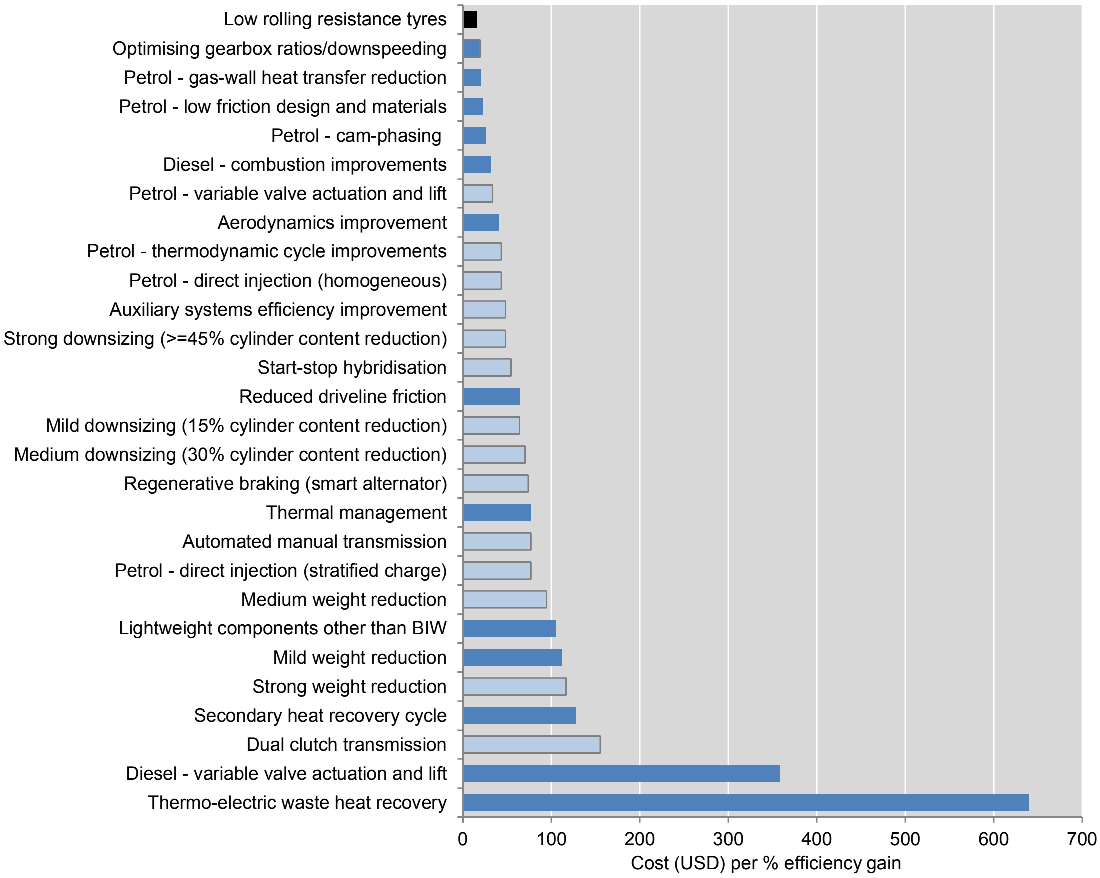
- Societal impacts:
  - public health and safety
  - impacts on developing countries
  - employment
  - road accidents.
- Environmental impacts:
  - resource consumption
  - use of energy.

Impact on public health and safety

The use of new nanomaterials in tyres without adequate environmental, health and safety (EHS) controls across the supply chain and the lifecycle of the product could pose risks to public health and safety. Nanomaterials in general have a range of potential health impacts depending on their chemical nature, particle size, shape, state of aggregation/agglomeration, etc. Under experimental conditions, the most common observed effects are potential to cause oxidative stress, inflammatory responses or genotoxic effects (European Commission, 2012). The relevance of these studies depends on whether the experimental data can be considered representative for real life conditions. In addition, it is equally important to study exposure, since in the real world the potential for harmful effects depends on the doses to which humans and the environment are exposed. The most significant concerns about nanotechnology risks relate to free materials that are in a particulate form at the nanoscale (EASAC/JRC, 2011). Where risks are identified, appropriate risk management measures need to be implemented (see Chapter 5 for more detail on this topic).

While benefits were found for consumers and society (environmental externalities) for both case study new nanomaterials, it is also worth considering alternative fuel-saving technologies available beyond different types of tyre. Figure 3.10 shows a comparison of the cost for each percent efficiency gain for different passenger car abatement options. Low rolling resistance tyres have the lowest cost for each percent efficiency gain compared to the other technologies; however, it is clear that the same or larger improvements in fuel efficiency can be achieved using other technologies (albeit at a higher cost). However, for existing cars, there are very few retrofittable options other than low rolling resistance tyres. It is also worth noting that improvements in fuel efficiency in tyre technology typically involve trade-offs with tyre lifetime and/or wet grip; therefore there is no directly comparable technology.

Figure 3.10. **Comparison of cost for each percent of efficiency gain for different technologies**



Notes: Dark blue represents <5% efficiency gain ; light blue represents >5% efficiency improvement.

Source: AEA (2012), “A review of the efficiency and cost assumptions for road transport vehicles to 2050”, Committee on Climate Change.

It is also worth considering how many products containing nanomaterials are already available to consumers. In the case of tyres, the main exposure points are through environmental pollution or unintentional human exposure during manufacturing and potentially during recycling. By comparison, other engineered nanoparticulate materials (such as food, cosmetics and healthcare) might lead to substantial direct exposure during use. The global market value of all types of synthetic amorphous silica was around EUR 2.7 billion in 2010. Precipitated silica is used in footwear, batteries, as an anti-caking agent in food powders, healthcare products such as toothpaste, detergent and cosmetics, matting agents in paints and others (European Commission, 2012). Public data was not available to clearly differentiate between conventional HD silica and the new HD-HS silica; however, according to the safety data sheet of an HD-HS silica product, the manufacturer has not classified it as hazardous (Rhodia, 2011).

Nanoclays are used in paints, inks, greases, cosmetics formulations, wastewater treatment and food packaging. The global market is around EUR 150 million. According to industry, nanoclays are naturally occurring clay minerals (ReachCentrum, 2013); however, this does not apply to nanoclays that have been subject to chemical surface modification.

Impacts on developing economies

Possible issues related to emerging economies include the impacts on trade and the potential effect on existing inequalities.

Impacts on trade of natural rubber could occur due to the improved tyre life times. The natural rubber market is heavily dependent on the tyre industry – 75% of globally marketed natural rubber is used in tyre production, which is primarily supplied from Indonesia, Malaysia, Thailand and Viet Nam (European Tyre and Rubber Manufacturers Association, 2011). Globally, around 20 million smallholder families rely on natural rubber for their livelihood (ETC, 2011). Increasing uptake of nano-enabled tyres could significantly reduce demand for natural rubber and thus affect workers and the local economy. Reductions in consumption of natural rubber compared to the baseline could be around 191 000 tonnes for HD-HS silica (around a 6% reduction), and 28 000 tonnes for nanoclay (around a 1% reduction in 2035).

However, in terms of overall and long-term impacts, there are many other factors at work, and the exact impact of nano-enabled tyres is not clear. There are opportunities to switch to other crops, as natural rubber competes for land with palm oil and cocoa, which are less labour intensive than rubber, have shorter production cycles and may offer higher returns. Other initiatives are being pursued in an effort to reduce the industry's reliance on natural rubber imports due to the issues with price volatility and shortages. For example, several tyre manufacturers have started to develop bio-based isoprene in as an alternative to natural rubber (ETC, 2011). Prototype tyres obtained from natural latex from Guayule and Russian Dandelion plants have also recently been developed under the EU-PEARLS project.

Any potential adverse impacts due to the displacement of natural rubber exports must also be weighed against the technical capacity for nano-enabled tyres to help reduce other problems. Nano-enabled tyres could help to reduce the externalities associated with air pollution and climate change from car emissions, where buyers in emerging markets are expected to drive future sales. In general, countries with poorer standards for fuel quality and vehicle emissions will benefit more from nano-enabled tyres since there is greater potential to reduce the air pollutants from transport – this is reflected in the relatively high reductions of NOx, SO_2 and PM found for China. Furthermore, it is the poorest countries that are most vulnerable to climate change impacts.

However, affordability in emerging markets will have a huge impact on the potential growth of the market for nano-enabled tyres. The development of new nanotechnologies in tyres is expected to cater to the premium market first. Market experience in regions such as Europe has shown that increasing prosperity tends to lead to higher willingness-to-pay for enhanced performance. Even though the case study nano-enabled tyres are expected to be cost-effective over the lifetime of the tyres, additional support is likely to be needed to increase consumer awareness and trust in the technology.

Impact on employment in the tyre manufacturing industry

Impacts on jobs will depend on changes in competitiveness and economic structure. A large-scale shift to new nano-enabled tyres will impact the supply chain, production and management processes. There are two main factors that could lead to impacts on employment, namely:

- changes in tyre manufacturing volumes due to longer tyre lifetimes
- changes in required skills and/or manufacturing practices due to the use of new nanomaterials.

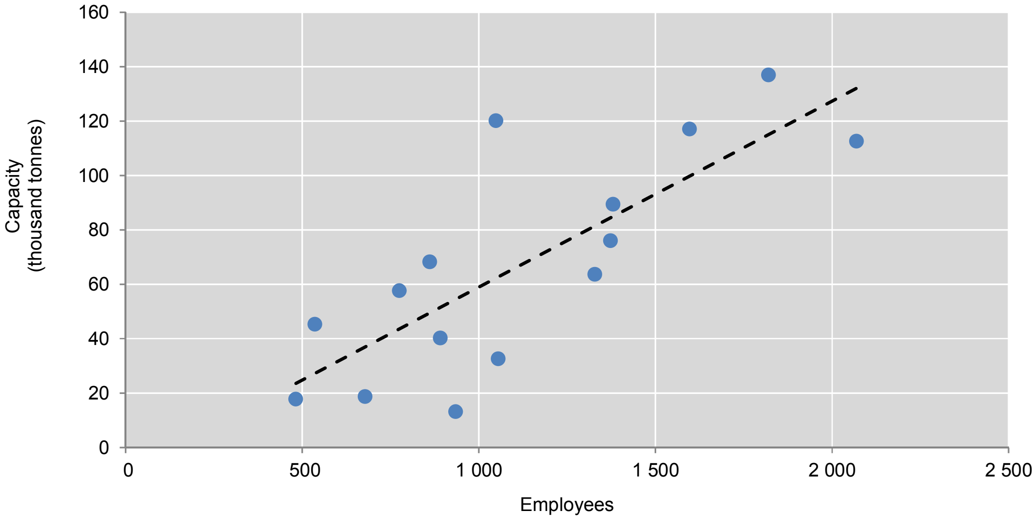
The scenarios developed for market uptake of HD-HS silica tyres indicate that around 135 million fewer tyres will be required in China, Europe and the United States (6% reduction compared to the baseline in 2035) due to the improvement in tyre lifetime. For nanoclay inner liners, the impact is more modest, with 20 million fewer tyres (around 1% reduction compared to the baseline in 2035).

Reductions in tyre production may result in a reduction in employment demand from the tyre manufacturing industry. In order to estimate the potential impact, it is assumed that employment will reduce in response to lower demand. Figure 3.11 shows the trend between tyre plant capacity output and the number of employees at each plant.

According to literature estimates, the annual productivity improvement for tyre manufacturing is generally in the range of 3-5% per year (Mullineux, 2004), but it is becoming increasingly difficult to maintain this rate of improvement as the easier savings have been made. Therefore, to estimate employment impacts, an annual productivity improvement for tyre plants of 2% was assumed to give a conservative estimate (a lower assumed improvement leads to larger reductions in employment).

An indication of the impact on employment is shown in Table 3.1. In the HD-HS silica scenario, demand for employment in the tyre manufacturing industry would reduce by around 11 700 jobs in 2035 due to reduced market volumes in China, Europe and the United States. There is a smaller reduction of 1 900 jobs in the nanoclay scenario. The location of the employment impacts cannot be precisely determined since tyres may not be manufactured locally, although manufacturers do tend to cater mainly to their domestic and neighbouring countries.

Figure 3.11. **Employees at tyre manufacturing plants with different capacities**



Source: Based on Michelin (2012), *2012 Annual and Sustainable Development Report* (EU and US plants), Michelin, www.michelin.com/corporate/EN/group/annual-and-sustainable-development-report.

Table 3.1. **Calculation of tyre industry employment impacts (in 2035)**

	HD-HS silica scenario			Nanoclay scenario		
	United States	European Union	China	United States	European Union	China
Tyre demand reduction (millions of tyres)	23.8	22.6	88.9	2.1	2.8	15.3
Average tyre weight (kg)	10.2	8.8	7.9	10.2	8.8	7.9
Tonnes avoided	242 282	198 515	705 482	21 463	24 287	121 170
Annual productivity improvement	2%	2%				
Reduction in employment	11 700			1 900		

By way of comparison, this level of employment demand reduction is not unheard of in the tyre industry. Employment in the United States tyre industry alone fell by around 10 000 people between 2007 and 2009 (from around 60 000 to 50 000 people) and recovered somewhat to 52 000 people in 2011 (Hufbauer and Lowry, 2012). It should be noted that the reduction in employment demand represents jobs that might otherwise have been created in the baseline (without new nanomaterials) scenario, but does not imply losses of existing jobs – i.e. employment still increases overall due to growth in tyre market volumes over the period. This may be considered less disruptive than redundancies. Reductions in employment could also occur further down the supply chain (e.g. suppliers of steel cord) but these suppliers tend to produce a range of products for different customers and are likely to be less affected (whereas tyre manufacturing plants are highly specialised and do not produce other products).

New requirements for working with nanotechnology may create new jobs but this is not likely to be significant, particularly for drop-in replacement materials. Companies engaged in nanotechnology have 75 nanomaterial workers on average (GenRe Research, 2011). Other job increases are likely to be associated with individuals and consultancies responsible for EHS assessment and control along the whole value chain. Some of this additional work will be absorbed within existing jobs, but there is likely to be a positive impact on job creation, with the majority of these new jobs being highly skilled. Finally, further efforts in R&D to develop and test the technologies will also require highly educated scientists and engineers, both in the tyre industry and in their suppliers.

Impact on road accidents

There are several potential ways in which the case study nanomaterials might reduce accident rates:

- HD-HS silica applications in the tyre tread may improve wet grip, which is generally associated with shorter stopping distances and thus lower accident rates. The precise impact on wet grip from the new generation of silica is uncertain.
- Improving the air retention of tyres is reducing under inflation and may improve vehicle handling – this impact was considered to be relevant for nanoclay inner liners.

While no specific data were available on the potential impact on accident rates, USDOT (2005) estimates that the introduction of tyre pressure monitoring systems (TPMS) in the United States could prevent around 8 500 non-fatal injuries and save around 120 lives each year due to reductions in skidding/loss of control, reduced stopping distance and avoided flat tyres/blowouts. These estimates were based on an assumed reduction in average steady state under inflation of around 12 percentage points (assuming 90% compliance rate with TPMS signal). By comparison, nanoclay inner liners could reduce average steady state underinflation by around 4 percentage points compared to typical United States tyres (see Annex A). Similarly, fitting all cars in Europe with TPMS could save 29 lives and avoid around 3 700 non-fatal injuries (European Commission, 2008).

Impact on resource consumption

Raw materials comprise a very significant proportion of manufacturing costs, and volatility in input cost needs to be carefully managed. Market uptake of HD-HS silica tyres could reduce consumption of natural rubber for tyres by 6% in 2035 compared to the baseline scenario, and uptake of nanoclay inner liners could reduce natural rubber consumption by 1% in 2035 (due to increased tyre lifetimes).

Although the specific nanomaterials used for the case studies did not result in very dramatic reductions in raw material consumption per tyre at the manufacturing stage, this is an active research area in the tyre industry. The potential for using recycled rubber in tyres is limited by technical issues and so access to natural rubber is a key concern, particularly given the reliance on imports and the high consumption of the sector. Some of the nanomaterials at very early stages of development identified in Chapter 1, such as graphene, could contribute in this area; however, there is still a great deal of caution in the industry with respect to developing any nanomaterials without better information on the risks (e.g. EHS issues and regulatory uncertainty).

Impact on use of energy

Reductions in fuel consumption due to improved rolling resistance of tyres will reach 356 PJ in 2035 (0.7% reduction compared to the baseline) for HD-HS silica and around 337 PJ (0.6% reduction) for nanoclay. These are relatively small reductions because the baseline tyre technologies are already of a high standard; the key benefit of the nanotechnology is maintaining the fuel efficiency performance while also improving tyre lifetimes.

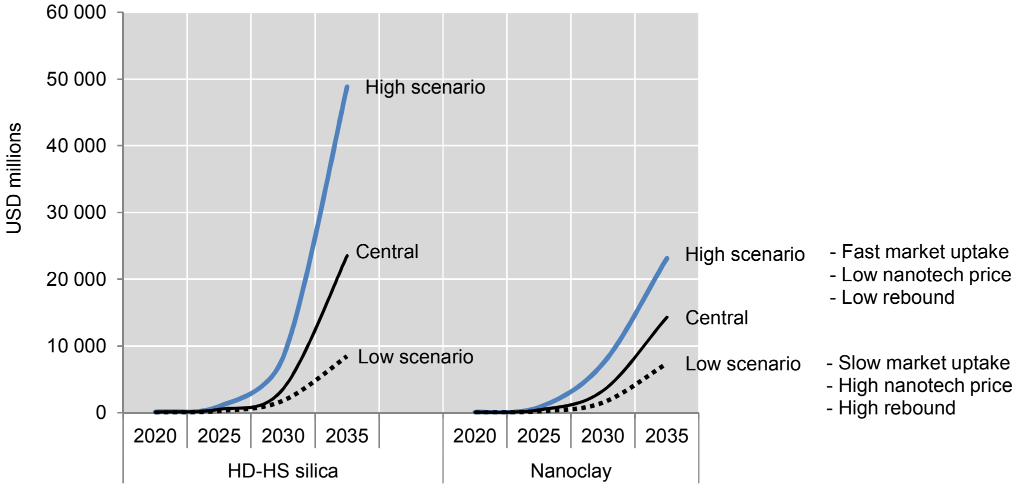
Reductions in manufacturing fuel consumption due to avoided tyre sales are relatively modest, reaching around 50 PJ in 2035 for HD-HS silica and 8 PJ for nanoclay. This reflects the fact that the majority of energy consumption over the tyre lifetime is in the use stage.

Overall assessment and concluding remarks

The scenarios explored here are not intended to act as forecasts; rather, they are intended to inform policy makers of the range of potential future impacts that could be expected from uptake of nanotechnology in tyres. The cost-benefit analysis identified the types of impact (positive or negative), the likely magnitude of these impacts and who is affected. This is an important step when making policy decisions about whether market development or uptake should be encouraged and whether any possible negative impacts could be mitigated.

The studied new nanomaterials appear to offer significant net benefits. Total discounted net benefits from 2015-35 in the central scenario were USD 52.6 billion for HD-HS silica and USD 35.6 billion for nanoclay (using a social discount rate of 3%). Net benefits were found under all sensitivity scenarios, as shown in Figure 3.12. By way of comparison, the total budget for all government R&D support for nanotechnology in the United States is around USD 1.8 billion, which would be equivalent to USD 27.7 billion (discounted) if the same budget were allocated annually from 2015-35.

Figure 3.12. **Net benefits under different market uptake scenarios, 2020-35**



Note: Shows net benefits due to tyres purchased in each year, over the lifetime of the tyres.

The cost-benefit analysis found that most of the net benefits were to consumers, with relatively small net benefits to producers and small reductions in environmental externalities. In the case of environmental externalities, this was partly due to a lack of reliable methods to monetise benefits in this area. In addition, many other impacts on society and the environment are not easily incorporated into a cost-benefit framework; therefore these were considered qualitatively.

Table 3.2 shows the overall assessment of the nanomaterials considered in the study, with impacts ranked from strongly negative to strongly positive. Economic and environmental impacts are positive on the whole, with particular benefits to consumers. Societal impacts could arise from impacts on employment, accidents and on developing economies.

Table 3.2. **Overall assessment of the new generation nanomaterials considered in the study compared to existing nanomaterials**

	HD-HS silica	Nanoclay
	Economic impacts	
Consumer benefits	✓✓ Increase in consumer benefits over the period 2015-35 of USD 41 100 million (discounted)	✓✓ Increase in consumer benefits over the period 2015-35 of USD 28 300 million (discounted)
Producer benefits	✓✓ Increase in producer benefits over the period 2015-35 of USD 5 200 million (discounted)	✓ Increase in producer benefits over the period 2015-35 of USD 150 million (discounted)
	Environmental impacts	
Environmental externalities (CO$_2$ and air pollutants – monetised)	✓✓ Reduction in environmental externalities over the period 2015-35 of USD 6 300 million (discounted)	✓✓ Reduction in environmental externalities over the period 2015-35 of USD 7 500 million (discounted)
Environmental externalities (air pollutants in China – not monetised)	✓ Reduction in air pollutants in 2035 of: 19 kt SO$_2$; 79 kt NOx;	✓ Reduction of air pollutants in 2035 of: 20 kt SO$_2$; 84 kt NOx;

	3 kt PM_{10}; 2 kt $PM_{2.5}$	3 kt PM_{10}; 2 kt $PM_{2.5}$
Resource consumption	✓✓ Reduction in natural rubber consumption of 192 000 tonnes in 2035 (around 6% reduction compared to baseline in 2035)	✓ Reduction in natural rubber consumption of 28 000 tonnes in 2035 (around 1% reduction compared to baseline in 2035)
Use of energy	✓ Reduction in transport fuel consumption of 356 PJ (around 0.7% reduction compared to baseline in 2035)	✓ Reduction in transport fuel consumption of 337 PJ (around 0.6% reduction compared to baseline in 2035)
Social impacts		
Public health and safety	? Uncertain due to lack of data (see also Chapter 5). Potential exposures and releases of nanomaterials during the use phase are expected to be less likely (due to being bound in the polymer matrix), although there is still a need for this to be verified for new nanomaterials.	
Road accidents	○ Negligible	✓ Potential for reduction in road accidents due to better air retention
Employment in the tyre manufacturing industry	× Reduction in employment demand of 11 700 jobs due to reduced demand for replacement tyres	× Reduction in employment demand of 1 900 jobs due to reduced demand for replacement tyres
Impact on developing economies	? Possible impacts due to reduction in natural rubber exports – mitigation could include education about possible impacts due to nano-enabled tyres and other technology developments, as well as crop switching; potential for social benefits if consumers gain access to nano-enabled tyres, although affordability could be an issue	

Key:

××	×	○	✓	✓✓	?
Strongly negative	Negative	Negligible	Positive	Strongly positive	Uncertain

The impacts on employment and trade depend on a wide variety of factors. For example, if the use of new nanomaterials tends to reduce employment demand, this demand is also dependent on the opportunities for workers to find jobs in other sectors. The reduction in consumption of natural rubber is beneficial in terms of minimising demand for a critical raw material, but many smallholders in developing countries rely on these exports for their livelihoods. Overall, the most pressing issue does not appear to be the changes in market conditions due to uptake of nano-enabled tyres per se, but rather the risk that stakeholders might not be prepared for any disruptive effects. Thus, it is important to understand the implications of nanotechnology developments as well as other market trends.

In a typical cost-benefit analysis, the trade-offs between "winners" and "losers" are compared. However, quantitative cost-benefit analysis functions best when the impacts can be accurately assessed, and the uncertainty over the EHS risks means this is not currently practical. The benefits outlined above include reductions in costs to consumers as well as reductions in externalities relating to air pollution and climate change. This must be weighed against the possibility of introducing a new and uncertain externality relating to nanotechnology EHS risks. Conventional tyre technologies typically involve trade-offs between fuel efficiency and tyre lifetime and/or wet grip; therefore there is no directly comparable technology.

As discussed in Chapter 2, market pull factors will be important in achieving significant uptake, including tyre labelling, minimum standards and indirectly through regulation of the automotive manufacturers. Newer nanotechnologies that are further from the market may have different impacts, which could be analysed using the same framework. All assumptions and calculation steps are detailed in Annex B. Any benefits from newer nanomaterials may be held up by the long development times that are typical for the tyre industry.

NOTES

[1]. The "new" nano-enabled tyres are the emerging new technologies based on HD-HS silica and nanoclay. The reference incumbent tyres are based on carbon black and conventional HD silica. It would not be very informative to use a "no nanotechnology" tyre as a reference because all tyres are made with varying amounts of nanotechnologies (carbon black was first introduced into tyres more than 100 years ago).

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CHAPTER 4

ENVIRONMENTAL IMPACTS IN THE CONTEXT OF LIFE-CYCLE ASSESSMENT

Using a life-cycle assessment methodology, this chapter evaluates potential environmental impacts of three different vehicle tyre technologies: the reference tyres (using nanoscale carbon black and highly dispersible [HD] silica); and next generation tyres, namely HD-HS silica nano-enabled tyres and nanoclay (montmorillonite) nano-enabled tyres. It looks, in particular, at impacts on greenhouse gases emissions across the product lifecycle, impacts on natural resource consumption and flows across the lifecycle, and impacts of nanowaste from end-of-life tyres. The chapter also makes recommendations aimed at improving the life-cycle assessment framework for assessing the relative impacts of baseline and nano-enabled tyres.

The wide range of applications of nanotechnologies potentially bring with them unverified or quantified risks, such as risks from the release of nanoparticles into the environment They also have the potential to influence positively the environment (e.g. energy saving in production processes, improvements in the final product making it more environmentally friendly). There continues to be a need to evaluate the environmental impacts from the use of new nanomaterials in tyres during research, development, industrialisation and end-of-life management. Potential positive and negative environmental impacts from different types of tyre technologies, including existing and emerging ones include, for example: impacts on greenhouse gases emissions across the product lifecycle, impacts on raw materials and natural resource consumption and flows across the lifecycle, impacts of nanowaste from end-of-life tyres.

Using a life-cycle assessment (LCA) methodology, this chapter aims to evaluate the differences in potential environmental impacts from three different vehicle tyre technologies:

- reference tyres (nanoscale carbon black and highly dispersible [HD] silica)
- next generation, highly dispersible high surface area (HD-HS) silica nano-enabled tyres
- nanoclay (montmorillonite) nano-enabled tyres.

Introduction to the life-cycle assessment methodology

LCA is a method for evaluating and comparing the environmental impacts of products over their entire life cycle. An LCA quantifies the use of energy and materials, as well as the releases to the air, water and land for each step in the life cycle of the product: from raw material extraction through end-of-life management. This systematic approach makes LCA a very comprehensive tool for evaluating the environmental sustainability of a product. As defined in the ISO 14040 and 14044 standards, a full LCA includes the following steps:

- Goal and scope definition: defines the boundaries of the product system to be examined.
- Life-cycle inventory (LCI): examines the sequence of steps in the life-cycle boundaries of the product system, beginning with raw material extraction and continuing on through product fabrication, use, reuse and recycling where applicable, and final disposition. For each life-cycle step within each life-cycle stage, the inventory identifies and quantifies the material inputs, energy consumption and environmental emissions (atmospheric emissions, waterborne and solid wastes). In other words, the LCI is the quantitative environmental profile of a product system. Substances from the LCI are organised into air, soil and water emissions or solid waste.
- Life-cycle impact assessment (LCIA): characterises the results of the LCI into categories of environmental problems or damages based on the substance's relative strength of impact. Characterisation models are applied to convert masses of substances from the LCI results into common equivalents of one category indicator (e.g. carbon dioxide equivalents for global warming potential). Note: for nanoscale emissions, no LCIA characterisation methodologies yet exist and so these have not been quantified and impacts are discussed qualitatively.
- Interpretation: uses the information from the LCI and LCIA to compare product systems, rank processes and/or pinpoint areas (e.g. material components or

processes) where changes would be most beneficial in terms of reduced environmental impacts. The information from this type of assessment is increasingly used as a decision-support tool.

Scope of the life-cycle assessment study

Vehicle tyres using the nanoclay and next generation HD-HS silica nanomaterial technologies, hereafter referred to as “nano-enabled” tyres, are evaluated relative to reference tyres (i.e. tyres that use current carbon black and HD silica technologies). Environmental impacts are examined at the level of the associated differences quantified for each life-cycle stage. Primary case study data were not available at the time of this analysis, either because quantitative data had not been gathered or because information and data were considered to be confidential. Therefore, the best available data for these steps have been used to compile a general framework for assessment of potential differences in LCI and/or LCIA at all life-cycle stages of baseline relative to nano-enabled tyres. Because of the lack of primary data, this study does not attempt to claim definitive results for these products or to make comparative statements for these products. Rather, a primary purpose of the study is as a guidance document for future work on assessing the environmental impact of new nanomaterials in tyres. More in-depth consideration of the environmental impacts over the nano-enabled tyre life cycles is supported by the assessment of environmental, health and safety issues provided in Chapter 5.

Life-cycle studies are carried out on the basis of the same defined function or unit of service (the functional unit). The general functional unit of this life-cycle study is defined as travel of 10 000 kilometres on the average market mix of highest selling vehicle replacement tyres for each tyre type in each investigated geographic region. A distance of 10 000 kilometres is selected for the basis of comparison as it is most representative of average annual travel distance for a tyre across regions.

The amount of nanomaterial used in tyres, the general composition of tyres and the performance parameters considered used to examine the use and end-of-life (EOL) stages of the tyre life cycles are determined by weighting the current and projected market share for each tyre type in each region (Europe, the People’s Republic of China and the United States). This approach takes into account that tyre sizes, formulations, use-stage parameters and EOL management vary by region. For example: *i)* sport utility vehicles (SUVs) are more prevalent in United States; whereas compact cars are more prevalent in Europe (European Tyre & Rubber Manufacturers’ Association, 2012); *ii)* commercial heavy duty trucks in different regions typically have different axle configurations (hence a different number of tyres); *iii)* tyres with a higher ratio of HD silica are more prevalent in the European Union where wet handling/improving fuel efficiency are higher priorities; whereas tyres with a higher ratio of nanoscale carbon black are more prevalent in the United States where cost and extended tyre life are higher priorities, see e.g. Tire Review (2009); *iv)* US vehicle tyres are typically used for a greater average mileage in the United States than in the European Union;[2] and *v)* a greater share of scrap tyres are sent to material recycling in the European Union than in China or the United States.[3]

Material weight composition data for the European Union were provided by the European Tyre and Rubber Manufacturers Association (ETRMA). These were adapted to the US market, considering the following key differences:

1. higher carbon-to-silica ratio
2. lower compounded rubber-to-steel ratio
3. higher average per tyre weight.

The average weight composition data for each tyre type in China assumes per tyre weights as specified by the reference tyre in Table 4.1 and weight percentage formulations equivalent to those in the United States. The data collection step has aimed to reflect geographic differences in tyre formulations as far as possible.

Reference composition, performance and production stage LCI data are compiled based on an LCA performed by the ETRMA. These LCI data are compiled for each of the following tyre types:

- summer passenger car tyres
- winter passenger car tyres
- run flat passenger car tyres
- steer-type, long haulage truck tyres
- drive-type, long haulage truck tyres
- trailer-type, long haulage truck tyres
- steer-type, regional haulage truck tyres
- drive-type, regional haulage truck tyres
- trailer-type, regional haulage truck tyres.

Table 4.1. **Summary of reference tyre types and sizes for each region**

Scenario name	Application	Type of tyre	Relative market share	United States reference tyre	EU reference tyre	China reference tyre
Summer tyre	Passenger car	Summer	80.0%	195/65 R 15, 205/55 R 16 (based on VW Golf)	P265/70R17 (based on Ford F150) UTQG grade	185/65 R14 86 T (based on Buick Excelle)
Winter tyre	Passenger car	Winter	20.0%			
Run flat tyre	Passenger car	Run flat	0%			
Long haul	Truck	Steer and drive Trailer	34.5%	295/75R22.5 or 275/80R22.5 (radial)	315/80 R22.5 (radial)	11R22.5 (US size) (radial) – 11.00R20 (tube tire, radial)
Regional haulage	Truck	Steer and drive Trailer	65.5%			

Since data for scenarios of nano-enabled truck tyres were unavailable and truck tyres only constitute approximately 20% of the tyres replacement markets, this analysis focuses on the larger passenger tyres market. From this point forward in the report, the LCI and LCA discussion and results refer to the average market mix of passenger tyres. Note that relative to passenger tyres, truck tyre compositions have a higher weight percent of natural rubber and carbon black; therefore, the LCA results for nano-enabled truck tyres would show less substitution of conventional HD silica and have different performance improvements.

The three product systems to be considered in the LCA are as follows:

1. reference tyres (i.e. containing nanoscale carbon black and HD silica)

2. next generation, HD-HS silica nano-enabled tyres
3. nanoclay (montmorillonite) nano-enabled tyres

An overview of the systems and data sources is provided in Table 4.2.

Table 4.2. **Summary of investigated technologies for each life-cycle assessment scenario and life-cycle inventory data status**

Technology	Life-cycle assessment scenario	Life-cycle inventory data status
Nanoscale carbon black and highly dispersible silica	Market mix of tyres using these products widely used and considered the reference scenario	LCI data for EU production are largely compiled; these data have been augmented with data specific to production of these nanomaterials and have been adapted for production in China and the United States; assumptions have been made to fill data gaps for market shares of tyre types and their respective filler content ratios
Next-generation, highly dispersible high surface area silica	Nano-enabled technology Scenario I	Primary LCI data collection required from nano-material manufacturers and nano-enabled tyre producers; data compiled from best available sources (e.g. using patents, reaction stoichiometry, LCI database averages for chemicals production)
Nanoclays (montmorillonite)	Nano-enabled technology Scenario II	

Detailed summaries of the primary data modules and data sources used for the LCI of reference and nano-enabled tyre product systems are presented in Annex C.

The following life-cycle stages are included for each of the investigated product systems:

- Nanomaterial production: fabrication of the nanomaterials from their raw materials to the finished nanomaterial filler additive, including all incoming transport required.
- Tyre production: raw material production of the other (i.e. non-filler) precursor tyre materials, which consists of all steps, from resource extraction through raw material production and process requirements for manufacturing of tyres, including all incoming transport required.
- Use stage: use of the reference and nano-enabled tyres in each investigated geographical scope, including accounting for differences in fuel consumption over the tyre lifespan; differences in material consumption due to varying tyre lifetimes; and wear and subsequent air, soil and water partitioning of the tyre tread particles; in other words, use stage impacts include comparative analysis of the environmental differences in fuel consumption given performance criteria as well as differences in the potential range of nanoscale particles released to air, soil and water during the use of both reference and nano-enabled tyres on roads (e.g. through tread wear).
- End-of-life (EOL): differences in potential releases of nanoscale particles through management and/or treatment of scrap tyres containing nanomaterial additives by reuse, material recycling, energy recovery and landfilling.

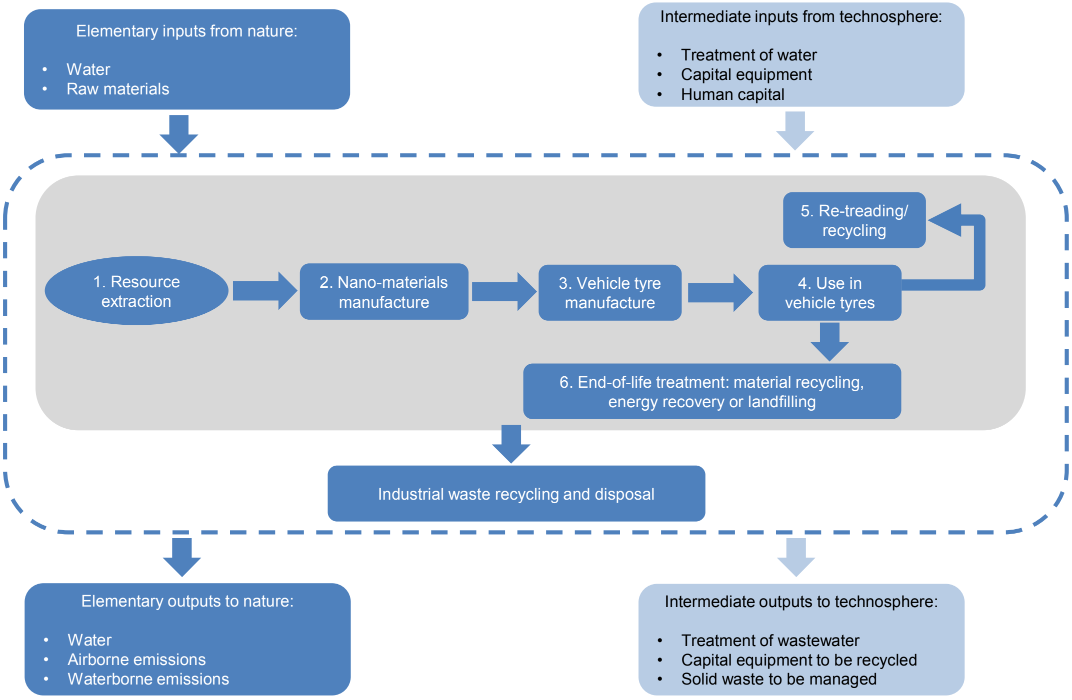
The study boundaries account for transport requirements between all life-cycle stages. Because of the very broad geographical scope of the nanomaterial tyre additives covered by the project, some simplifying assumptions have been made regarding transport distances and modes for shipping nanomaterials from manufacturers to consumers.

Average national statistics for levels and modes of scrap tyre treatment are assumed for each geographic region. These statistics have been developed from research, recent publications and previous work conducted by the OECD. For scrap tyre treatment, the analysis models the differences in potential nanoscale substance release to air, water and soil through tyre reuse, material recycling, energy recovery at a waste incineration-type process and landfilling. Reuse rates are applied to the reference life-cycle inventory such that they account for average tread wear releases of tyres. Material recycling of scrap tyres accounts for potential nanoscale releases from dust emissions at granulation facilities. Examples of applications for granulated tyre rubber (GTR) are: asphalt modification, sports surfacing and playgrounds. For the energy recovery treatment route, differences in potential releases on nanoscale substances are modelled for a general waste incineration process. Generally, energy is recovered from scrap tyres via cement kilns and/or pulp and paper mills.

The production stage of the reference tyre scenario is based on the ETRMA LCI data for production of each of the reference tyre types in the EU. These data include: average material inputs, transport requirements for incoming materials, energy and water consumption at the production step, air and water emissions at the production step, and performance criteria to be considered for the use stage. As described, the data have been adapted to account for key differences in China and the United States geographic scopes.

A summary flow diagram of the boundaries for the reference and nano-enabled tyre product systems is shown in Figure 4.1.

Figure 4.1. **System boundaries of tyre nanomaterials life-cycle assessment**



Life-cycle inventory model framework development

The development of the LCI inventory both for reference and nano-enabled tyres includes compilation of the additional LCI stages. Tables 4.3-4.6 present references to tyre LCI data. These were adapted from data provided by the ETRMA and compiled to reflect the baseline framework from which to compare conventional carbon black and silica tyres to nano-enabled tyres for all three geographic scopes. These data reflect differences in China and US reference tyre weights, life spans and some key differences in tyre formulations in the United States market relative to the European Union market (i.e. the higher carbon-to-silica ratio; the lower compounded rubber-to-steel ratio).

Table 4.3. **Summary of baseline tyre composition for reference passenger car tyres**

Passenger car tyres	Market-weighted average (kg/tyre)		
	United States	European Union	China
Synthetic rubber	2.55	2.14	1.93
Natural rubber	1.74	1.46	1.32
Carbon black	1.95	1.54	1.39
HD silica	0.93	1.00	0.90
Sulphur	0.11	0.090	0.081
ZnO	0.15	0.13	0.11
Stearic acid	0.065	0.055	0.049
Accelerators and vulcanization agent	0.095	0.079	0.071
Antidegradants	0.16	0.13	0.12
Cobalt salts	0.019	0.016	0.014
Steel	1.06	1.03	0.93
Rayon	0.12	0.093	0.08
Reinforcing resins	0.097	0.081	0.073
Nylon	0.14	0.11	0.10
Plasticisers	0.69	0.58	0.52
Polyester	0.22	0.17	0.15
Silanes	0.11	0.093	0.084
Total reference tyre weight (kg)	10.2	8.79	7.94

Data from literature, existing databases and research are used to compile best-available LCI data modules for production and incorporation of nanomaterials into nano-enabled tyres. These data are also used to assess key differences at each life-cycle stage between baseline and nano-enabled tyres. Key parameters compiled for the comparative framework are presented in Tables 4.7-4.9 and reflect the aspects unique to the life cycles of nano-enabled tyre product systems relative to those utilising carbon black and conventional HD silica fillers: percent of total nanomaterial inputs and relative splits to air, water and landfill of nanomaterial releases during manufacturing and waste incineration processes in this analysis are estimated using those assessed for global life cycles of engineered nanomaterials by Keller et al. (2013).[4]

Table 4.4. **Summary of transport requirements for materials to reference passenger car tyre production**

Passenger car tyres tonne-kilometres of transport for incoming materials	United States		European Union		China	
	Truck	Ship	Truck	Ship	Truck	Ship
Synthetic rubber	2.57	26.6	2.15	22.3	1.94	20.1
Natural rubber	0.98	29.9	0.82	25.1	0.74	22.6
Carbon black	2.51	0.61	1.99	0.48	1.79	0.44
Silica	0.90	0.0077	0.97	0.0082	0.87	0.0074
Sulphur	0.091	0.25	0.076	0.21	0.069	0.19
ZnO	0.13	0.0070	0.11	0.0059	0.098	0.0053
Stearic acid	0.059	0.019	0.050	0.016	0.045	0.014
Accelerators and vulcanization agent	0.097	0.36	0.082	0.30	0.074	0.27
Antidegradants	0.14	0.39	0.12	0.32	0.11	0.29
Cobalt salts	0.019	0.19	0.016	0.16	0.014	0.14
Steel	1.33	2.45	1.30	2.38	1.17	2.14
Rayon	0.064	0.0078	0.050	0.0061	0.045	0.0055
Reinforcing resins	0.092	0.038	0.077	0..032	0.070	0.029
Nylon	0.30	0.12	0.23	0.093	0.21	0.084
Plasticisers	0.71	0.38	0.59	0.32	0.53	0.29
Polyester	0.14	1.22	0.11	0.94	0.10	0.85
Silanes	0.091	0.31	0.077	0.26	0.069	0.24

Table 4.5. **Summary of process requirements for reference passenger car tyre production**

Passenger car tyres		Per US market average tyre	Per EU market average tyre	Per Chinese market average tyre
Energy consumption (kWh)	Electricity	7.95	7.95	7.95
	Coal	1.13	1.13	1.13
	Fuel oil	0.012	0.012	0.012
	Natural gas	7.61	7.61	7.61
	Renewable energies	0.062	0.062	0.062
	Steam purchased	4.66	4.66	4.66
	Total	21.4	21.4	21.4
Water consumption (L)	Water withdrawal	75.0	75.0	75.0
Air emissions (kg)	VOCs	0.0093	0.0093	0.0093
	NOx	0.0031	0.0031	0.0031
	SOx	0.0017	0.0017	0.0017
	PM_{10}	3.0E-04	3.0E-04	3.0E-04
	$PM_{2.5}$	1.6E-05	1.6E-05	1.6E-05
	Ethanol	0.018	0.018	0.018
Water emissions (kg)	BOD (biochemical oxygen demand)	1.9E-04	1.9E-04	1.9E-04
	COD (chemical oxygen demand)	0.0051	0.0051	0.0051
	TSS (total suspended solids)	0.0012	0.0012	0.0012
	Zinc	3.7E-06	3.7E-06	3.7E-06
	Total hydrocarbons	4.4E-05	4.4E-05	4.4E-05

Table 4.6. Summary of electricity grid profiles per region

Fuel sources	United States	European Union	China
Coal and peat	45%	25%	79%
Natural gas	23%	23%	1.4%
Nuclear	20%	25%	1.9%
Petroleum	1.2%	2.6%	0.45%
Hydropower	7.1%	16%	17%
Renewables	2.2%	4.6%	0.74%
Biomass	1.19%	2.6%	0.064%
Other	0.55%	1.2%	0%
Total (% of composite kWh)	100%	100%	100%

Source: Based on information from International Energy Agency (2009), *World Energy Outlook 2009*, OECD Publishing, Paris, http://dx.doi.org/10.1787/weo-2009-en.

Differences in LCI for production of novel nanomaterial tyre fillers relative to reference nano-fillers are notified below (additional information regarding production processes and unit operations for nano-fillers are presented in Chapter 5):

- Carbon black: reference nano-filler carbon black is typically produced from gas and oil feedstock resulting from the hydrocracking process; these feedstocks are converted to aggregates using high-heat furnace reactors; this life-cycle step has a unique LCI profile; high and low estimates of nanoscale releases from this step are estimated using mass balance and rates given by Keller et al. (2013) for manufacturing of nanomaterials, a recent and seminal work on potential global releases of engineered nanomaterials. The production reaction is modelled as for the oil furnace process: $C_XH_Y + O_2 \rightarrow C + CH_4 + CO + H_2 + CO_2 + H_2O$; inputs are crude oil, water, energy and transport; outputs are solid waste, air emissions (macro- and nanoscale particulates, carbon dioxide [CO_2], carbon monoxide [CO], nitrogen oxides [NO_x] sulphur dioxides [SO_x] and polycyclic aromatic hydrocarbons [PAHs]), and water emissions (chemical oxygen demand [COD], macro- and nanoscale particles, and oil).
- Highly dispersible silica: reference nano-filler HD-Si is typically produced from sand and sodium carbonate in a high-heat glass furnace through alkaline fusion and then water-shocked and pulverised; the resulting silica glass may be dissolved, heated and precipitated with sulphuric acid; the suspension is filtered, dried and formed into agglomerates; this life-cycle step has a unique LCI profile; high and low estimates of nanoscale releases from this step are estimated using mass balance and rates given by Keller et al. (2013) for manufacturing of nanomaterials. The production reaction is modelled as for precipitated silica from water glass: $Na_2O_2xnSiO_2{+}H_2SO_4 \rightarrow nSiO_2 + Na_2SO_4 + H_2O$, with $n = 2$ to 4; inputs are water glass, sulphuric acid, water for washing, energy and transport; outputs are solid waste, air emissions (macro- and nanoscale particulates) and water emissions (COD, salt and macro- and nanoscale particles).
- Highly dispersible, high-surface area silica: novel nano-filler HD-HS Si is assumed to be produced in a manner similar to that of HD-Si; the process for HD-Si per SASSI (2008) is used as a proxy for production of the next-generation HD-HS Si and high and low estimates of HD-HS silica nanoscale releases from this step are estimated using mass balance and rates given by Keller et al. (2013) for manufacturing of nanomaterials.
- Nanoclay montmorillonite: novel nano-filler MMT is modelled as produced from bentonite, the ore which contains clay montmorillonite minerals. The ore is highly refined through suspension, centrifugation, reaction, filtering, drying and grinding; this life-cycle step has a unique LCI profile; high and low estimates of nanoscale releases from this step are estimated using mass balance and rates given by Keller et al. (2013) for nanomaterials manufacturing. The production reaction is modelled assuming extraction and transport of the bentonite ore and water materials to the manufacturing facility and energy inputs; outputs are solid waste, air emissions (macro- and nanoscale particulates) and water emissions (COD and macro- and nanoscale particles).

Table 4.7. **Summary of emissions estimated at production of carbon black tyre additives**

Life-cycle inventory data for production of carbon black		
	SI units (Basis: 1 kg)	
Outputs to technosphere		
Carbon black	100 kg	
Environmental emissions	**Low estimate**	**High estimate**
Atmospheric emissions	1.0E-04 kg	0.025 kg
Nanoscale carbon black		
Solid wastes		
Non-hazardous waste to landfill	0.028 kg	0.025 kg
Nanoscale carbon black to landfill	8.0E-04 kg	0.0040 kg
Waterborne wastes		
Nanoscale carbon black	1.0E-04 kg	0.0080 kg

Table 4.8. **Summary of emissions estimated at production of silica tyre additives**

Life-cycle inventory data for production of highly dispersible silica (HD-Si)		
	SI units (Basis: 1 kg)	
Outputs to technosphere		
Highly dispersible silica	1.00 kg	
Environmental emissions	**Low estimate**	**High estimate**
Atmospheric emissions		
Nanoscale silicon dioxide	1.0E-04 kg	0.0080 kg
Solid wastes		
Non-hazardous waste to landfill	0.028 kg	0.025 kg
Nanoscale silicon dioxide to landfill	8.0E-04 kg	0.0040 kg
Incinerated	5.0E-04 kg	
Waterborne wastes		
Nanoscale silicon dioxide	1.0E-04 kg	0.0080 kg

Table 4.9. **Summary of emissions assumed for production of nanoclay tyre additives**

Data for production of nanoclay MMT		
	SI units (Basis: 1 kg)	
Outputs to technosphere		
Montmorillonite clay (MMT)	1.00 kg	
Environmental emissions	**Low estimate**	**High estimate**
Atmospheric emissions		
Nanoscale MMT	1.0E-04 kg	0.0080 kg
Solid wastes		
Non-hazardous waste to landfill	0.028 kg	0.025 kg
Nanoscale MMT to landfill	8.0E-04 kg	0.0040 kg
Incinerated	5.0E-04 kg	
Waterborne wastes		
Nanoscale MMT	1.0E-04 kg	0.0080 kg

Potential effects on the tyre production process due to incorporation of novel nano-filler materials relative to conventional nano-fillers are not reflected in the LCI model, except as the tyre formulations are affected; the following observations are noted:

- Carbon black and extender oils are typically stored in heated tanks prior to entering a mixing silo where they are blended for uniformity; immediately after carbon black pellets are incorporated into the rubber matrix, the aggregates are released to chemically link to the rubber molecules.
- Silica mixing requires a chemical reaction in order to provide reinforcement to the elastomers of the tyre rubber formulations; the reaction must be controlled with a chemical binding agent.
- Though variations in non-nanomaterial tyre material inputs have been reflected for the nano-enabled tyre scenarios at this step, no changes in energy requirements or process emissions have been reflected. Based on a site visit to a tyre manufacturing facility and interviews with industry representatives, potential differences in energy requirements due to the switching of HD to HD-HS silica, or to the addition of nanoclay fillers, are suspected to be minimal. Though Chapter 5 qualitatively discusses potential nanomaterial releases at the tyre manufacturing process, a detailed and quantitative evaluation based on testing or modelling has not been conducted and is a potential area for future research. Also, there are no generally estimated nanomaterial release rates in Keller et al. (2013) for manufacturing steps involving nanomaterial raw material inputs. Therefore, potential nanoscale releases and/or differences in releases among the filler scenarios have not been quantified for this step in the LCI.

Key assumptions and uncertainties in compiling tyre formulation data are the following:

- Due to a lack of quantitative data, high and low estimates of nanoscale releases from the manufacturing steps are estimated using mass balance and rates given by Keller et al. (2013). Though the estimated range of releases are derived from top-level global material flow analysis data, they capture a broad range of potential releases (0.1-2.0% of total nanomaterials produced) and have been applied uniformly to the manufacture of nanomaterial fillers, despite the filler species. Use of these data introduces uncertainty into the analysis. Refinement based on future data is another potential area for future research.
- Nanoclay MMT fillers are used primarily in the tyre inner liner for improved air retention. As per Nanocor (2013), MMT fillers may be used effectively with relatively light loading (i.e. 3-8%) and as per California Air Resource Board (2008), nanoclay is approximately 8.9% of the inner liner by weight. In the nanoclay-enabled tyre scenario of this analysis, the MMT is assumed to be incorporated into passenger tyres such that it comprises 8.9% by weight of the tyre inner liner. According to Rubber Manufacturers Association (2011), the inner liner of a passenger tyre is assumed to comprise ~12.4% of the average total compounded rubber potion of a passenger tyre. Based on the weight of each region's reference tyre and the weight of the MMT filler in the nanoclay-enabled tyre scenario, this average MMT filler weight is assumed to displace an equal weight of baseline carbon black and HD silica filler weights in a 50/50 proportion. The assumed MMT filler concentration and conventional filler displacements are applied to the composition profiles for each region separately in

order to obtain the resulting filler composition ratios for the nanoclay-enabled tyre scenario of each region.

- HD-HS silica fillers are assumed to entirely replace carbon black and HD silica fillers in the HD-HS silica-enabled tyre scenario of this analysis.
- Given the reference weight of each region's average passenger tyre and the above-mentioned assumptions for the nano-enabled tyre filler weights, Table 4.10 presents the filler weights estimated for each scenario.

Table 4.10. **Summary of baseline and nano-enabled filler amounts for passenger tyre production**

Weight per tyre (kg)		United States	European Union	China
Baseline passenger tyres	Carbon black	1.95	1.54	1.39
	HD silica	0.93	1.00	0.90
MMT-enabled passenger tyres	MMT nanoclay	0.10	0.086	0.078
	Carbon black	1.90	1.50	1.35
	HD silica	0.88	0.95	0.86
HD-HS silica-enabled passenger tyres	HD-HS silica	0.93	1.00	0.90
	Carbon black	1.95	1.54	1.39

Potential effects on the usage phase of tyres from differences in nano-enabled tyres relative to baseline tyres are linked to:

- Differences in material and/or energy consumption due to the change in tyre performance (rolling resistance, tyre life time): key performance criteria are considered for each region's reference tyre as discussed in Chapter 3. Given each region's average vehicle fuel profile, these criteria are utilised to estimate the differences in use stage fuel consumption and associated criteria tailpipe emissions for passenger tyres. The inventoried parameters are presented in Table 4.11 (note: based on the results of this LCA, these differences comprise the bulk of discrepancies in the comparative use stage impacts of baseline versus nano-enabled tyres).
- Differences in nanoscale substance releases during tyre use due to tread wear particle release: assessing environmental impacts at this life-cycle stage would require assessment of potential degradation of tread-wear particles and their subsequent environmental inter-compartmental partitioning. However, derivations for impact factors that reflect differences in the physico-chemical characterisation of the HD-HS silica and nanoclay fillers contained in compounded rubber tread particles (e.g. nanoparticle/object size, shape, surface area and surface chemistry, agglomeration/aggregation, z-potential, redox potential, solubility, etc.) are not currently available. Nevertheless, the potential nanoscale substance releases are inventoried and estimated using tread-wear rates and baseline versus nano-enabled tyre composition for each region. Maximum release potentials are conservatively inventoried in this chapter for the functional unit in each region and presented as potential weights of nanoscale particle releases to soil during the use stage in Annex C. Additional discussion pertaining to nanomaterial releases during the use stage is presented in Chapter 5. Studies have been performed to evaluate the characteristics, toxicity and environmental impacts of tyre particles generated from tread wear during the tyre use phase (Dahl et al. 2006;

Gualtieri et al., 2005; Mantecca et al. 2007; Marwood et al., 2011; Pysklo et al., 2006; NHTSA, 2008; Wik and Dave 2006); these studies reflect tread wear particles containing conventional carbon black and silica fillers.

Potential differences in nanoscale releases at tyre end-of-life (EOL) from baseline versus nano-enabled scrap tyres include:

- High and low estimates of nanoscale releases from the waste incineration processes (WIPs) at EOL are estimated using mass balance and rates given by Keller et al. (2013). Though the estimated range of releases are derived from top-level global material flow analysis data, they capture a broad range of potential releases (0.05-1.0% of total nanomaterials processed) and are the only data known at this time that are applicable for use in a life-cycle inventory. They have been applied uniformly to WIPs for nanomaterial fillers, despite the filler specificities.
- Rates for scrap tyre management are assessed with national/regional statistics (Table 4.12) and applied to the LCI of each tyre: reuse rates are applied to the reference life-cycle inventory such that they account for average tread wear releases of both new and reused tyres. Material recycling of scrap tyres accounts for potential nanoscale releases from dust emissions at granulation facilities. Examples of applications for granulated tyre rubber (GTR) are: asphalt modification, sports surfacing and playgrounds. For the energy recovery treatment route, differences in potential releases on nanoscale substances are modelled for a general waste incineration process. Generally, energy is recovered from scrap tyres via cement kilns and/or pulp and paper mills.
- Percent of total nanomaterial inputs and relative splits to air, water and landfill of low and high potential nanomaterial releases during waste incineration processes in this analysis are estimated using those assessed for WIPs from the global life cycles of engineered nanomaterials per Keller et al. (2013).
- Based on the results of an LCA on scrap tire management performed by ERG (2010), maximum dust emissions from ambient-temperature mechanical material recycling processes are on the order of 6.2E-5 kg per kg of processed scrap tyres. Given this value, the weight of each region's reference passenger tyre, and the filler content for each tyre scenario, a per tyre maximum filler emission factor is established. Potential nanoscale filler substance emissions are assumed to be released to the air.
- All nanoscale filler weights of scrap tyre materials directed to landfilling are conservatively assumed to be partitioned as potential releases to soil by 0-100%.

The following paragraphs detail the overall notes on assumptions for potential nanoscale releases in life cycle of nano-enabled tyres.

High and low estimates of nanoscale releases from manufacturing and WIPs at EOL are estimated using mass balance and rates given by Keller et al. (2013). Though the estimated range of releases are derived from top-level global material flow analysis data, they capture a broad range of potential releases (0.1-2.0% and 0.05-1.0% of total nanomaterial inputs at the life-cycle steps, respectively) and have been applied uniformly to WIPs for nanomaterial fillers, despite the filler species. Future research and acquisition of primary data may provide information to refine and improve the associated life-cycle study.

For each life-cycle stage, high-level assumptions on the environmental compartments to which potential nanoscale emissions are released have been made:

- Releases during nanomaterial manufacturing:
  - For the low estimate of 0.1% of nanomaterial released, 10% are released to air, 10% to water and 80% to landfills; for the high estimate of 2.0% of nanomaterial released, 40% are released to air, 40% to water and 20% to landfills, per Keller et al. (2013).
  - For this analysis, emissions to landfill are conservatively assumed to be transported to soils.
- Releases during the use stage:
  - Through tread wear, 0-100% of the nanoscale filler content of the estimated tread-wear weight are assumed to be released to water.
- Releases during EOL:
  - During material recycling, a scrap tyre LCA by ERG (2010) indicates that only dust emissions occur during tyre granulation; 0-100% of the dust emissions indicated in the LCA are assumed to be emissions to air.
  - During energy recovery, releases are estimated for WIPs; for the low estimate of 0.05% of nanomaterial released, 50%, and ~50% are assumed to be released to slag or into filters; whereas, for the high estimate of 1.0% of nanomaterial released, 1% and 98% are assumed to be released to slag or filters – these ranges are per Keller et al. (2013); for this analysis, nanoscale releases to slag and filters are conservatively assumed to be transported to soils.
  - During landfilling of scrap tyres, 0-100% of nanoscale fillers in this analysis are assumed to be transported to soils.
- Potential releases are discussed in Chapter 5, which further details data availability and data gaps for assessing the implications of these potential releases.

Table 4.11. **Summary of use stage parameters for reference passenger tyres**

			Weight factor in units per tyre for reference flow – Travel of 10 000 km								
			Baseline tyres			HD silica-enabled tyres			MMT-enabled tyres		
			United States	European Union	China	United States	European Union	China	United States	European Union	China
Market-weighted average tyre life span (km)			61 667	38 333	56 000	74 006	46 169	67 446	62 906	39 483	57 977
Fuel consumption	Gasoline	MJ	28 495	13 855	26 974	27 512	13 420	26 127	28 164	13 616	26 424
	Ethanol	MJ	1 981	632	550	1 913	612	533	1 958	621	539
	Conventional diesel	MJ	873	8 926	226	843	8 646	219	863	8 771	222
	Low-sulfur diesel	MJ	0	0	99.1	0	0	96.0	0	0	97.1
	Biodiesel	MJ	17.8	453	4.95	17.2	439	4.80	17.6	446	4.85
	CNG	MJ	48.6	22.9	285	47.0	22.2	276	48.1	22.6	279
	LPG	MJ	56.1	22.9	285	54.2	22.2	276	55.4	22.6	279
	Hydrogen	MJ	0	0	0	0	0	0	0	0	0
	Electricity	MJ	22.8	18.1	50.7	22.0	17.5	49.1	22.5	17.8	49.7
Tailpipe emissions	SO_2	kg	0.044	0.011	0.20	0.042	0.011	0.19	0.043	0.011	0.19
	NOx	kg	6.33	5.56	8.86	6.11	5.38	8.58	6.26	5.46	8.68
	PM_{10}	kg	0.051	0.17	0.097	0.049	0.16	0.094	0.050	0.16	0.095
	$PM_{2.5}$	kg	0.047	0.15	0.089	0.045	0.15	0.086	0.046	0.15	0.087
Tread loss	Compounded rubber	Kg	0.22	0.30	0.19	0.18	0.25	0.16	0.21	0.29	0.18

Table 4.12. **Summary of regional rates for end-of-life management of scrap tyres**

	Total scrap tyres produced		Land-filling	Material recycling	Energy recovery	Re-treading	Reuse and export	Source
	(M tonnes)	(M ELTs)	(LF)	(MR)	(ER)	(RT)	(RX)	
United States	4.60	184	15%	34%	40%	7.2%	3.0%	US EPA MSW (2012)
European Union	3.30	132	4.0%	40%	38%	8.0%	10%	ETRMA (2012)
China	5.00	200	83%	10%	0%	6.8%	0%	WBCSD (2012); Yang (2010)

Total potential nanoscale releases for tyre life cycles

Though environmental impacts of some tyre filler substances have been characterised at the macro-material scale, data sufficient to characterise the impacts of nanoscale releases are not yet available. For example, carbon black is considered to contribute to winter smog in the 1995 version of the EcoIndicator[4] LCIA methodology. Carbon black particulates may also contribute to respiratory effects, cytotoxicity and/or ecological damage at the nanoscale. However, they are not yet formally characterised by existing LCIA methodologies. Likewise, silica particulates may or may not pose cytotoxicity depending on their shape, size and mechanism of releases; these are also not yet characterised at the nanoscale in existing LCIA factorisation profiles.

In order to create an LCA framework for analysing the impacts of nanoscale substance releases, the quantities and characteristics of the releases must first be inventoried. Given sufficient data on the fate, transport and exposure of a particular substance at the nanoscale, the potential impacts of these releases may be further characterised. As described in the LCI framework, the range of potential releases at production, use and EOL stages of baseline and nano-enabled tyres have been estimated using very conservative assumptions and/or release rates estimated in Keller et al. (2013). Though the potential releases are not characterised in terms of environmental impacts, this LCA framework includes a separate inventory of nanoscale substances such that they may be characterised and assessed in future work. Implications of nanoscale releases of the tyre fillers are discussed qualitatively in Chapter 5. However, definitive conclusions cannot be made at this time due to the number of data gaps. For purposes of developing the LCA discussed in this report, quantitative estimates for potential releases are presented in Annex C for each passenger tyre scenario on the basis of the functional unit of this analysis, i.e. 10 000 km travelled by the tyre in each region.

Industry stakeholders including manufacturers of both HD-HS silica and nanoclay were contacted in an attempt to acquire industry-specific information and primary data regarding the production of nanomaterials and subsequent incorporation into tyres at the manufacturing step. Stakeholders were unable to provide information either because quantitative data has not been gathered or because information and data are considered to be confidential. Practitioners have compiled the best available data for these steps using stoichiometric analysis and estimates from the following sources of data: interviews with experts, existing public and private LCI averages for organic and inorganic chemicals production and other industrial processes, publicly available textbooks, encyclopaedias, patent documents and peer-reviewed journals. This general framework for assessment of potential differences in LCI and/or impacts at all life-cycle stages of baseline relative to nano-enabled tyres is presented as a current best practices approach for such an analysis.

Impact assessment

The LCIA results are relative expressions of the potential of inventory flows to contribute to various health and environmental impacts and do not predict actual impacts on category endpoints (e.g. cancer cases, deaths, etc.), exceeding of thresholds, safety margins or risks. Midpoint classification of impacts on the cause-effect chain between stressors and endpoints is used because it is “inclusive of the endpoints which are a result of the midpoint category,” and it “generally enjoys a higher level of scientific consensus than models conducted at the endpoint and damage levels” (Bare and Gloria, 2008). The following potential impact categories are included:

- global warming potential (GWP)
- cumulative energy demand

- ozone depletion potential
- consumptive water use
- acidification potential
- eutrophication potential
- photochemical oxidant formation potential (photochemical smog)
- solid waste production.

This portion of an LCA study focuses on environmental impacts; human health impact categories are outside the project scope. Additionally, modelling human health impacts introduces a higher level of uncertainty to the study results as human health impacts are dependent not only on emission quantities, but also on the fate and transport of the emitted substances and the concentrations and pathways by which organisms are exposed to these substances. As discussed, these detailed types of exposure information are not tracked in this LCI. They require an additional layer of assumptions about the environmental mechanism to be made by the developer of the LCIA methodology. In the multi-criteria analysis (see Chapter 3), a discussion on public health and safety impact is provided, based on various assumptions about the use of the vehicle (driving patterns, population density), which will determine the damage factors.

In the LCIA phase of an LCA, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalised to a common reporting basis, using characterisation factors that express the impact of each substance relative to a reference substance. This study addresses the aforementioned global, regional and local impact categories. For most of the impact categories examined, the ReCiPe Midpoint (E) methodology is employed. The ReCiPe LCIA methodology includes factors harmonised for both mid- and end-point modelling using European-scale models for the environmental mechanisms as defined by Goedkoop et al. (2009). For the category of GWP in both geographic scopes, contributing elementary flows are characterised using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2007 with a 100-year time horizon, as required by PAS 2050 in Forster et al. (2007). In addition, some inventory results are included in the results reported in the analysis (cumulative energy demand, consumptive water use and solid waste production).

Impact assessment

Global warming potential

The GWP is based on a 100-year time frame and represents the heat-trapping capacity of the gases relative to an equal weight of carbon dioxide. The primary 100-year GWPs used in the models are fossil carbon dioxide (1), methane (25) and nitrous oxide (298), as developed by IPCC in 2007. The results for the GWP are expressed in units of carbon dioxide (CO_2) equivalents per tyre for 10 000 km of travel in the specified region. Figure 4.2 shows that the use stage dominates the GWP impacts among the tyre life-cycle stages; however, the discrepancy between the GWP impacts among stages is most significant for production of the HD-HS silica filler material relative to baseline fillers, as seen in Figure 4.3.

Figure 4.2. **Global warming potential results by life-cycle stage for tyre scenarios**

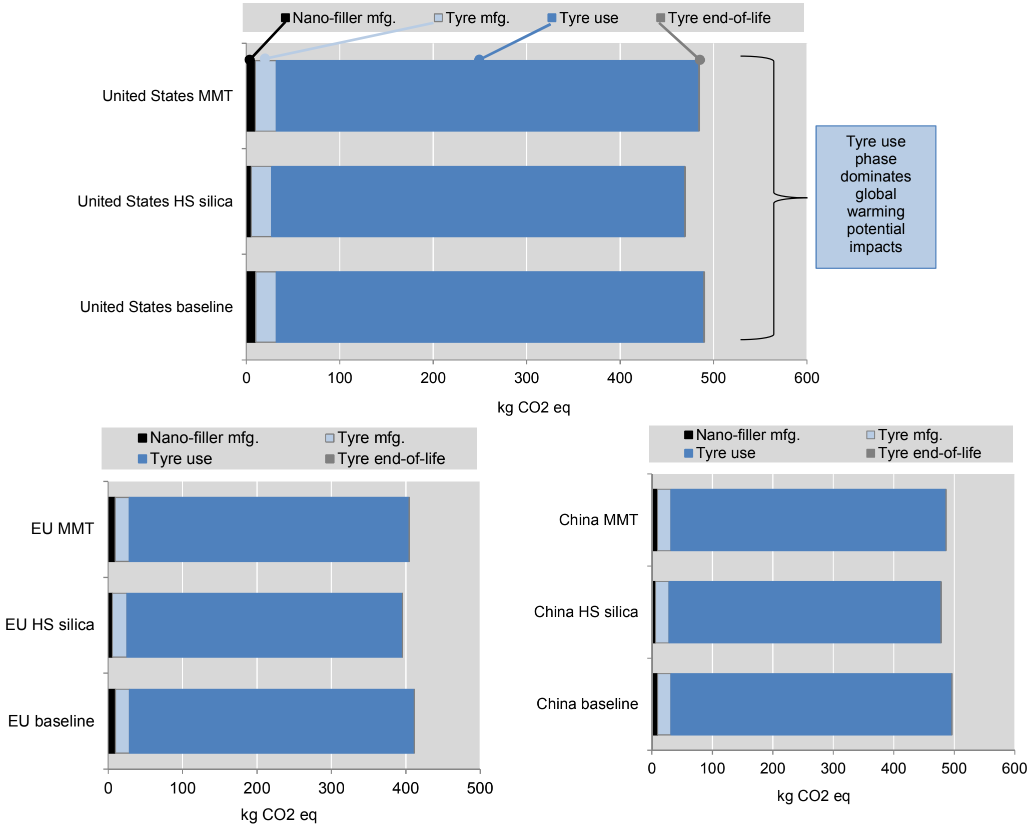
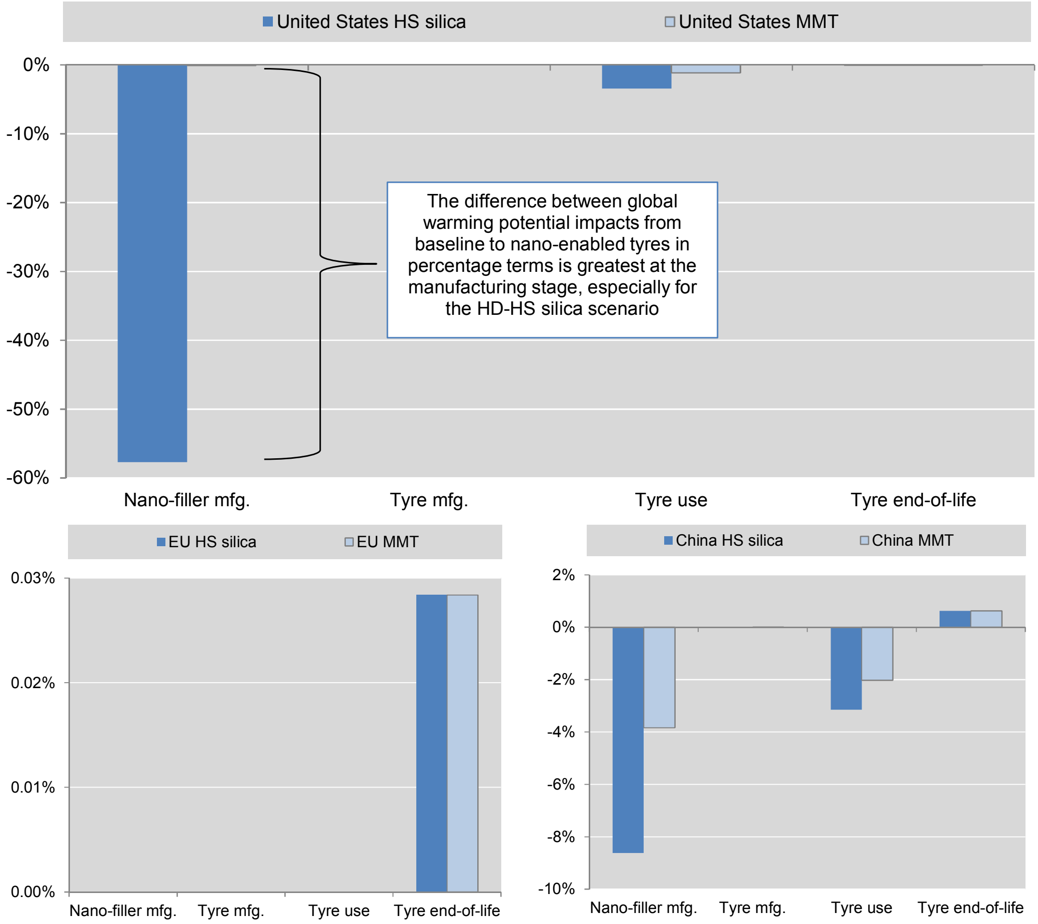


Figure 4.3. **Global warming potential impacts of nano-enabled tyres as a percent of baseline tyres**


The difference between global warming potential impacts from baseline to nano-enabled tyres in percentage terms is greatest at the manufacturing stage, especially for the HD-HS silica scenario

Cumulative energy demand

Cumulative energy demand (CED) is based on the energy values for fuels and electricity consumed in each process and are summed and categorised into an energy profile according to the energy sources: *i)* natural gas; *ii)* petroleum; *iii)* coal; *iv)* nuclear; *v)* hydropower; *vi)* biomass; *vii)* renewables; and *viii)* other. The "renewables" category includes sources such as solar, wind and geothermal energy. The "other" category refers to other fossil fuels. Natural gas, petroleum, coal and nuclear are considered non-renewable energy sources; whereas, hydropower, biomass and renewables are considered renewable energy sources. The results for the CED are expressed in units of megajoules (MJ) of energy per tyre for 10 000 km of travel in the specified region. Figure 4.4 shows that the use stage dominates the CED among the tyre life-cycle stages; however, the discrepancy between the CED impacts among stages is most significant for production of the HD-HS silica filler material relative to baseline fillers, as seen in Figure 4.5.

Figure 4.4. **Cumulative energy demand results by life-cycle stage for tyre scenarios**

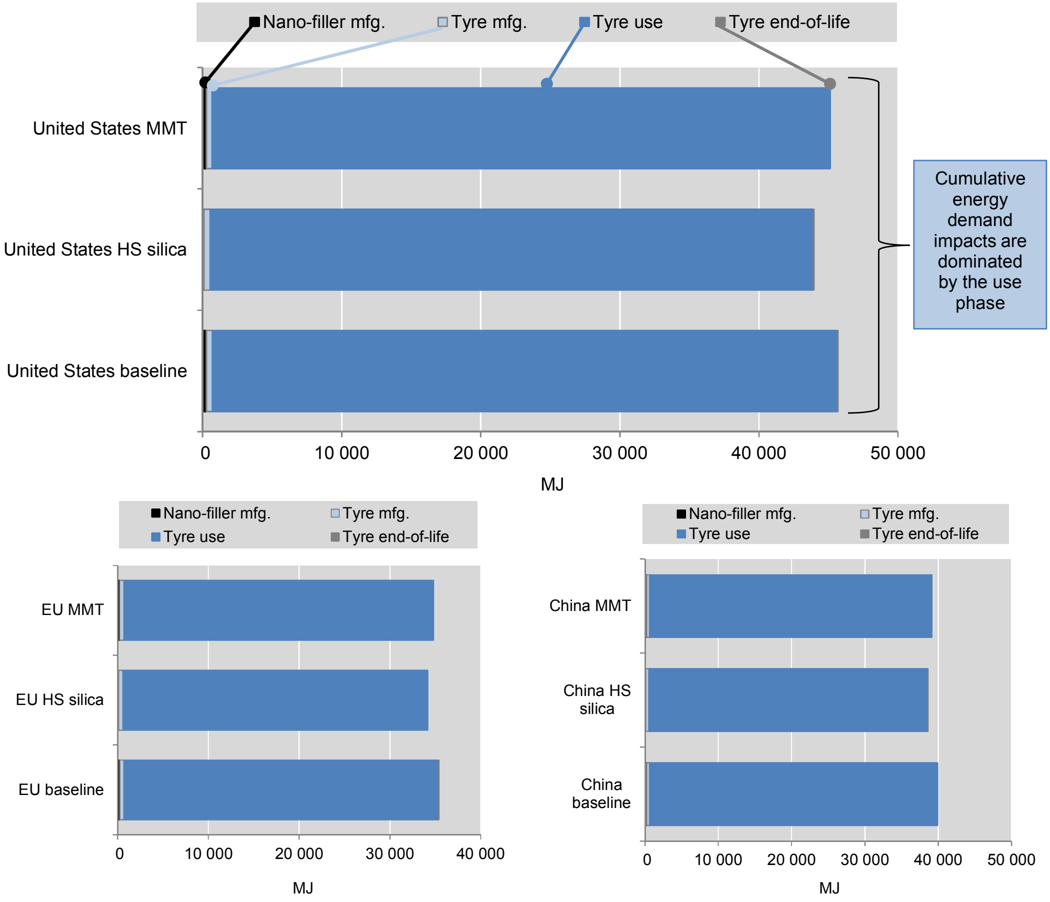
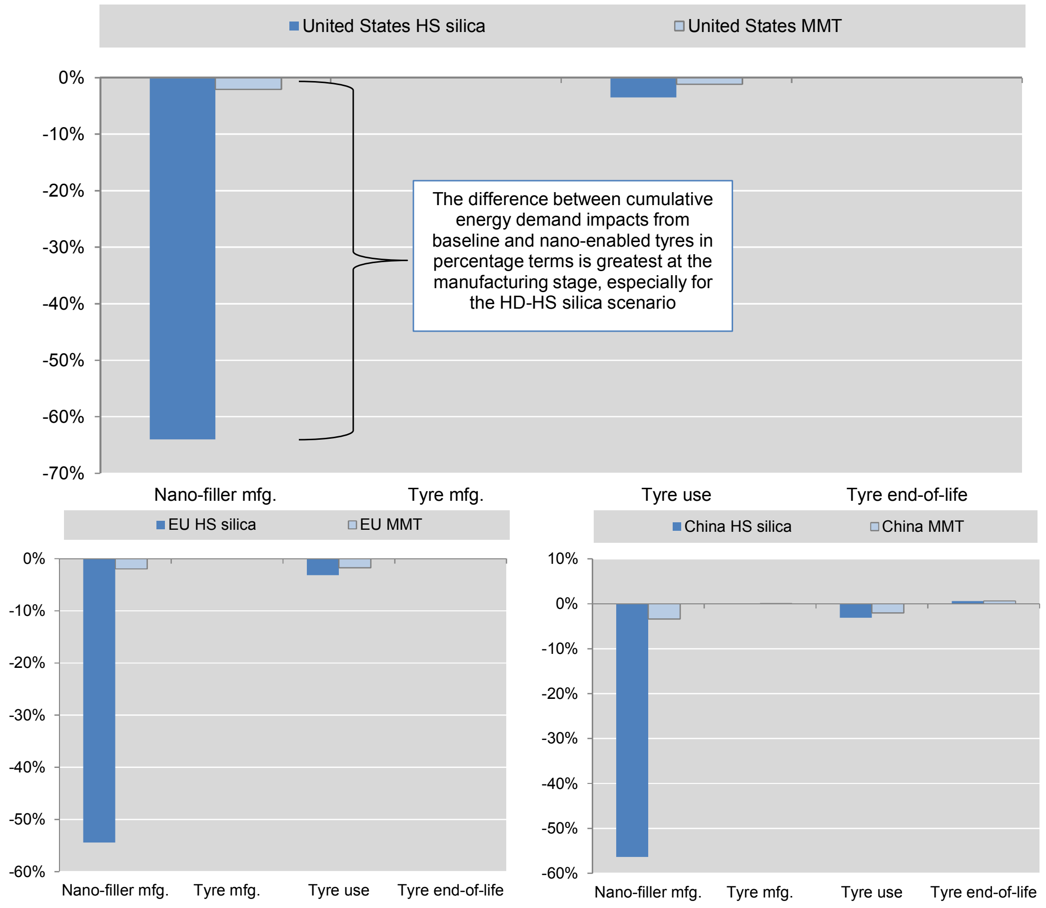


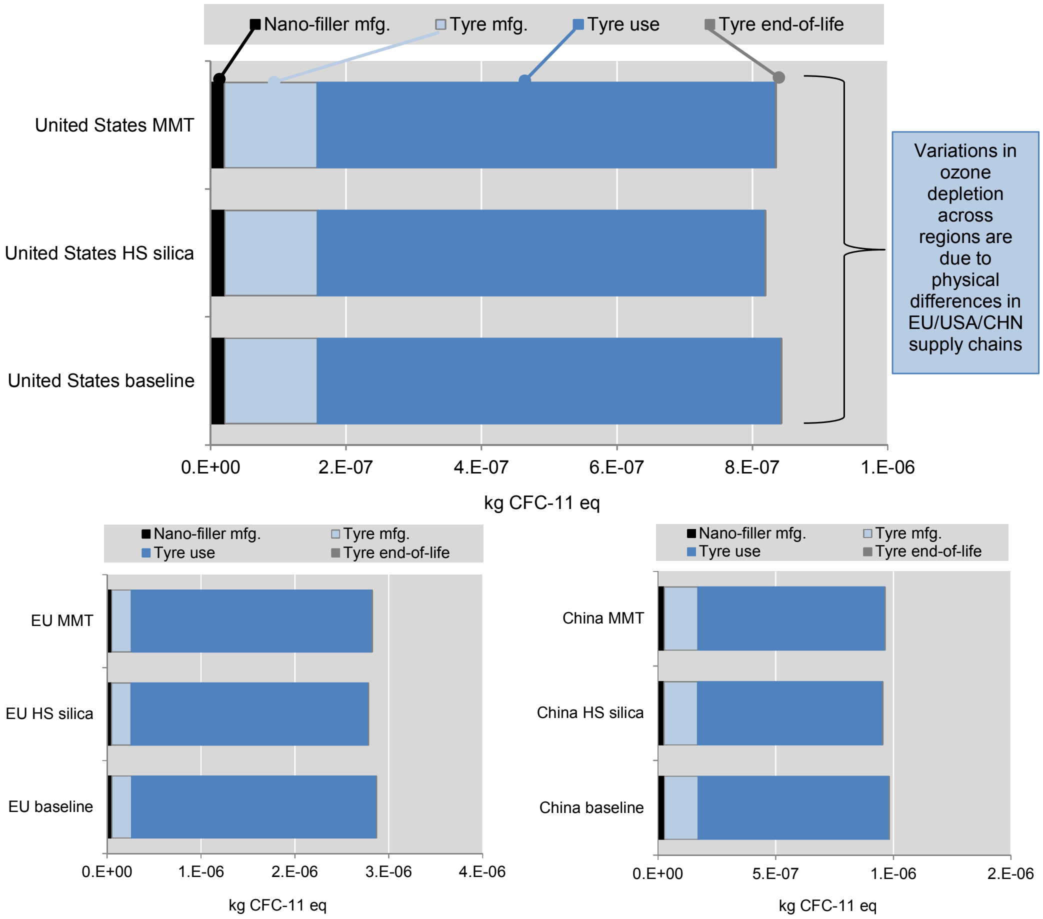
Figure 4.5. **Cumulative energy demand impacts of nano-enabled tyres as a percent of baseline tyres**



Stratospheric ozone depletion

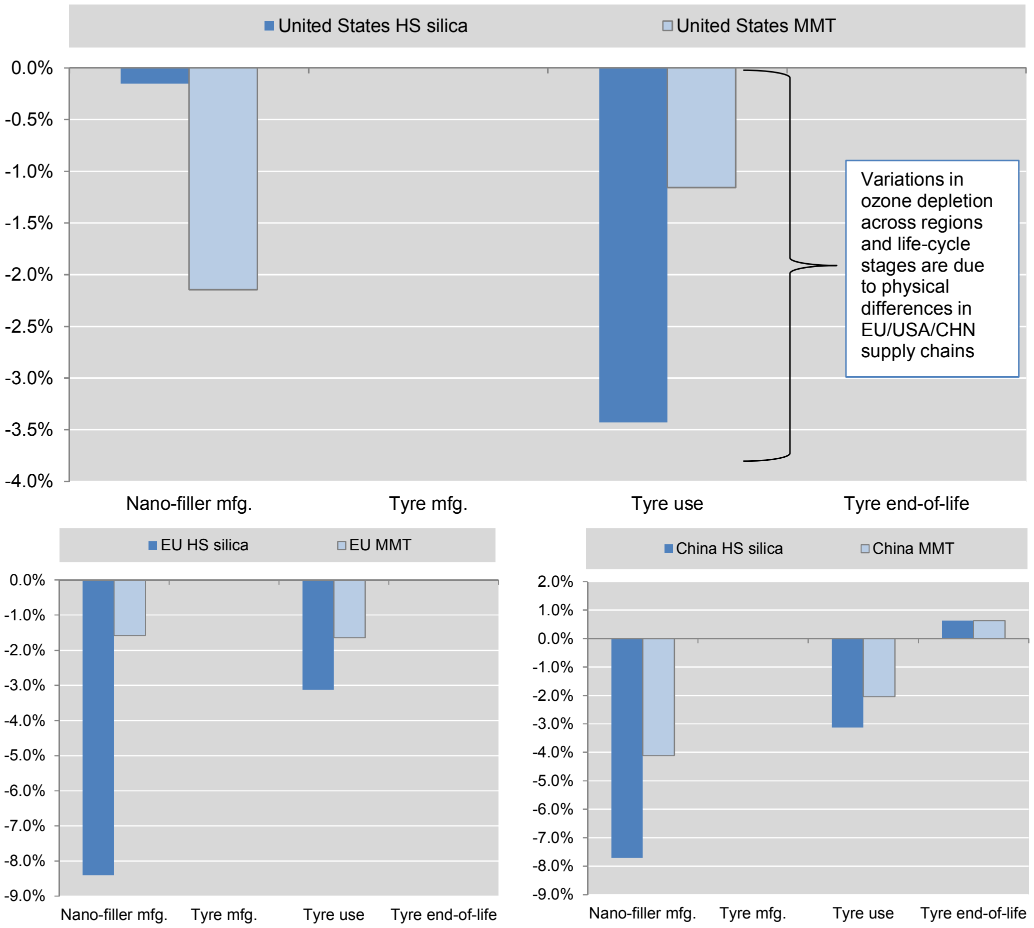
Stratospheric ozone depletion (ODP) is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substance (e.g. CFCs and halons). The ozone depletion impact category characterises the potential to destroy ozone based on a chemical's reactivity and lifetime. Destruction of the ozone can lead to increasing levels of ultraviolet-B (UVB) radiation that reach the earth's surface. Damage related to increasing levels of UVB radiation includes skin cancer, cataracts, material damage, immune system suppression, crop damage and other plant and animal effects. Ozone depletion impacts associated with bromo-trifluoromethane (Halon 1301) and bromo-chlorodifluoromethane (Halon 1211) emissions from crude oil production were removed from this analysis, because the data sets used to model corresponding processes in the United States LCI data do not include similar emissions. The European data sets also reported ozone depletion impacts for Russian natural gas pipeline transport. These impacts were not deleted, as they reflect a difference in the supply chain for European and US natural gas. The results for the ODP are expressed in units of CFC-11 (trichlorofluoremethane) equivalents per tyre for 10 000 km of travel in the specified region. Figure 4.6 shows that the use stage dominates the ODP among the tyre life-cycle stages; however, the significance of discrepancy between the ODP impacts among stages varies across regions due to physical differences in the regional supply chains, as seen in Figure 4.7.

Figure 4.6. **Ozone depletion results by life-cycle stage for tyre scenarios**



Variations in ozone depletion across regions are due to physical differences in EU/USA/CHN supply chains

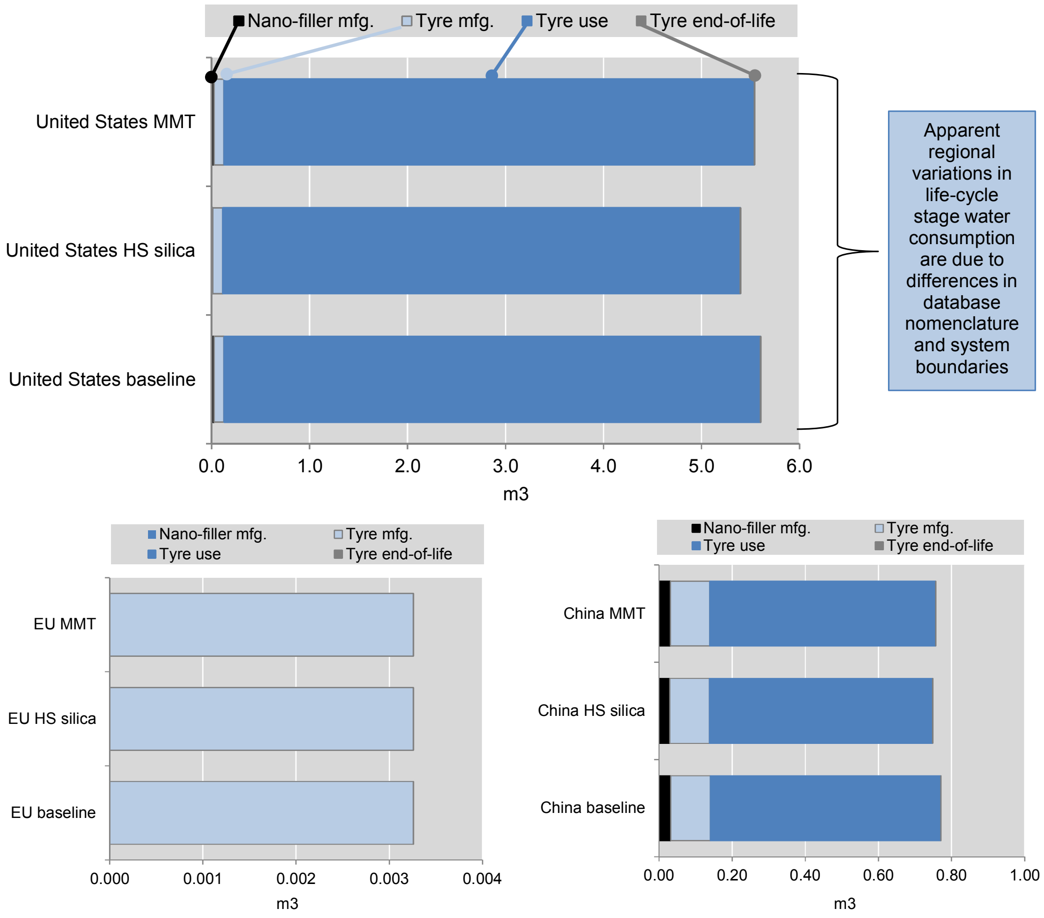
Figure 4.7. **Ozone depletion impacts of nano-enabled tyres as a percent of baseline tyres**



Water consumption

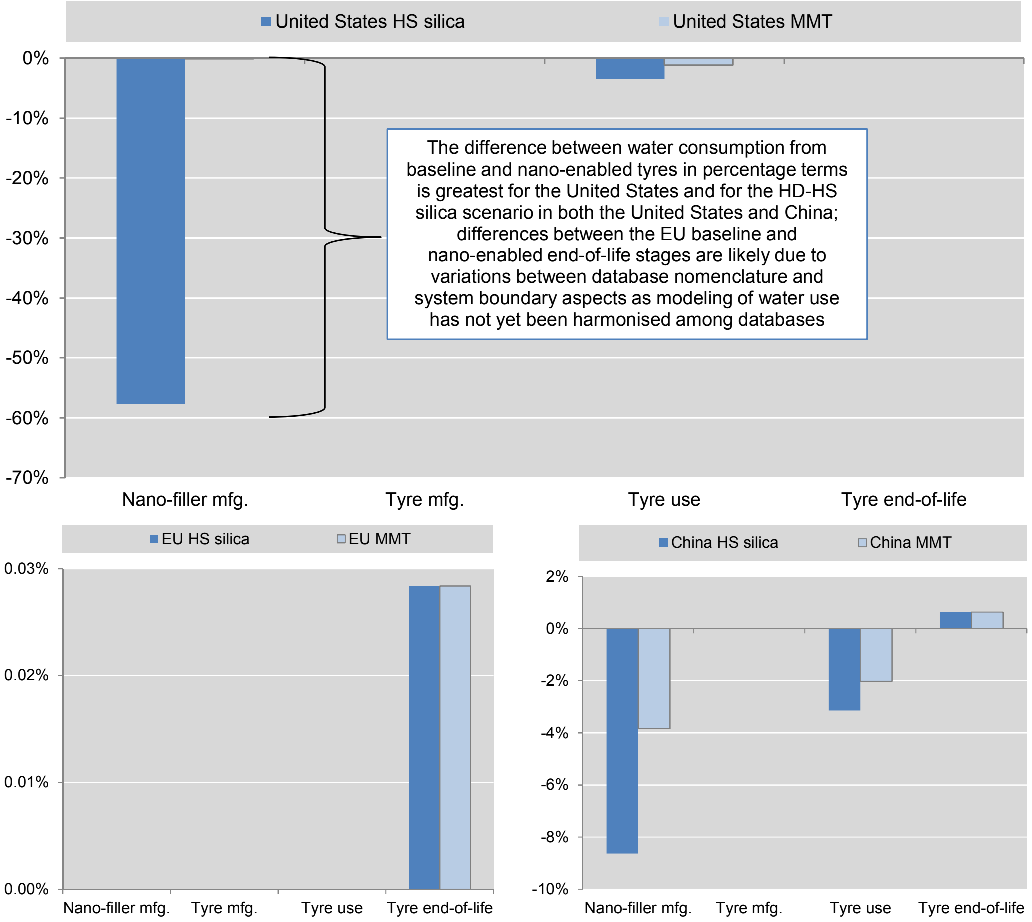
When water is withdrawn from one water source and returned to another source, it is considered as consumption, as there is a net removal (depletion) of water from the original water source. Consumption also includes water that is withdrawn and evaporated or incorporated into the product. Water consumption is only included as an inventory category in this study, and does not attempt to assess water-related damage factors. For instance, there is no differentiation between water consumption that occurs in water-scarce and water-abundant regions of the world. Water results are displayed on a consumptive basis of cubic metres (m^3) of water volume per tyre for 10 000 km of travel in the specified region. Figure 4.8 shows that the use stage dominates water consumption among the tyre life-cycle stages in the United States and regions in China; however, differences between the European Union and other regional results are due to variations between database nomenclature and system boundary aspects. Due to these variations, there is an apparent discrepancy between differences in water consumption among stages in the United States and regions in China relative to the European Union region, as seen in Figure 4.9.

Figure 4.8. **Water consumption results by life-cycle stage for tyre scenarios**



Apparent regional variations in life-cycle stage water consumption are due to differences in database nomenclature and system boundaries

Figure 4.9. **Water consumption results for nano-enabled tyres as a percent of baseline tyres**



The difference between water consumption from baseline and nano-enabled tyres in percentage terms is greatest for the United States and for the HD-HS silica scenario in both the United States and China; differences between the EU baseline and nano-enabled end-of-life stages are likely due to variations between database nomenclature and system boundary aspects as modeling of water use has not yet been harmonised among databases

Acidifying potential

Acid rain leads to the acidification of soil and water, often causing serious harm to plant and animal life as well as damage to infrastructure. ReCiPe Midpoint (E) utilises base saturation (BS) as an indicator to express terrestrial acidity. The BS is defined as the sum of basic cations divided by the total cation exchange capacity (CEC) of a soil and is used to estimate the degree to which the adsorption complex of a soil is saturated with basic cations. Terrestrial acidification potential (AP) results are expressed on a normalised basis of kilogrammes of sulphur dioxide equivalents (SO_2 eq) per tyre for 10 000 km of travel in the specified region. Figure 4.10 shows that the use stage dominates the AP impacts among the tyre life-cycle stages; however, the discrepancy between the AP impacts among stages is most significant for the production of HD-HS silica filler material relative to baseline fillers, as seen in Figure 4.11.

Figure 4.10. **Acidification potential results by life-cycle stage for tyre scenarios**

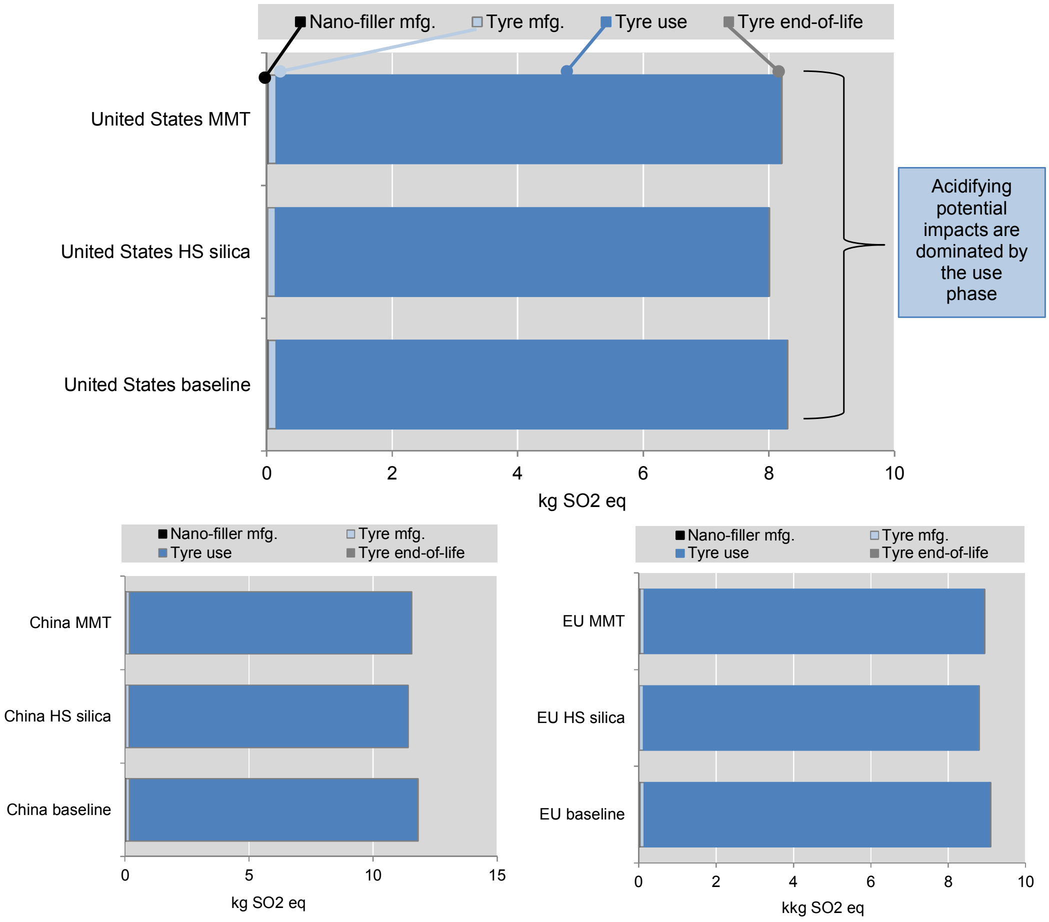
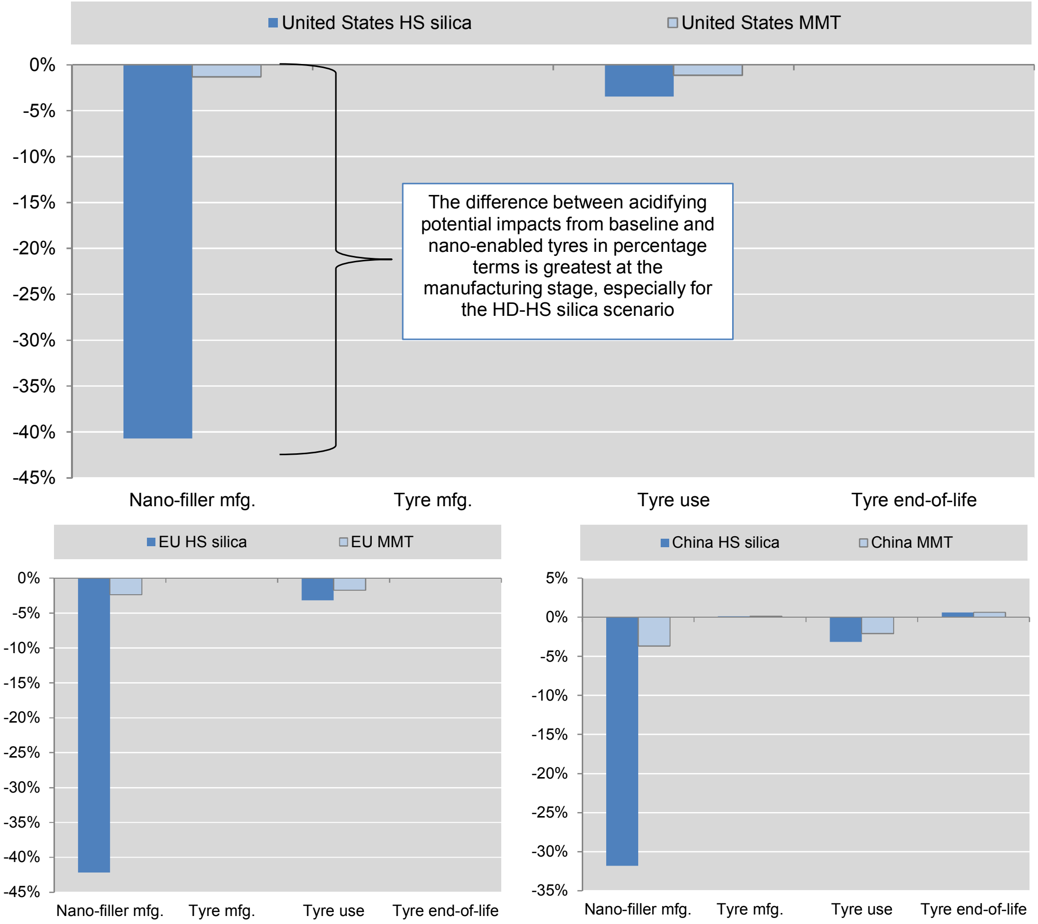


Figure 4.11. **Acidification potential impacts for nano-enabled tyres as a percent of baseline tyres**



The difference between acidifying potential impacts from baseline and nano-enabled tyres in percentage terms is greatest at the manufacturing stage, especially for the HD-HS silica scenario

Eutrophication potential

Eutrophication potential (EP) occurs when excess nutrients are introduced to surface water causing the rapid growth of aquatic plants. This growth (commonly referred to as an "algal bloom") reduces the amount of dissolved oxygen in the water, thus decreasing oxygen available for other aquatic species. Characterisation of aquatic eutrophication in LCIA factors typically accounts for nutrients that control the production of primary aquatic biomass (i.e. limiting nutrients). Algal blooms, for example, depend on the availability of phosphorous (P) and nitrogen (N). Local factors such as topography and the ecology of receiving water bodies determine whether nutrient loading leads to aquatic eutrophication. For the European Union and China geographic scope of this analysis, several inventory items contributing to eutrophication impacts were removed in order to align the system boundaries of the analysis with those used in the United States geographic scope. Specifically, eutrophication impacts associated with the disposal of spoil from coal and lignite mining to surface landfill, disposal of red mud from bauxite processing to residual landfill, and disposal of incineration residues to residual landfill were removed. North American data sets for the corresponding disposal processes did not include eutrophication impacts; therefore, this is considered a difference in the data sets rather than an actual difference in impacts. Freshwater eutrophication results are expressed in kilogrammes of phosphorous equivalents per tyre for 10 000 km of travel in the specified region. Figure 4.12 shows that the use stage dominates the EP impacts among the tyre life-cycle stages; however, the discrepancy between the EP impacts among stages is most significant for the production of HD-HS silica filler material relative to baseline fillers, as seen in Figure 4.13.

Figure 4.12. **Eutrophication potential results by life-cycle stage for tyre scenarios**

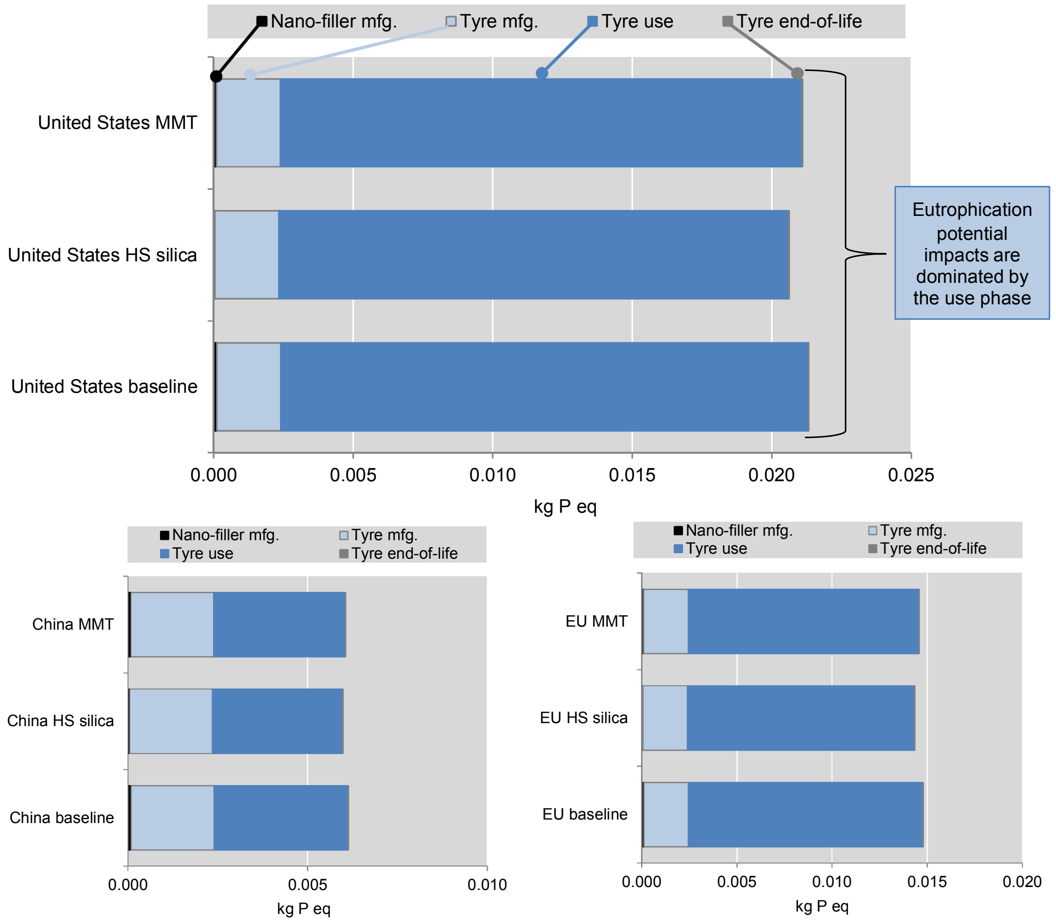
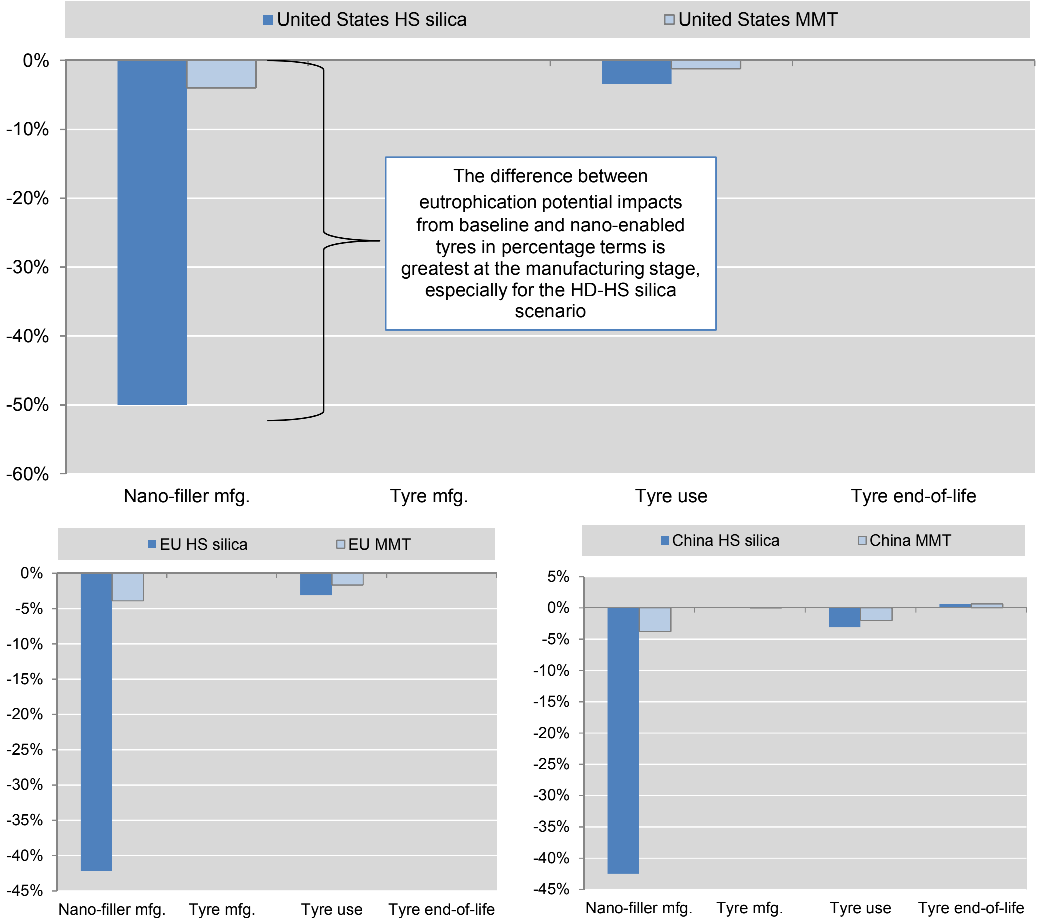


Figure 4.13. **Eutrophication potential impacts for nano-enabled tyres as a percent of baseline tyres**



The difference between eutrophication potential impacts from baseline and nano-enabled tyres in percentage terms is greatest at the manufacturing stage, especially for the HD-HS silica scenario

Photochemical smog potential

The photochemical smog impact category characterises the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation include increased human mortality, asthma and deleterious effects on plant growth. The results are expressed in kilogrammes of non-methane volatile organic carbons (NMVOC) equivalent per tyre for 10 000 km of travel in the specified region. Figure 4.14 shows that the use stage dominates smog impacts among the tyre life-cycle stages; however, the discrepancy between smog impacts among stages is most significant for the production of HD-HS silica filler material relative to baseline fillers, as seen in Figure 4.15.

Figure 4.14. **Photochemical ozone creation potential results by life-cycle stage for tyre scenarios**

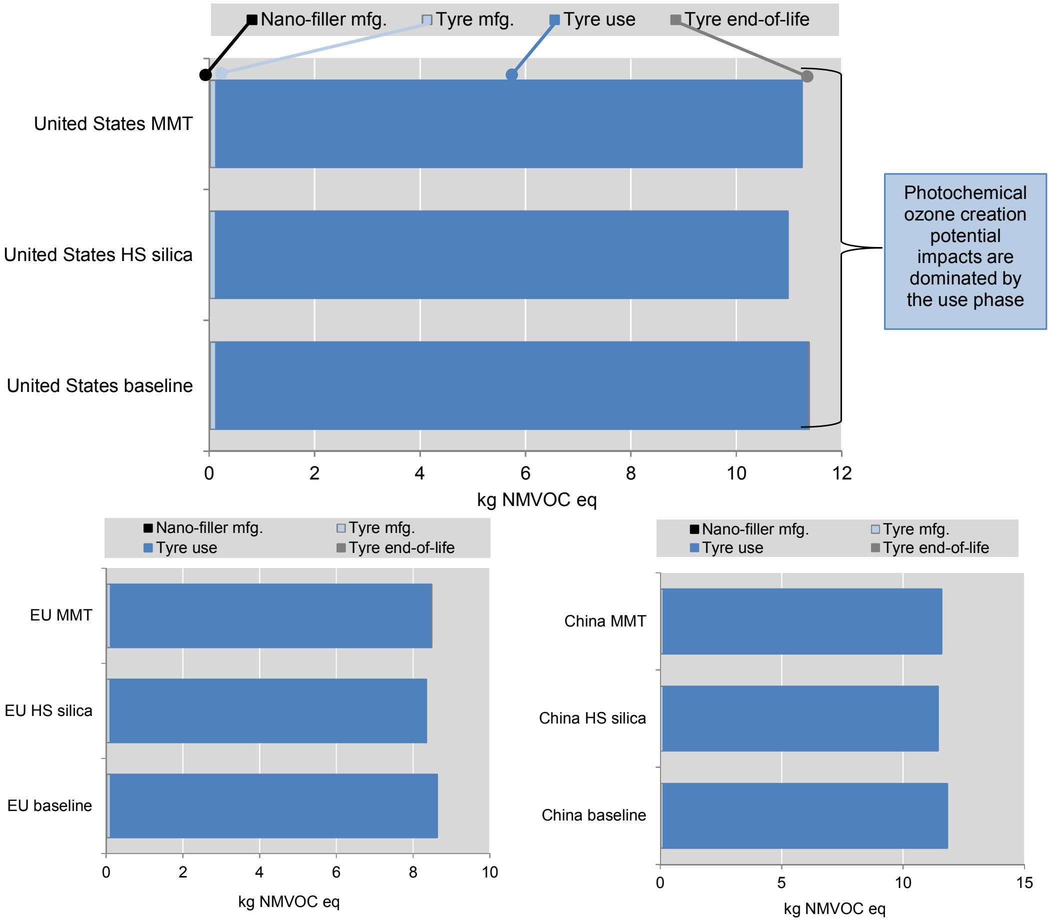
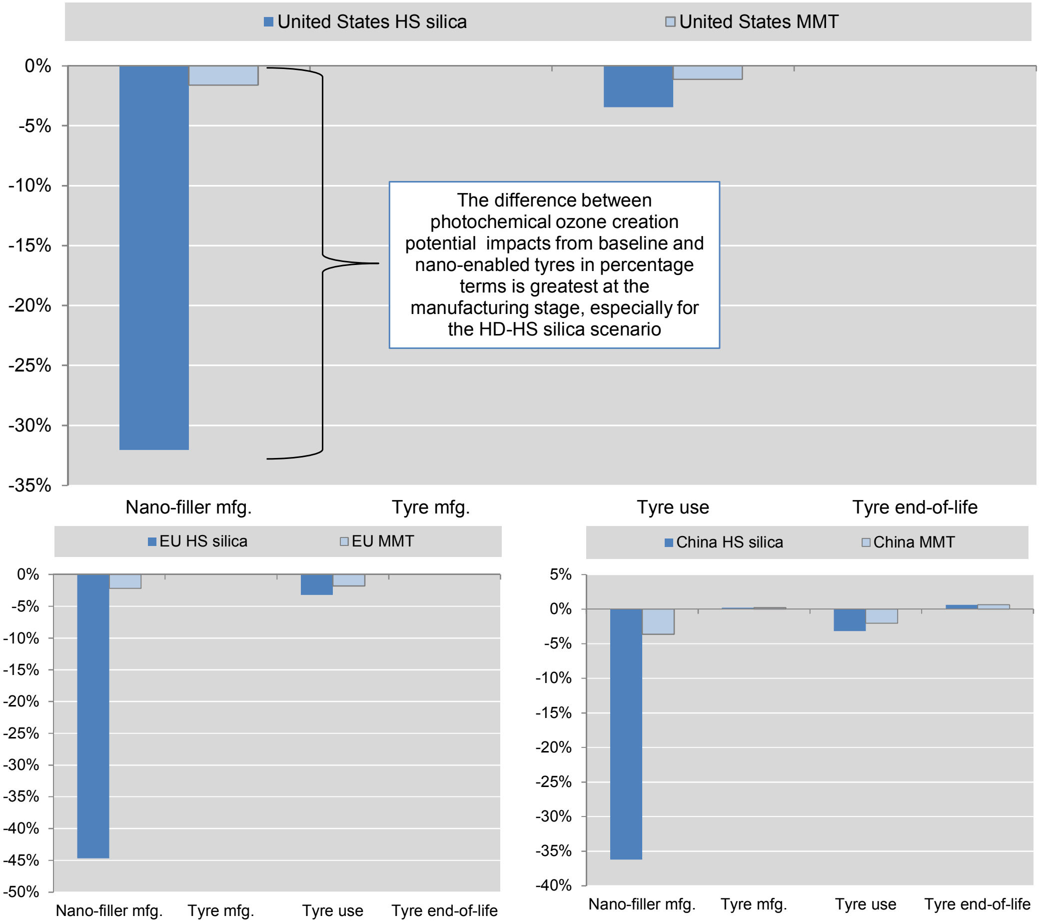


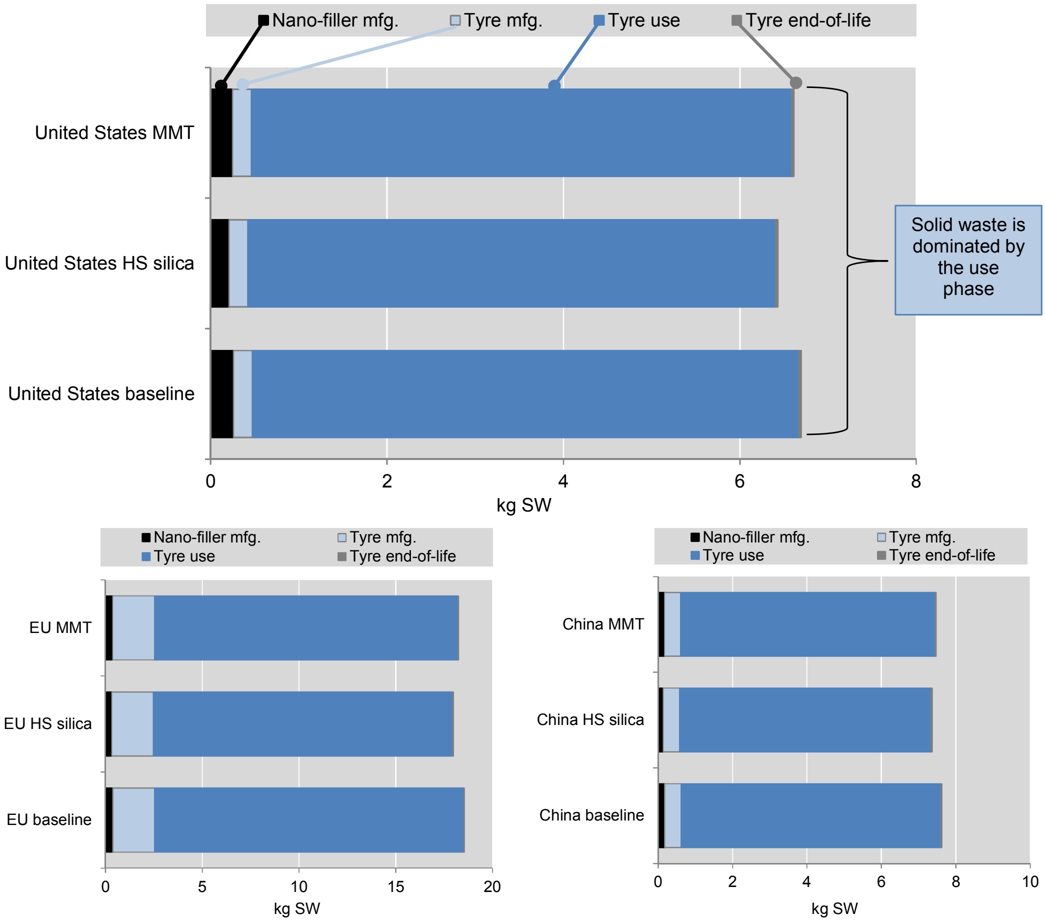
Figure 4.15. **Photochemical ozone creation potential impacts for nano-enabled tyres as a percent of baseline tyres**



Solid waste production

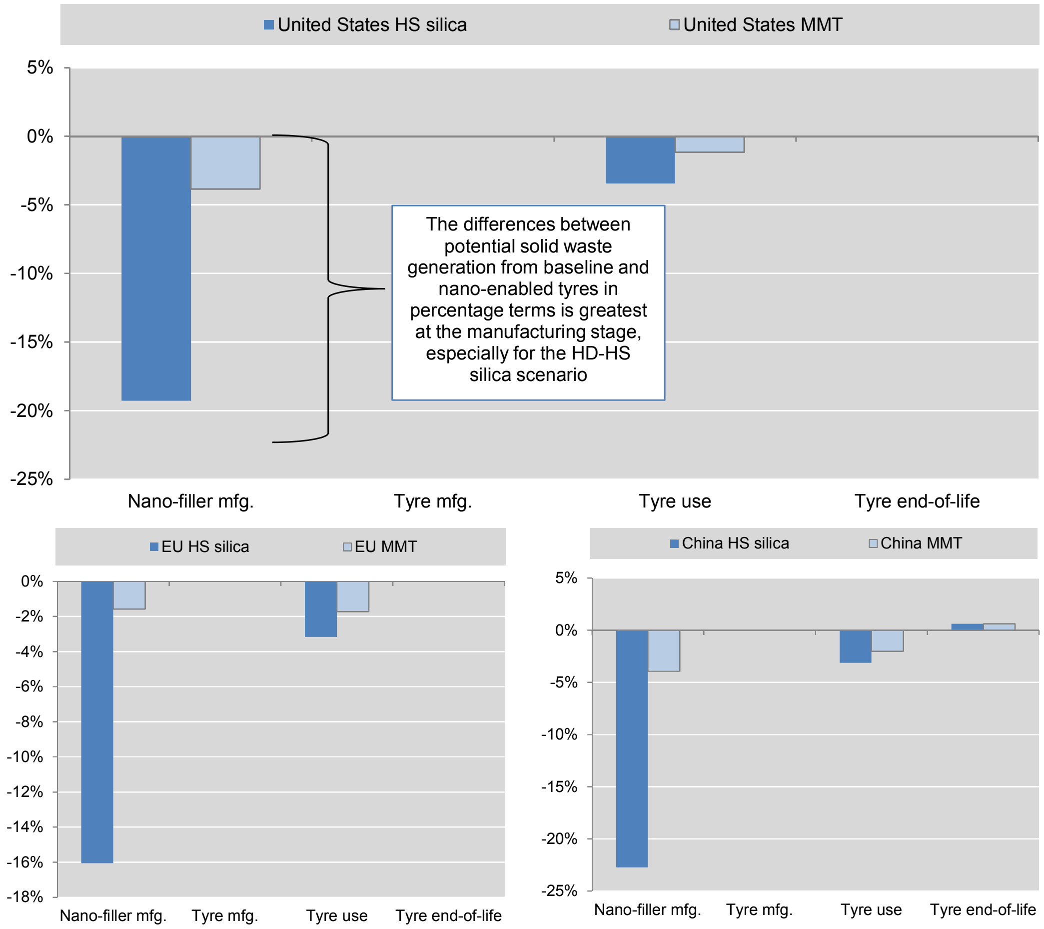
Solid waste impacts are a sum of all relevant solid waste inventory items including process and fuel-related wastes (together categorised as industrial solid waste) and post-consumer wastes (waste discarded by the end user of the product). Solid waste in this study is reported on a weight basis (as opposed to a volume basis). Solid waste results represent total waste flows to a specific fate (waste to landfill, waste to incineration and/or waste-to-energy combustion). For the European Union and China geographic scope of this analysis, several inventory items contributing to cumulative solid waste were removed in order to align the system boundaries of the analysis with those used in the United Sates geographic scope. Specifically, solid wastes for "spoil from lignite mining, in surface landfill" and "spoil from coal mining, in surface landfill" were removed. The wastes reported in the European data sets are very high and are likely to represent mining overburden (rock or soil removed in the process of accessing underlying coal). In the United States' coal mining data sets, overburden is returned to the extraction site, not a landfill. Therefore, the mining spoil is considered a difference in the way the United States and European data sets report wastes rather than an actual difference in processes. Figure 4.16 shows that the use stage dominates solid waste generation among the tyre life-cycle stages; however, the discrepancy between solid waste generation among stages is most significant for the production of HD-HS silica filler material relative to baseline fillers, as seen in Figure 4.17.

Figure 4.16. **Solid waste generation by life-cycle stage for tyre scenarios**



Solid waste is dominated by the use phase

Figure 4.17. **Solid waste generation impacts for nano-enabled tyres as a percent of baseline tyres**



The differences between potential solid waste generation from baseline and nano-enabled tyres in percentage terms is greatest at the manufacturing stage, especially for the HD-HS silica scenario

Concluding remarks

This chapter summarised the key differences between the life-cycle impacts of baseline and nano-enabled tyres for each geographic scope.

The goal of this chapter was to use the context of life-cycle assessment (LCA) to evaluate the differences in potential environmental impacts from three different vehicle tyre technologies: *i)* reference tyres (i.e. containing nanoscale carbon black and HD silica); *ii)* next generation, HD-HS silica nano-enabled tyres; and *iii)* nanoclay (montmorillonite) nano-enabled tyres. Environmental impacts were examined at the level of the associated differences quantified for each life-cycle stage. The potential nanoscale releases and environmental impacts were compared on the basis of travel of 10 000 km on the average market mix of highest selling vehicle replacement tyres for each tyre type in each investigated geographic region.

The reference composition, performance and production stage LCI data were compiled based on an LCA performed by the European Tyre and Rubber Manufacturers Association (ETRMA) and adapted to Chinese and US markets, considering differing average carbon-to-silica ratios, compounded rubber-to-steel ratios and average per tyre weights among the regions. Data from literature, existing databases and research were used to estimate and present a best-practices framework of the LCI of the production and incorporation of nanomaterials into nano-enabled tyres. Nanomaterial production, tyre production, tyre use and scrap tyre management were included for average tyres in each investigated region.

For each life-cycle stage, high-level assumptions on the environmental compartments to which potential nanoscale emissions are released have been made. Implications of nanoscale releases of the tyre fillers are discussed qualitatively in Chapter 5. Quantitative estimates for these potential releases are presented in Annex C. The ReCiPe Midpoint (E) methodology is employed to determine differences in life-cycle impacts of the three tyre types (i.e. conventional baseline and the two types of nano-enabled tyres) for each region.

In the figures of the results for impacts by life-cycle stage, it is clear that the use stage dominates impacts among the tyre life cycle. The only exceptions to this trend is for water consumption in the tyre life cycle in the European Union region, in which case, the results indicate that manufacturing of the tyres contributes most significantly to water consumption. This discrepancy is likely due to differences in nomenclature and system boundaries between the LCI databases. The discrepancy between impacts of life-cycle stages for baseline versus nano-enabled tyres is most significant for production of HD-HS silica filler material relative to production of baseline fillers. Exceptions to this trend are for water consumption in the European Union region, in which case, the largest discrepancy among impacts of life-cycle stages for baseline versus nano-enabled tyres is seen in the EOL stage. However, as mentioned, this discrepancy may not be physical and is more likely due to differences in the nomenclature and system boundaries between LCI databases. In contrast, the results for ODP in the United States region indicate the largest difference in impacts for baseline versus nano-enabled tyres is in the use stage. This discrepancy is due to physical differences in the fuel supply chains among United States and European/China regions. Besides impacts of nanoscale releases, which are discussed only qualitatively in Chapter 5, the results of the LCA framework generally indicate that fuel consumption in the tyre use phase dominates impacts across life-cycle stages and that there are potential savings in the use of nano-enabled tyres relative to conventional tyres because of lower rolling-resistance and/or longer tyre lifetimes. The framework results also indicate that the largest relative differences in impacts between baseline and nano-enabled tyres are potentially realised in the production stage of baseline versus HD-HS silica fillers.

Primary recommendations to improve the LCA framework for assessing the relative impacts of baseline and nano-enabled tyres include:

- Refining LCI data for the nanomaterial manufacturing step with primary data from producers (e.g. using data from quantitative evaluations based on testing or modelling).
- Refining LCI data for the tyre manufacturing step to better assess potential nanoscale releases (e.g. using data from quantitative evaluations based on testing or modelling).
- Refining of nanomaterial release rates and environmental compartmentalisation at use and EOL life-cycle stages (e.g. using data from quantitative evaluations based on testing or modelling).
- Application of impact assessment factors for nanoscale versus macroscale substance releases for each environmental compartment to determine potential environmental impacts of estimated nanomaterial releases.

NOTES

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[2]. Data provided by the Tyre Industry Project.

[3]. ETRMA, please see more information at: www.etrma.org › Tyres › End of Life Tyres; and US RMA Scrap Tyre Market Statistics (1990-2010) please see more information at: www.rma.org/scrap_tires.

[4]. Keller et al. (2013) draws from a very large body of previous experimental and modelling studies (although none specific to tyres); hence, generic high and low estimates for nanomaterial releases were used to estimate potential nanomaterial releases from tyres in this study.

[4]. Eco-Indicator 95 method was developed under the Dutch NOH programme by Pre consultants: www.pre.nl. The method indicates that dust and SO_2 are considered to contribute to winter smog. However, dust can refer to a broad range of microscopic particle types (e.g. biologicals, mineral matter, cellulose, synthetic fibers, glass fibers, paint chips, metallic minerals and soot, etc.) and includes carbon black per the LCIA factors in the software.

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CHAPTER 5

ENVIRONMENT, HEALTH AND SAFETY: DEVELOPMENT OF A RISK MANAGEMENT FRAMEWORK

This chapter attempts to develop a risk management framework for nanomaterial used as an additive in any nano-enabled tyre. It provides a first insight into a methodology for evaluating the potential human health and environmental concerns associated with the entire life cycle of nanomaterials used in tyres, focusing on tyre manufacturing operations. It gives examples of how to use this methodology using two new nanomaterials that have potential real-world application in nano-enabled tyres: high-dispersion, high surface area (HD-HS) silica and nanoclays.

Whilst the potential benefits of the development of new nanomaterials in tyres could be very significant on a global scale, there is a need to ensure that any nanomaterial used in tyres is safe for humans and the environment across the tyre life cycle and value chain. Even if more generic environment, health and safety (EHS) good practice guidance may serve as a good starting point for the tyre industry, there is a recognised gap, which was highlighted in the first chapters of this report, concerning the lack of sector-specific guidance for dealing with new nanomaterials in tyre production.

This chapter aims to develop a risk management framework for any nanomaterial used as an additive in any nano-enabled tyre. The chapter aims to:

- Provide industry stakeholders with a first insight into a method for evaluating the potential human health and environmental concerns associated with the entire life cycle of nanomaterials used in tyres, focusing on tyre manufacturing operations. This general methodology has been developed as guidance for stakeholders to minimise proactively potential concerns for any nanomaterial of interest that is under development or retroactively for any existing processes to identify and mitigate unreasonable risk.
- Provide examples of how to use this methodology using two case studies of new nanomaterials that have potential real-world application in nano-enabled tyres: high-dispersion, high-surface area (HD-HS) silica and nanoclays.

Introduction to the risk management framework

This framework provides guidance that can be used to develop site- or company-specific risk assessments or risk management strategies for using nanomaterials as additives in tyres. This framework follows the risk-based decision-making framework discussed in the OECD's "Important issues on risk assessment of manufactured nanomaterials" (OECD, 2012a). The OECD adapted its framework from the National Research Council's (NRC) *Science and Decisions: Advancing Risk Assessment* (NRC, 2009).

Guidance can change as research reveals new findings and experts reach consensus on methods and protocols. Therefore, this framework specifically includes steps for continual revision and improvement based on future site-specific and/or general evaluations that improve the state-of-the-science and knowledge pertaining to nanomaterial use.

Further, the framework focuses on a qualitative approach to assessing and managing risk in occupational settings called the risk/control banding approach. For non-occupational settings, the framework recommends an exposure pathway evaluation. The risk/control banding approach follows the guidance presented in the International Organization for Standardization (ISO) document "Nanotechnologies – Guidelines for Occupational Risk Management Applied to Engineered Nanomaterials – Part 2: The Use of the Control Banding Approach in Occupational Risk Management" (ISO, 2012).[1] In general, ISO (2012) provides guidelines that follow these steps:

1. assign a hazard band ranking based on quantitative toxicological data or qualitative health hazard indicators (which are based on toxicity data)
2. assign an exposure band based on a description of processes and physical forms of the nanomaterials.

For proactive risk assessments, the hazard band and exposure band rankings are fed into a control banding matrix. The control banding matrix provides guidance on the proper selection of control strategies to manage risk. For retroactive risk assessments, the hazard band and exposure band rankings are fed into a risk-banding matrix to provide a qualitative assessment of the risk of a given process.

The qualitative risk/control-banding approach of ISO/TS 12901-2 focuses on industrial settings. Therefore, the framework developed in this report expands beyond the risk/control-banding approach in order to cover all life-cycle stages. The general approach proposed is as follows:

1. use of the risk/control-banding approach to assess or manage human health risks due to nanomaterials in occupational settings, particularly the manufacture of nanomaterials and processing of these materials for the manufacture of tyres
2. evaluate the general population and ecological endpoint exposure pathways over all life-cycle stages to assess the potential risk nanomaterials pose to these endpoints.

A risk management approach (i.e. similar to the risk/control-banding approach) is not presented because a generally accepted approach does not currently exist. However, the exposure pathway evaluation guidance can be used to critically evaluate the exposure potential over the entire product life cycle. In the absence of toxicological data for these endpoints, and fate and transport data for the nanomaterial, it is suggested that conservative control methodologies that aim to entirely eliminate exposures be applied.

Although this framework focuses on qualitative risk/control-banding, it also addresses topics of a quantitative risk assessment. If adequate data are available, a quantitative risk assessment can be used to assess risk over the entire life cycle of the use of nanomaterials in tyres. However, this framework is not intended to provide guidance on quantitative risk assessments. Risk-assessor expertise should be sought if a quantitative risk assessment is desired.

As with other recently published guidance, this framework presents the steps to perform a risk assessment following three phases (OECD, 2012a):

1. Phase I – Problem formulation and scoping
2. Phase II – Planning and conducting the risk assessment
3. Phase III – Risk management.

Figure 5.1 illustrates the organisation and flow of this framework.

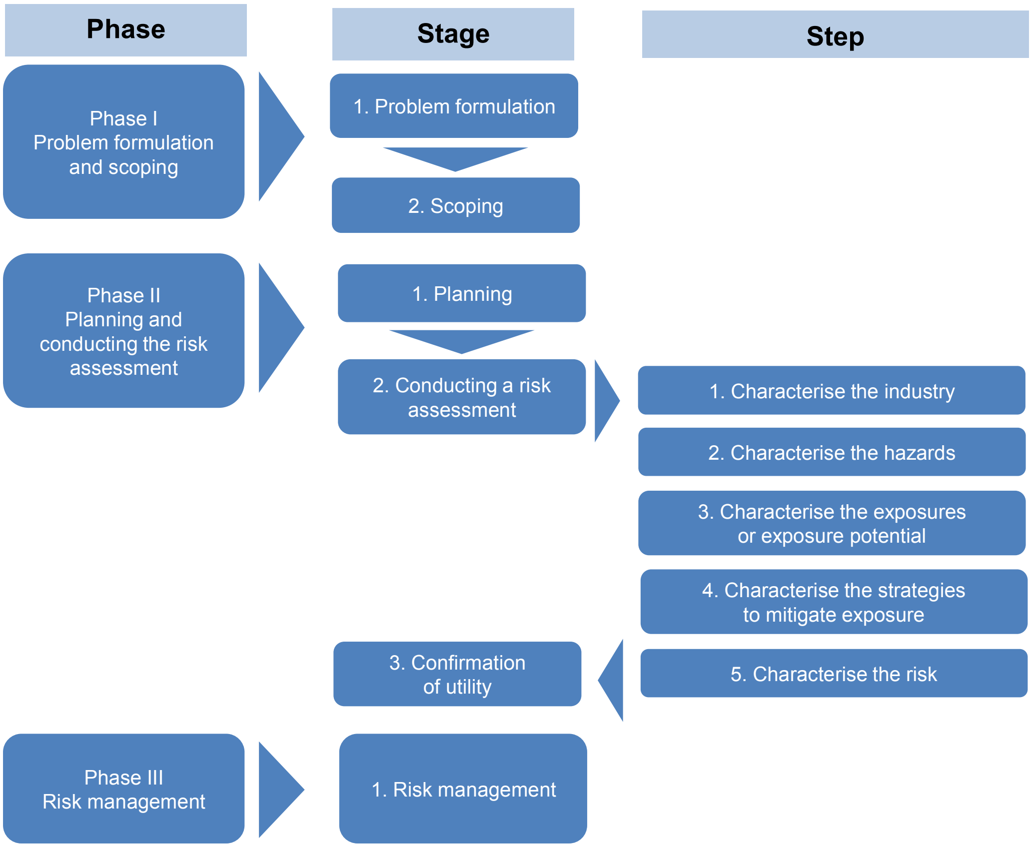
Phase I – Problem formulation and scoping

Problem formulation

Problem formulation should begin by considering the following questions:

1. Who is potentially at risk?
2. What are they at risk from?
3. Will this be a retroactive risk assessment or a proactive risk management strategy?
4. What risk assessment output types are desired?

Figure 5.1. **Organisation and flow of this risk management framework**



This risk management framework is specific to the use of nanomaterials in tyres. Therefore, this framework answers the first two questions above:

1. Question: Who is potentially at risk?
    - workers who manufacture the nanomaterial of interest
    - workers who mount, repair and/or balance nano-enabled tyres on vehicles
    - workers involved with nano-enabled tyre recycling and/or disposal
    - consumers who mount nano-enabled tyres on vehicles
    - the general population
    - key ecological endpoints.
2. Question: What are they at risk from?
    - Hazards associated with nanomaterials used in tyres.

The remaining two questions (questions 3 and 4) are left to the user of this framework to answer. The user should decide if this framework will be used to conduct a retroactive risk assessment for an existing facility or operation or, alternatively, to develop a proactive risk management strategy.

The user should also decide what risk assessment outputs are desired. For example, are quantitative results desired? If quantitative results are desired, will they be deterministic or probabilistic? Deterministic risk assessments provide a single point estimate of risk at a site of concern, while probabilistic risk assessment methods generate a range of values from probability distribution functions. Alternatively, is a qualitative risk-banding approach desired?

Problem scoping

The proposed risk management framework is specific to the following scope: the life cycle of a nanomaterial of interest used in tyres. For the purposes of this framework, the scope includes:

- manufacture of the nanomaterial being evaluated
- manufacture of tyres containing the nanomaterial
- use of the nano-enabled tyres
- end-of-life of the nano-enabled tyres.

The reader is referred to Chapter 4 for a detailed discussion of the life cycle along with guidance for completing a life-cycle assessment.

Phase II – Planning and conducting the risk assessment

Phase II consists of planning and then conducting the risk assessment. This phase is divided into three stages:

- Stage 1 – Planning for the risk assessment
- Stage 2 – Conducting the risk assessment
- Stage 3 – Confirmation of the utility of the risk assessment.

Although these stages are presented in a linear fashion, risk assessments should allow for refinement and continual improvement. Stage 3 – Confirmation of the utility of the risk assessment – should be performed to evaluate whether the risk assessment results meet the requirements set forth during Phase I – Problem formulation and scoping. Uncertainty associated with the risk assessment results should be characterised, and judgment should be used to determine if the results can be meaningfully interpreted for the purposes of risk management and decision making given the uncertainties. If the risk assessment results do not meet the goals set forth during Phase I, or are not adequate for risk management or decision making, then Phase II, Stage 1 should be revisited to design a new approach for the risk assessment. Additionally, the planning stage should be revisited if new data or techniques become available that will enhance and improve the risk assessment. Allowing feedback loops for continual improvement is particularly important for nanomaterials, since information regarding toxicity, fate and transport, and exposures is limited and significant research to increase the general scientific knowledge base is ongoing.

Phase II, Stage 1 – Planning for the risk assessment

Planning for the risk assessment should begin by answering the following questions.

- What data are needed?
- What data are available?

Data needs

The following information is important when conducting a risk assessment of a nanomaterial:

- characterisation and physical/chemical properties data
- toxicological data
- exposure data and information.

Each of these points is explained further below.

Characterisation and physical/chemical properties data

Because of their unique properties (even compared to their macro-scale counterparts), an adequate set of specific data is required to identify and characterise the nanomaterials. This includes data that characterises the different materials both at the macro- and nano-scale. For example, not all types of silica are equivalent. One may need to specify, as a minimum, the morphology (amorphous or crystalline); production method (precipitation or pyrogenic); particle size distribution; aggregation and agglomeration characteristics (e.g. sizes of primary particles, aggregates and agglomerates); and specific surface area to be able to distinguish between different types of silica. Properties of importance include, but are not necessarily limited to, the following:

- Data to identify the nanomaterial:
  - nanomaterial name
  - CAS number
  - structural formula and molecular structure
  - composition of nanomaterial
  - basic morphology
  - description of surface chemistry
  - method of production.
- Physical and chemical characteristics of the nanomaterial:
  - melting point
  - relative density
  - flammability
  - solubility (in water or other biologically relevant fluids)
  - dispersibility (in water or other biologically relevant fluids)
  - other relevant dispersibility data (e.g. zeta potential, isoelectric point)
  - partition coefficient (n-octanol/water)
  - physical state at standard conditions
  - crystalline phase
  - crystallite size
  - dustiness
  - representative transmission electron microscopy (TEM) images
  - aggregation and agglomeration potential
  - particle size distribution

  - specific surface area
  - surface chemistry
  - catalytic or photocatalytic activity
  - pour density
  - porosity
  - reduction/oxidation potential
  - radical formation potential.

Toxicological data

The following types of toxicological data should ideally be collected for the risk assessment:

- pharmacokinetics (absorption, distribution, metabolism, elimination)
- acute toxicity
- repeated dose toxicity
- chronic toxicity
- reproductive toxicity
- developmental toxicity
- genetic toxicity
- dose-response data
- experience with human exposure
- epidemiological data
- environmental fate and transport data
- environmental persistence data
- bioaccumulation data.

Exposure data and information

The following data elements should ideally be collected for each life-cycle stage to characterise exposure for the risk assessment.

- physical form of the nanomaterial
- amount of nanomaterial handled or processed
- description of how the nanomaterial is handled or processed
- duration (time per day) and frequency (occurrences per year) workers or members of the general population are potentially exposed to nanomaterials
- determination of the potential for dust generation during the processes and worker activities
- description of worker activities

- actual exposure measurement data
- identification of potential release sources
- amount of nanomaterial released into the environment (per event or period such as per day or per year, and the frequency of release events such as per year).

Data availability

The planning stage should also include a step to identify and obtain all potentially applicable data for use in the risk assessment (including a literature search). It is recommended that search criteria and results be documented for future reference and refinement of the evaluation. After obtaining the data, planning should also include a data gap analysis to determine what data needs remain. Then, planning should include the development of approaches to satisfy the identified data gaps. Consider the following questions:

- Will testing be performed to satisfy data gaps (e.g. physical or chemical testing, toxicity testing, exposure monitoring)?
- In lieu of data for the nanomaterial being evaluated, is it appropriate to use surrogate data? Are surrogate data available? How will the surrogate data be used? What are the uncertainties associated with use of the surrogate data? For example, will the risk assessment use toxicity or exposure data of the bulk (macro-scale) version of the nanomaterial? Will the risk assessment use toxicity or exposure data of a similar nanomaterial? If surrogate data are used, how will they be evaluated to determine their appropriateness for the nanomaterial of interest?
- In lieu of data for this nanomaterial, is it appropriate to use extrapolation or modelling techniques to characterise hazards or exposures?
- How will the risk assessment results be evaluated to account for uncertainties introduced by the use of surrogate data or extrapolation or modelling techniques?

Phase II, Stage 2 – Conducting the risk assessment

A risk assessment typically follows five key steps:

- Step 1 – Characterise the industry
- Step 2 – Characterise the hazards
- Step 3 – Characterise the exposures or exposure potential
- Step 4 – Characterise the strategies or techniques to mitigate exposure
- Step 5 – Characterise the risk.

Phase II, Stage 2, Step 1 – Characterise the industry

The first step is to characterise the industry within the scope of the risk assessment. The industry characterisation is important to help understand the processes, equipment and worker activities involved in the industry. This information is used to identify potential sources of exposure and environmental releases as well as work practices, engineering controls and personal protective equipment (PPE) that may mitigate or minimise exposures and releases.

The scope of this effort is the entire life cycle of a nanomaterial used in tyres. Therefore, industry characterisation includes all life-cycle stages. This section begins with a detailed characterisation of the tyre industry, which comprises process descriptions and potential sources of releases and exposures. Since this framework is applicable to any nanomaterial for use in tyres, guidance is presented for the user of this framework to characterise the manufacturing industry of a nanomaterial of interest once selected by the user.

For the purposes of this framework, the tyre industry is defined as the manufacture of tyres, mounting tyres on vehicles, the use of tyres on vehicles and the end-of-life of tyres. Information presented here on the characterisation of the tyre industry, particularly tyre manufacturing, was obtained from multiple interviews with industry stakeholders and a site visit to a US tyre manufacturing plant.

Tyre manufacturing

Tyre manufacturers receive raw materials from suppliers, typically in bulk containers. Raw materials include: elastomers (natural or synthetic rubber); fillers (including silica, carbon black and nanomaterials such as next generation HD-HS silica and nanoclays); plasticisers (e.g. oil); and chemical additives (e.g. vulcanisers, accelerators and antioxidants). Silica and carbon black can be transported via rail car or tank truck. Solid chemical additives can be transported in one-tonne flexible intermediate bulk containers (FIBCs).

Silica and carbon black are typically unloaded into silos prior to blending. Transfer of silica can include pneumatic transfer in pressurised piping. Transfer of carbon black can also include pneumatic transfer, as well as mechanical conveyer systems. From the silos, silica and carbon black are blown through lines into a high-temperature mixer, such as a Banbury mixer. Elastomers are added to the mixer as shredded rubber blocks. Chemical additives (except for vulcanisers and accelerators) are also added to the mixer.

From the high-temperature mixer, the compounded rubber masterbatch is rolled into sheets to cool and then added to a low-temperature mixer for further milling. Here, rubber blocks containing vulcanisers and accelerators are added. The milled, final rubber mix is rolled, flattened, coated with an anti-stick solution, dried and folded for tyre fabrication.

Each ply, or layer, is made and reinforcements (such as textiles and metals) are added. The tyre is then built and cured (vulcanised).

Worker exposure to nanomaterials will depend on the manner in which the nanomaterials are handled. For example, industry stakeholders indicate next generation HD-HS silica would replace currently used silica, essentially as a drop-in replacement using the same process steps. Therefore, exposures associated with handling a solid powder in bulk can be expected. Workers can be exposed to HD-HS silica when connecting and disconnecting transfer lines for unloading the silica from rail cars or tank trucks. If the silica is transported via pressurised, pneumatic lines, then workers could also be exposed to dusts and spills generated from leaks in the transfer lines. Workers can further be exposed to silica dusts in the air that are not captured by a ventilation system.

Other nanomaterial additives may be needed in smaller amounts (and/or for other purposes). Therefore, their processing may be similar to other solid chemical additives currently used in tyres. For example, if nanoclay is to be used at a small loading per tyre, then it may be shipped in one-tonne FIBCs. If the nanoclay is poured directly into the Banbury mixer by a worker, inhalation exposure to dusts can be expected. There is also the potential for inhalation and contact exposure if small manual blending operations are conducted and controls must be carefully evaluated for this work. Worker exposures in these situations could be minimised by using an automated filling system to use the FIBCs to load smaller (such as 25 kg size) plastic bags with the proper quantity of nanoclay as well as each chemical additive. A hopper and mechanical conveyer system could be used to load each bag. The plastic bag can be sealed and then dumped directly into the Banbury mixer without requiring workers to open the bag. In such a system, workers can be exposed to nanoclay dusts generated from the mechanical conveyer at the point in which it dumps the nanoclay into the plastic bag. Local exhaust ventilation can be used to capture generated dusts.

Another potential method for processing smaller quantity nanomaterials that was identified is the lab-scale formulation of nanomaterials into the rubber blocks that are added to the low-temperature mixer. Here, exposures to nanomaterials can be further minimised through the use of laboratory controls such as chemical fume hoods.

Once the nanomaterials are blended with the elastomers, inhalation and dermal exposures are expected to be less likely because the nanomaterials are bound within a polymer matrix. Once the tyre is built and vulcanised, nanomaterials are not expected to migrate from (or diffuse out of) the polymer matrix because of its cross-linked chemical structure.

Nanomaterial additives can be released to the environment from these industrial operations due to the disposal of nanomaterial-containing wastes. These wastes can be generated from cleaning rail cars or tank trucks, pipes/hoses and process vessels; cleaning spills; disposing scrap blended rubber; disposing spent FIBCs; and disposing filter bags and collected blow-down dust from dust collectors. Nanomaterial particulates can also be released to the environment from fugitive dusts generated inside the plant, captured by local or general ventilation, and released to ambient air through a stack due to filter bag or other removal inefficiencies. Accidental spills or releases at tank truck or rail car unloading stations can also be sources of the release of nanomaterials directly into the environment if unloading occurs outdoors.

The site-specific potential for worker exposures and environmental releases from these sources should be considered during the exposure pathway evaluation as discussed in Phase II, Stage 2, Step 3 of this framework. The mitigation strategies to reduce worker exposures and environmental releases should be considered as discussed in Phase II, Stage 2, Step 4.

Mounting tyres on vehicles

Tyres are mounted onto vehicles by workers (at original equipment manufacturers [OEMs] and mechanic shops) and by consumers in do-it-yourself (DIY) applications. Exposures and releases are less likely during these operations as the nanomaterials are bound within a cross-linked polymer matrix.

Use of tyres on vehicles

Tyres are used during the driving of automobiles and trucks. Nanomaterials could potentially be released to the environment from rubber particles wearing off or from blowouts. According to BLIC (2001), car tyres in Europe were observed to lose 10-20% of their weight by wear during use, due to abrasion from friction.

Chapter 4 includes more detailed data on tyre wear, which are reproduced in Table 5.1. These data represent the mass of tread loss per 40 000 km travelled per tyre for each of the reference passenger tyres studied in the life-cycle assessment of Chapter 4. Table 5.1 also summarises the market-weighted average life span for each reference tyre. The tread loss and life-span data can be used together to estimate the mass of tyre lost over its life span. Combined with data on the content of nanomaterials in a tyre, the user can calculate the release of rubber containing nanomaterials.

These mechanisms release vulcanised rubber containing nanomaterials. The subsequent release of nanomaterials from the rubber would depend on the properties of the nanomaterial and the degradation potential of the rubber in the environment.

Table 5.1. **Passenger tyre tread loss and life span for the reference tyres studied in the life-cycle analysis***

Reference passenger tyres from the life-cycle analysis*	Tread loss (kg per 40 000 km traveled)			Market-weighted average tyre life-span (km)		
	United States	Europe	China	United States	Europe	China
Baseline tyres	0.88	1.21	0.75	61 667	38 333	56 000
High dispersion silica-enabled tyres	0.73	1.01	0.62	74 006	46 169	67 446
MMT enabled tyres	0.86	1.18	0.72	62 906	39 483	57 977

Note: * See Chapter 4.

End-of-life of tyres

A tyre at its end-of-life is referred to as an end-of-life tyre (ELT). ELTs are recovered for reuse, material or energy recovery, or disposal. Material recovery includes using whole or shredded tyres in a variety of civil engineering projects such as embankments, backfill for walls, road insulation, field drains, erosion control/rainwater runoff barriers, wetlands and marsh establishment, crash barriers and jetty bumpers. ELTs can also be converted into ground or crumb rubber that can then be used for rubber-modified asphalt (resulting in reduced traffic noise), running tracks, sports fields, ground cover under playgrounds, molded rubber products and mulch in landscape applications. Ground rubber is produced either by ambient grinding or cryogenic (freeze) grinding, the latter producing finer particles by using liquid nitrogen to cool the tyres before processing (WBCSD, 2008). Energy recovery of tyres is the use of tyre-derived fuel (TDF) in applications such as cement kilns, thermal power stations, pulp and paper mills, steel mills and industrial boilers (WBCSD, 2008).

The percentage of tyres sent to each disposition varies among the major global tyre markets. Table 5.2 summarises the disposition of tyres in the major global markets: China, Europe and the United States (also see discussion in Chapter 4). The end-of-life evaluation includes landfilling and incineration, material recycling, energy recovery, re-treading, and reuse and export.

Potential exposures and releases vary depending on the disposition method. Re-treading, reuse and material recycling scenarios can lead to potential exposures to workers who handle the tyres. Releases can result from scrap rubber generated from the re-treading and material recycling process. Workers who handle tyres in transit to landfilling, incineration and energy recovery scenarios are less likely to be exposed because the nanomaterials are bound within a cross-linked polymer matrix. However, releases of nanomaterials are anticipated during these scenarios. Releases from landfilled tyres could result from the rubber, depending on the properties of the nanomaterial that may allow migration over time, and the degradation potential of the rubber itself in the landfill. Releases of nanomaterials are also anticipated from incineration and energy recovery. The incineration process completely combusts the rubber, potentially releasing nanomaterials even from cross-linked rubber. Releases of the nanomaterial will depend on the chemistry of the nanomaterial in the combustion chamber and the air pollution control technologies used by the incinerator or energy recovery system.

Table 5.2. **Disposition of tyres at their end-of-life for major global markets**

Region	Total volume		% of tyres for each end-of-life disposition method					Source
	Millions of tonnes	Millions of end-of-life tyres	Landfilling	Material recycling	Energy recovery	Re-treading	Reuse and export	
United States	4.60	184	15%	34%	40%	7.2%	3.0%	US Environmental Protection Agency MSW (2012)
Europe	3.30	132	4.0%	40%	38%	8.0%	10%	European Tyre and Rubber Manufacturers Association (2012)
China	5.00	200	83%	10%	0%	6.8%	0%	WBCSD (2012); Yang (2010)

This framework is applicable to any nanomaterial for use in tyres. Therefore, a characterisation of the nanomaterial manufacturing industry is not presented herein since the processes can vary greatly from one nanomaterial to another. Instead, the user of this framework should characterise the manufacture of the nanomaterial of interest once one has been selected for risk assessment and management. The following data elements should be included:

- process description
- identification of sources of occupational exposures to nanomaterials (note: exposure pathways are discussed in more detail under Phase II, Stage 2, Step 3)
- identification of sources of nanomaterial releases to the environment
- practices and technologies used to mitigate exposures and releases.

Phase II, Stage 2, Step 2 – Characterise the hazards

During the planning stage (Phase II, Stage 1), the user of this framework should have determined if toxicological data will be collected from the literature, obtained through toxicity testing or both. Whether reviewing toxicology studies in the literature or planning and conducting toxicity testing, the user should pay attention to key issues that affect the applicability and characterisation of test results:

- sample preparation
- dosing
- physical/chemical characterisation
- nanomaterial identification (CAS#)
- composition of nanomaterial being tested
- basic morphology
- method of production
- epidemiological data, if available.

The OECD's "Guidance on sample preparation and dosimetry for the safety testing of manufactured nanomaterials" (OECD, 2012b) can be referenced for preliminary guidance on sample preparation and dosimetry during toxicity testing. An important aspect of dosimetry to which the user should pay attention is dose metrics. Toxicity tests of non-nanomaterials use mass-based metrics to describe dose-response relationships. However, mass-based metrics alone may not be sufficient for nanomaterials – additional metrics, such as number of particles or particle surface area, may need to be considered. Another important consideration of toxicity testing is the use of models developed for non-nanomaterials. For example, models can be used for interspecies extrapolation of toxic effects (e.g. extrapolating the toxic effects on rats to humans) and for predicting bioaccumulation from partition coefficients. Careful consideration should be given prior to applying such models to nanomaterials, and their use should be accompanied with adequate discussion of the limitations or uncertainties of the results.

Please note that guidance may change as additional research reveals new findings and as experts reach consensus on methods and protocols. For example, new occupational exposure limits may be determined and published as toxicological properties of nanomaterials become better understood.

The following subsection of this framework provides a summary of recommendations utilising the hazard banding approach as discussed in ISO (2012). This approach can use either quantitative toxicological data or qualitative health hazard indicators to assign the hazard band ranking.

Human health

The planning stage of the risk assessment (Phase II, Stage 1) identifies the categories of toxicological data needed for the risk assessment. These toxicological data can be used to describe the following human health hazard indicators as identified in ISO (2012):

- acute toxicity (Acute Tox.)
- skin irritation/corrosion (Skin Irrit./Skin Corr.)
- serious eye damage/eye irritation (Eye Dam./Eye Irrit.)
- respiratory or skin sensitisation (Resp. or Skin Sens.)
- mutations in germ cells (Muta.)
- cancer (Carc.)
- reproductive toxicity (Repr.)
- experience with human exposure
- epidemiological data
- Systemic Target Organ Toxicity – Single Exposure (STOT-SE)
- Systemic Target Organ Toxicity – Repeated Exposure (STOT-RE)
- aspiration hazard (Asp. Tox.).

The toxicological data and hazard indicators can be used to assign a human health hazard category to the nanomaterial of interest. Table 5.3 displays the human health hazard category allocation criteria for use in the control banding approach.

Ecotoxicity

Currently, ISO (2012) does not incorporate ecotoxicity into the control banding approach. The control banding approach is only meant for addressing human health concerns in occupational settings. However, some of the human toxicological data elements are also applicable for ecotoxicity (e.g. acute (LD50) and chronic toxicity data for terrestrial organisms, LC50 data for aquatic organisms). Ecotoxicity studies typically require fate, transport and bioaccumulation data to provide a complete picture of ecological effects. Toxic effects on single species should be evaluated in the context of entire community and ecosystem effects. For example, if a nanomaterial is toxic to a prey terrestrial organism and causes a decline in its population, this effect can cause a decline in a predator population by reducing the predators' food source.

The following list provides key environmental fate, transport and bioaccumulation topics to be considered when evaluating ecotoxicity of nanomaterials. This list is not comprehensive and is not meant to replace toxicological data. Rather, these data elements should be evaluated along with ecotoxicological data:

- environmental transport data (e.g. how the nanomaterial partitions between water and sediment media or between groundwater and soil media)
- environmental fate data, which comprises:
  - transformations (e.g. surface chemistry changes; aggregation/agglomeration or disaggregation)
  - biodegradation
  - abiotic degradation (e.g. hydrolysis, reduction, oxidation)
  - bioaccumulation (i.e. the transfer of nanomaterial between trophic levels in the food chain).

Phase II, Stage 2, Step 3 – Characterise the exposures or exposure potential

Given the level of uncertainty in work-related potential health risks from nanomaterials, control banding can be particularly useful for the risk assessment and management of nanomaterials for occupational settings. It can be used for risk control management in both a proactive and retroactive manner. In a proactive manner, potential risks are evaluated without the consideration of control measures. A risk management plan can then be implemented and control measures can be selected. In a retroactive manner, the risk of a current process is assessed with consideration of existing control measures. The risk assessment can be used to evaluate the adequacy of the existing control measures.

Table 5.3. **Health hazard category allocation**

Toxicological result or health hazard indicator	Category A	Category B	Category C	Category D	Category E
OEL dust (mg/m^3) (8-hr TWA)	1-10	0.1-1	0.01-0.1	< 0.01	--
Acute toxicity	Low	Acute tox 4	Acute tox 3	Acute tox 1-2	--
LD50 oral route (mg/kg)	> 2 000	300-2 000	50-300	< 50	--
LD50 dermal route (mg/kg)	> 2 000	1 000-2 000	200-1 000	< 200	--
LC50 inhalation 4H (mg/L) aerosols/particles	> 5	1-5	0.5-1	< 0.5	--
Severity of acute (life-threatening) effects	--	STOT SE 2-3 Asp. Tox 1	STOT SE 1	--	--
Adverse effects per oral route (mg/kg) (single exposure)	--	Adverse effects seen ≤ 2 000	Adverse effects seen ≤ 300	--	--
Adverse effects per dermal route (mg/kg) (single exposure)	--	Adverse effects seen ≤ 2 000	Adverse effects seen ≤ 1 000	--	--
Sensitisation	Negative	Slight cutaneous allergic reactions	Moderate/strong cutaneous allergic reactions Skin sens. 1	--	Prevalent moderate to strong respiratory allergic reactions Resp. Sens. 1
Mutagenicity/genotoxicity	Negative	Negative	Negative	Negative	Mutagenic in most relevant *in vivo* and *in vitro* assays Muta 2 Muta 1A – 1B
Irritant/corrosiveness	None to irritant Eye Irrit. 2; Skin Irrit. 2 EUH 066	--	Severe irritant to skin/eyes Irritant to respiratory tract STOT SE 3 Eye Dam. 1 Corrosive Skin Cor. 1A – 1B	--	--
Carcinogenicity	Negative	Negative	Some evidence in	--	Confirmed in animals or

			animals Carc. 2		humans Carc. 1A – 1B
Developmental/reproductive toxicity	Negative	Negative	Negative	Reprotoxic defects in animals and/or suspected or proven in humans Repr. 1A, 1B, 2	--

Table 5.3. **Health hazard category allocation** (*cont.*)

Toxicological result or health hazard indicator	Category A	Category B	Category C	Category D	Category E
Likelihood of chronic effects (e.g. systemic)	Unlikely	Unlikely	Possible STOT RE 2	Probable STOT RE 2	--
Adverse effects per oral route (mg/kg-day) (90-day chronic study)	--	--	Adverse effects seen ≤ 100	Adverse effects seen ≤ 10	--
Adverse effects per dermal route (mg/kg-day) (90-day chronic study)	--	--	Adverse effects seen ≤ 200	Adverse effects seen ≤ 20	--
IH/occupational health experience	No evidence of adverse health effects	Low evidence of adverse health effects	Probably evidence of adverse health effects	High evidence of adverse health effects	High evidence of severe adverse health effects

Source: International Organization for Standardization (ISO) (2012), *Nanotechnologies – Guidelines for Occupational Risk Management Applied to Engineered Nanomaterials – Part 2: The Use of the Control Banding Approach in Occupational Risk Management*, ISO TC 229/SC N.

If a retroactive occupational risk assessment is being conducted, the existing exposures should be characterised. The exposure characterisation should include information on the efficacy of any existing exposure mitigation controls. However, the use of personal protection equipment (PPE) should not be included – exposures should be assessed as if no PPE is used. The use of PPE can then be taken into account after characterising the risk as part of an evaluation of an existing risk management strategy.

If a proactive occupational risk management strategy is being developed, the exposure potential should be characterised. As described above, the exposure potential should not account for any exposure mitigation controls, such as ventilation, enclosures or containment. However, the exposure potential should account for the physical form and process technologies that will be used. The results of the risk assessment will be used to help select appropriate control measures as part of the risk management strategy. PPE requirements should be determined after the consideration of work practices and control measures.

For non-occupational settings and receptor populations, control banding cannot be used. Here, exposure potential should be characterised considering existing controls (such as incinerator air pollution controls) and the fate and transport of nanomaterials along their exposure pathway.

Exposures or exposure potential should be characterised for complete exposure pathways. The United States Agency for Toxic Substances & Disease Registry (ATSDR) defines an exposure pathway as:

> The route a substance takes from its source (where it began) to its end point (where it ends), and how people can come into contact with (or get exposed to) it. An exposure pathway has five parts: a source of contamination (such as an abandoned business); an environmental media and transport mechanism (such as movement through groundwater); a point of exposure (such as a private well); a route of exposure (eating, drinking, breathing or touching), and a receptor population (people potentially or actually exposed). When all five parts are present, the exposure pathway is termed a completed exposure pathway. (ATSDR, 2009)

Exposure pathways should be characterised for each receptor population, as defined during problem formulation, for each life-cycle stage:

- workers who manufacture the nanomaterial of interest
- workers who mount, repair and/or balance nano-enabled tyres on vehicles
- workers involved with nano-enabled tyre recycling and/or disposal
- consumers who mount nano-enabled tyres on vehicles
- the general population
- key ecological endpoints.

An evaluation can be made to determine which receptor populations are appropriate for each life-cycle stage during exposure characterisation. For example, exposure pathways for the general population and key ecological endpoints should be evaluated for all life-cycle stages. However, exposure pathways for the OEM and shop workers and the do-it-yourself (DIY) consumers who mount tyres need not be evaluated during nanomaterial and tyre manufacturing.

This framework presents guidance below on determining the exposure potential of nanomaterials without the use of controls (i.e. for a proactive approach) during the industrial operations: nanomaterial and tyre manufacturing. This framework uses the exposure banding approach (as part of the control banding approach) as described in ISO (2012). The exposure banding approach assigns an exposure band (EB) ranking based on a qualitative assessment of exposure potential without the consideration of controls.

If performing a retroactive risk assessment, the exposure can be characterised in the same manner as for a proactive risk assessment. An exposure band ranking can be assigned based on the exposure potential without consideration of the exposure mitigation controls in place. The risk assessment can proceed similarly as for a proactive risk assessment. Then, the control banding approach can be used to determine the recommended control strategy, which can be compared to the existing controls in place to evaluate the current risk management strategies. The use of the control banding approach is described below under Phase II, Stage 2, Step 5 – Characterise the Risk.

Note that the control banding approach is currently only applicable for assessing exposure potential for workers who directly handle the nanomaterials or nano-enabled tyres in occupational settings. The control banding approach is not applicable for assessing exposure potential for consumers, the general population or ecological endpoints. However, future editions or future versions of ISO (2012) may expand the exposure banding approach to qualitatively assess exposures during other (e.g. consumer) scenarios. Because of this limitation in ISO (2012), this framework presents additional guidance on identifying the five parts of an exposure pathway for each life-cycle stage.

With regard to quantitative exposure data, actual exposure measurements, when feasible, typically represent the best information for the selection of the appropriate exposure band. Therefore, their use should be encouraged. However, it should be understood that exposure measurement data can be misinterpreted, not used correctly or even be unnecessary in certain circumstances. Therefore, when measurement data are used, they must be carefully applied and scrutinised. When both personal sampling and area measurements are available, the preference should be given to personal exposure measurements, if appropriate. The results should be taken into account when determining the corresponding exposure band. ISO/TS 12901-1 provides information on available measurement equipment, possible measurement strategies and results interpretations (ISO, 2012).

Nanomaterial manufacturing: Exposure potential

This section of the framework presents guidance on identifying exposure pathways and exposure band rankings of nanomaterials during their manufacture.

Since this framework is intended to provide guidance for any nanomaterial used as an additive in tyres, the exact exposure pathways are not described herein. Rather, this framework provides guidance on identifying exposure pathways once the nanomaterial is chosen and its method of manufacture determined. Table 5.4 summarises some guidance and key points to consider when identifying exposure pathways during nanomaterial manufacturing.

Exposure band rankings for worker exposures should be assigned for nanomaterial manufacturing based on the production technology type used. ISO (2012) assigns the exposure bands for the listed production technology types in Table 5.5.

Table 5.4. **Guidance for identifying complete exposure pathways of nanomaterials during their manufacture**

Potential sources from common manufacturing operations	Expected environmental media and transport mechanism	Point of exposure	Route of exposure	Receptor population
Openings in process vessels (e.g. sample ports, leaks)	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Loading of nanomaterial into containers	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Loading of nanomaterial into containers	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Cleaning up spilled nanomaterials	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Cleaning up spilled nanomaterials	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Spraying of nanomaterials	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Spraying of nanomaterials	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Blending small amounts of nanomaterials	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Blending small amounts of nanomaterials	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Packaging activities	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Packaging activities	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Maintenance activities	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Maintenance activities	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Dumping of nanomaterials	Indoor air and transport of aerosolised solid particles or mists of liquid dispersions	Workers' breathing zones	Inhalation	Workers
Dumping of nanomaterials	Contact of solids or liquid dispersions against skin	Workers' skin	Dermal	Workers
Dusts generated from solid powder nanomaterials	Collection via exhaust ventilation, passing through air pollution control device and emission from stack to air	Ambient air	Inhalation	General population
Collection of process aqueous waste, including rinsing process vessels with wash water, and their disposal down the drain or to on-site	Nanomaterials passing through treatment system to surface water and nanomaterials subsequently passing through drinking water plant	Drinking water	Ingestion	General population

wastewater treatment				
Collection of process solid or hazardous waste, including rinsing process vessels with solvent or wash water treated as solid or hazardous waste, and their disposal via incineration	Nanomaterials passing through incinerator and air pollution control device to ambient air	Ambient air	Inhalation	General population
Collection of process aqueous waste, including rinsing process vessels with wash water, and their disposal down the drain or to on-site wastewater treatment	Nanomaterials passing through treatment system to surface water, with nanomaterials dispersing in surface water or partitioning to sediment	Surface water or sediment	--	Aquatic ecological endpoints (e.g. pelagic species, benthic species)

Table 5.5. **Exposure band rankings for nanomaterial production technology types**

Production technology type		Exposure band
– Gas-phase synthesis – Flame pyrolysis – Laser ablation – Electrospraying		EB4
Mechanical reduction	Grinding	EB4
	Cutting	EB2
– Laser ablation in liquid – Sintering		EB3
Chemical vapour condensation		EB4
Wet chemistry	Introduced into solution	EB2
	Produced within solution	EB1

Source: International Organization for Standardization (ISO) (2012), *Nanotechnologies – Guidelines for Occupational Risk Management Applied to Engineered Nanomaterials – Part 2: The Use of the Control Banding Approach in Occupational Risk Management*, ISO TC 229/SC N.

Tyre manufacturing: Exposure potential

This section of the framework presents guidance on identifying exposure pathways and exposure band rankings of nanomaterials during their use in tyre manufacturing.

The exposure pathways of nanomaterials during their incorporation into tyres depend on the manner in which the nanomaterials are handled. Some nanomaterial handling procedures may be similar to procedures that are currently used for tyres that do not use nanomaterials. In other cases, nanomaterials may be incorporated into tyres using new procedures. Table 5.6 presents guidance for identifying complete exposure pathways of nanomaterials during their incorporation into tyres. This guidance is not meant to cover all possible methods that may be used to incorporate nanomaterials into tyres, since some methods may not yet be developed or implemented. Therefore, both industrial hygiene and environmental stewardship expertise should be sought when evaluating current or potential methods for incorporating nanomaterials into tyres.

This framework discusses guidance below on assigning exposure band rankings for nanomaterials used as additives in tyres following the exposure banding approach discussed in ISO (2012). This approach is only applicable for the workers within the tyre manufacturing plant. It is not applicable for other receptor populations. The guidance is presented for three different physical forms of nanomaterials. The appropriate ranking must be determined on a case-by-case basis for the applicable situation:

1. nanomaterials in solid powder form
2. nanomaterials in suspension in a liquid
3. nanomaterials dispersed in solid materials (solid matrix).

Table 5.7 summarises exposure band rankings for the nanomaterial physical forms and associated processes that could be encountered during the manufacture of tyres. Table 5.7 does not encompass all exposure band rankings of nanomaterials during processing and use – it does not reproduce the processes discussed in ISO (2012) that are unlikely to be encountered during tyre manufacturing. ISO (2012) should be consulted for a comprehensive discussion of all possible exposure band rankings. The subsequent subsections below discuss the physical forms and processes identified in Table 5.7.

Table 5.6. **Guidance for identifying complete exposure pathways of nanomaterials during their incorporation into tyres**

Potential sources from common processing operations	Expected environmental media and transport mechanism	Point of exposure	Route of exposure	Receptor population
Connecting and disconnecting transfer lines to rail cars and tank trucks	Indoor air and transport of aerosolised solid particles	Workers' breathing zones	Inhalation	Workers
Cleaning up spilled or leaked nanomaterials	Indoor air and transport of aerosolised solid particles	Workers' breathing zones	Inhalation	Workers
Cleaning up spilled or leaked nanomaterials	Contact of solids against skin	Workers' skin	Dermal	Workers
Dumping of nanomaterials into mixer	Indoor air and transport of aerosolised solid particles	Workers' breathing zones	Inhalation	Workers
Dumping of nanomaterials into mixer	Contact of solids against skin	Workers' skin	Dermal	Workers
Automatic charging of nanomaterials into small bags	Indoor air and transport of aerosolised solid particles	Workers' breathing zones	Inhalation	Workers
Blending small amounts of nanomaterials into rubber blocks	Indoor air and transport of aerosolised solid particles	Workers' breathing zones	Inhalation	Workers
Blending small amounts of nanomaterials into rubber blocks	Contact of solids against skin	Workers' skin	Dermal	Workers
Dusts generated from solid powder nanomaterials	Collection via exhaust ventilation, passing through air pollution control device and emission from stack to air	Ambient air	Inhalation	General population
Using water to rinse spilled solid nanomaterials from the floor, and disposing the rinse water down the drain or to on-site wastewater treatment	Nanomaterials passing through treatment system to surface water, and nanomaterials subsequently passing through drinking water plant	Drinking water	Ingestion	General population
Using water to rinse	Nanomaterials passing	Surface water or	x	Aquatic

spilled solid nanomaterials from the floor, and disposing the rinse water down the drain or to on-site wastewater treatment	through treatment system to surface water, with nanomaterials dispersing in surface water or partitioning to sediment	sediment		ecological endpoints (e.g. pelagic species, benthic species)
Collection of process solid or hazardous waste (including collected solid nanomaterials, scrap blended rubber and captured dust), and their disposal via incineration	Nanomaterials passing through incinerator and air pollution control device to ambient air	Ambient air	Inhalation	General population
Collection of process solid or hazardous waste (including collected solid nanomaterials, scrap blended rubber and captured dust), and their disposal via landfill	Degradation of rubber and leaching of nanomaterials through landfill liner and/or leachate collection system into soil and groundwater	Soil, groundwater	x	Terrestrial ecological endpoints (e.g. plants)
Nanomaterials in groundwater from above pathway	Nanomaterials passing through drinking water plant or getting into drinking water wells	Drinking water	Ingestion	General population

Note: x: not applicable.

If the nanomaterial is shipped to the tyre manufacturer in a solid powder form, then the exposure potential should be considered from the point of arrival at the site through blending operations. Once a nanomaterial is blended into molten elastomers (a viscous liquid), exposure banding should follow the guidance for nanomaterials in suspension in a liquid, presented below.

Table 5.7. **Exposure band rankings for processing nanomaterials during the manufacture of tyres**

Physical form	Process type	Exposure band
Solid powder (not deliberately aerosolised; > 1 kg)	High potential of dust generation	EB4
	Low potential of dust generation	EB3
Suspension in a liquid (not deliberately aerosolised; > 1 g of nanomaterial and > 1 L of liquid)	High potential of aerosol generation	EB3
	Low potential of aerosol generation	EB2
Dispersed in solid materials – unbound or weakly bound	High energy process	EB4
	Low energy process	EB3
Dispersed in solid materials – strongly bound	High energy process	EB2
	Low energy process	EB1

Source: International Organization for Standardization (ISO) (2012), *Nanotechnologies – Guidelines for Occupational Risk Management Applied to Engineered Nanomaterials – Part 2: The Use of the Control Banding Approach in Occupational Risk Management*, ISO TC 229/SC N.

According to the control banding approach (ISO, 2012), general guidance is such that the deliberate aerosolisation or spraying of powdered nanomaterials should be assigned an exposure potential of EB4.

All other handling of solid powder nanomaterials is assigned an exposure band ranking depending on the amount of nanomaterial handled and whether there is a high or low potential for dust generation.

For tyre manufacturing, deliberate aerosolisation or spraying of the nanomaterials is not expected. Further, greater than 1 kg of nanomaterial per batch is likely to be handled. Therefore, according to the control banding approach, the exposure band ranking should be EB3 for a low potential of dust generation or EB4 for a high potential of dust generation. The determination of the level of potential dust generation should be made on a process-specific basis.

If the nanomaterial is shipped to the tyre manufacturer in a liquid suspension, then the exposure potential should be considered from the point of arrival at the site up until the point of curing (vulcanisation). Alternatively, if a nanomaterial is shipped to the tyre manufacturer as a solid powder (as described above), then exposure potential for nanomaterials in suspension in a liquid should be considered from the point of blending the nanomaterial with the elastomers up until the point of vulcanisation. Once the tyre is cured, the exposure banding should follow guidance for nanomaterials dispersed in solid materials, presented below.

According to the control banding approach (ISO, 2012), the deliberate aerosolisation or spraying of the liquid suspension should be assigned an exposure potential of EB4. All other handling of the liquid suspension is assigned an exposure band ranking depending on the amount of nanomaterial handled and whether there is a high or low potential for aerosol generation.

For tyre manufacturing, deliberate aerosolisation or spraying of the liquid suspension is not expected. Further, it is expected that greater than 1 gram of nanomaterial (or greater than 1 L of the liquid suspension) will be handled per batch during the manufacture of tyres. Therefore, according to the control banding approach, the exposure band ranking should be EB3 for a high potential of aerosol generation or EB2 for a low potential of aerosol generation. The determination of the level of potential aerosol generation should be made on a process-specific basis.

After the tyre is built, the elastomers are then cured (vulcanised). Once the tyre is vulcanised, the nanomaterials can be assessed as nanomaterials dispersed in solid materials (solid matrix).

According to the control banding approach (ISO, 2012), the exposure band ranking of a nanomaterial dispersed in solid materials depends on whether the nanomaterial is weakly bound or unbound to the solid matrix, or strongly bound to the solid matrix. Additional consideration is given and assigned depending on the level of mechanical or thermal energy associated with the processes involving the solid materials. For unbound or weakly bound nanomaterials, high energy processes or activities are assigned an exposure band ranking of EB4. Low energy processes or activities are assigned an exposure band ranking of EB3. For strongly bound nanomaterials, high energy processes or activities are assigned an exposure band ranking of EB2, while low energy processes or activities are assigned an exposure band ranking of EB1. The definitions of "high energy" and "low energy" processes are qualitative terms that are not defined in ISO (2012) and are instead left to the discretion of the user.

For tyre manufacturing, it is anticipated that processes or activities involving the vulcanised tyre can be considered low energy. However, the determination of how the nanomaterial is bound within the tyre should be made on a nanomaterial-specific basis. For example, silica, in the presence of silanes, becomes chemically bonded to emulsion-polymerised styrene-butadiene rubber (SBR) during blending. Nanomaterials chemically bonded to the rubber can be considered strongly bound. Note that chemical bonding alone should not be the sole consideration for determining whether there is a strongly bound situation. Non-chemically bonded nanomaterials can also be considered strongly bound based on the tyre's cross-linking and the nanomaterial's properties within the vulcanised tyre.

Worker and consumer mounting of tyres on vehicles

Tyres are mounted on vehicles by workers (both in the OEM and commercial aftermarket shops) and by consumers in DIY applications.

During the mounting of tyres, workers and consumers handle vulcanised tyres containing nanomaterials. The associated exposure pathways are expected to be limited to the dermal contact with nanomaterial-containing (nano-enabled) tyres by these workers and consumers.

As described under tyre manufacturing for vulcanised tyres, the bounding of nanomaterials in the tyres and the level of energy associated with processes and activities of the tyres are used to determine the exposure band ranking. The mounting of tyres on vehicles is a low energy process or activity. Therefore, following ISO (2012) for nanomaterials dispersed in solid materials, the exposure band ranking for tyre mounting should be considered EB3 for unbound or weakly bound nanomaterials or EB1 for strongly bound nanomaterials.

Use of tyres: Exposure potential

Since the use of tyres is a non-occupational setting, the exposure band ranking approach is not appropriate for this life-cycle stage. Because the ISO (2012) exposure band ranking does not apply, this subsection discusses guidance for the evaluation of the general population and ecological endpoint exposure pathways.

Nanomaterials can be released to the environment from rubber particles wearing off or from blowouts. These mechanisms release vulcanised rubber that contains nanomaterials. The release of nanomaterials from the rubber depends on the properties of the nanomaterial and the degradation potential of the rubber in the environment. Table 5.8 presents guidance for identifying exposure pathways of nanomaterials during the use of tyres.

Table 5.8. **Guidance for identifying exposure pathways of nanomaterials during the use of tyres**

Potential sources from tyre blowouts or worn-off particles	Expected environmental media and transport mechanism	Point of exposure	Route of exposure	Receptor population
Vulcanised rubber particles or pieces laying on the ground	Degradation of rubber and leaching of nanomaterials onto soil or into groundwater or captured in stormwater runoff to surface water and sediments	Soil, groundwater, surface water or sediment	–	– Terrestrial ecological endpoints (e.g. plants) – Aquatic ecological endpoints (e.g. pelagic species, benthic species)
Nanomaterials in groundwater or surface water from above pathway	Nanomaterials passing through drinking water plant or getting into drinking water wells	Drinking water	Ingestion	General population

End-of-life of tyres: Exposure potential

At their end-of-life, tyres are recovered for reuse, burned for energy recovery or disposed. The percentage of tyres sent to each disposition for each major global tyre market is summarised in Table 5.2.

To determine exposure pathways of nanomaterials associated with the end-of-life of tyres, each final disposition must be considered. Table 5.9 presents guidance on identifying complete exposure pathways for the major disposition of tyres: re-treading, material recovery, disposal and incineration (including energy recovery).

Key concepts to consider in analysing the exposure pathways of nanomaterials from tyres that are landfilled or shredded with the resulting product used as playground surfacing include, but are not limited to, the following:

- degradation (through biological or chemical mechanisms) of the rubber in the landfill or playground environment
- leaching of nanomaterials from rubber into the environment
- leaching of nanomaterials through soil or through landfill liners or leachate recovery systems.

Key concepts to consider in analysing the exposure pathways of nanomaterials from an incinerator or energy recovery system include, but are not limited to, the following:

- oxidation or other reactions that occur in the combustion chamber (e.g. a carbon-based nanomaterial that is fully or partially oxidised; a fully oxidised metal nanomaterial that cannot further oxidise)
- breakdown of larger, nanostructured, non-oxidisable nanomaterials into smaller particles
- transport of nanomaterials, or nanomaterial combustion by-products, through an air pollution control device.

Table 5.9. **Guidance for identifying complete exposure pathways of nanomaterials during the end-of-life of tyres**

Disposition method	Potential sources from common disposition methods	Expected environmental media and transport mechanism	Point of exposure	Route of exposure	Receptor population
Disposal and re-treading	Re-treading of tyres	Dust formation of rubber during re-treading	Workers' breathing zones	Inhalation	Workers
	Landfilling of disposed tyres or scrap generated during tyre re-treading	Degradation of rubber and leaching of nanomaterials through landfill liner and/or leachate collection system into soil and groundwater	Soil, groundwater	x	Terrestrial ecological endpoints (e.g. plants)
	Nanomaterials in groundwater from above pathway	Nanomaterials passing through drinking water plant or getting into drinking water wells	Drinking water	Ingestion	General population
Material recovery (e.g. shredded tyres used as playground surfacing)	Vulcanised rubber particles or pieces laying on the ground	Degradation of rubber and leaching of nanomaterials onto soil or into groundwater or captured in stormwater runoff to surface water and sediments	Soil, groundwater, surface water or sediment	x	– Terrestrial ecological endpoints (e.g. plants) – Aquatic ecological endpoints (e.g. pelagic species, benthic species)
	Nanomaterials in groundwater or surface water from above pathway	Nanomaterials passing through drinking water plant or getting into drinking water wells	Drinking water	Ingestion	General population
	Vulcanised rubber particles or pieces laying on the ground	Children eating small pieces of rubber	Oral	Ingestion	General population (children)
Incineration (including energy recovery)	Nanomaterials not or only partially oxidised in combustion chamber	Nanomaterials passing through air pollution control device to ambient air	Ambient air	Inhalation	General population
	Nanomaterials in ambient air from above pathway	Nanomaterials condensing or depositing into surface water, and subsequently passing through drinking water plant	Drinking water	Ingestion	General population
	Nanomaterials in ambient air from above pathway	Nanomaterials condensing or depositing onto soil and surface water	Soil, surface water or sediment	x	– Terrestrial ecological endpoints (e.g. plants) – Aquatic ecological endpoints (e.g. pelagic

					species, benthic species)
	Nanomaterials not or only partially oxidised in combustion chamber	Nanomaterials captured in wet scrubber, scrubber wash down sent to wastewater treatment, and nanomaterials subsequently passing through treatment system to surface water, with nanomaterials dispersing in surface water or partitioning to sediment	Surface water or sediment	x	Aquatic ecological endpoints (e.g. pelagic species, benthic species)
	Nanomaterials in surface water from above pathway	Nanomaterials passing through drinking water plant	Drinking water	Ingestion	General population

Table 5.9. **Guidance for identifying complete exposure pathways of nanomaterials during the end-of-life of tyres** (*cont.*)

Disposition method	Potential sources from common disposition methods	Expected environmental media and transport mechanism	Point of exposure	Route of exposure	Receptor population
Incineration (including energy recovery) (*cont.*)	Nanomaterials not or only partially oxidised in combustion chamber	Nanomaterials captured by dry system (filter bag, cyclone, electrostatic precipitator), and dust/ash sent to landfill, and subsequent leaching of nanomaterials through landfill liner and/or leachate collection system into soil and groundwater	Soil, groundwater	x	Terrestrial ecological endpoints (e.g. plants)
	Nanomaterials in groundwater from above pathway	Nanomaterials passing through drinking water plant or getting into drinking water wells	Drinking water	Ingestion	General population

Note: x: not applicable.

As described under tyre manufacturing for vulcanised tyres, the bounding of nanomaterials in the tyres and the level of energy associated with processes and activities of the tyres are used to determine the exposure band ranking. The re-treading and shredding of tyres is anticipated to be a low energy process or activity. Therefore, following ISO (2012) for nanomaterials dispersed in solid materials, the exposure band ranking for tyre re-treading and shredding should be considered EB3 for unbound or weakly bound nanomaterials or EB1 for strongly bound nanomaterials. However, unlike previous discussions, the potential for dust generation during tyre re-treading and shredding exists and should be evaluated. The associated potential health hazards, both for general dusts and dusts containing nanomaterials, should also be evaluated.

Phase II, Stage 2, Step 4 – Characterise the strategies or techniques to mitigate exposure

Exposure control measures that are, or can be, implemented in the workplace should be identified. They can lower exposures by reducing emission (the release of nanomaterials from a source), transmission (the transport of nanomaterials from an emission source to an endpoint) and immission (the introduction of nanomaterials into an endpoint, e.g. a worker). The reduction of nanomaterial emission from the source can be achieved through work practice controls such as handling nanomaterials in suspension into a liquid or dispersed into a paste or a solid matrix rather than in the form of dry powders. Handling nanomaterials in these physical forms is likely to reduce fugitive dust emissions. It is also recommended to avoid high thermal or mechanical energy processes or other activities that are likely to release nanomaterials from their matrix.

Engineering controls can also be very useful in reducing the transmission from the source to the worker. Two generic transmission control measures that may be applicable during tyre manufacturing operations are: *i)* local control, e.g. containment and/or local exhaust ventilation; and *ii)* general ventilation, e.g. natural or mechanical ventilation. The reduction of emission has three generic control measures: *i)* personal enclosure/separating the worker from the source, e.g. a ventilated cabin; *ii)* segregation of the source from the worker, i.e. isolation of sources from the work environment in a separate room without direct containment of the source itself; *iii)* use of PPE. Use of PPE is usually the last resort in exposure reduction (ISO, 2012).

Administrative and engineering controls can also be implemented to mitigate releases of nanomaterials into the environment. Administrative controls can include work practices such as handling all wastes that contain, or may potentially contain, nanomaterials as hazardous waste. Work practices can even include treating nanomaterial-containing wastewater as hazardous waste and avoiding the discharge of any nanomaterials to on-site or off-site wastewater treatment.

Engineering controls to prevent the release of nanomaterials into the environment can include air pollution control devices on stack air vents and incinerators that combust nanomaterial-containing wastes. Air pollution control devices for removing particulates from gaseous waste streams can include filter bags, wet and dry electrostatic precipitators, cyclones and scrubbers. These control technologies should be evaluated for their removal or capture efficiency of nanomaterials.

Phase II, Stage 2, Step 5 – Characterise the risk

This section discusses characterising the resulting risk for both occupational and non-occupational settings, both quantitatively and qualitatively.

Occupational human health risk assessment

This framework uses the risk/control banding approach to assess and manage occupational human health risks (i.e. during nanomaterial and tyre manufacturing).

The use of a quantitative risk assessment is briefly discussed for informative purposes only. The remainder of this subsection demonstrates the use of the risk/control banding approach following ISO (2012). As previously described, the best information to base the selection of the appropriate exposure band is typically exposure measurements. The determination as to what sampling/monitoring should be performed will depend on many variables, such as: the specific nanomaterial being measured; the tasks that workers are performing; whether area or personal sampling is preferable; the number of workers involved; what instrumentation/capabilities are available; and the intended use of the data. Preference should typically be given to individual exposure measurements as opposed to area monitoring results. The results should be taken into account when determining the corresponding exposure band. ISO/TS 12901-1 provides information on available measurement equipment, possible measurement strategies and interpreting the results (ISO, 2012).

As an alternative to the risk/control banding approach, quantitative exposure measurements can be used for a risk assessment. However, a quantitative risk assessment also requires quantitative toxicological data. If such quantitative data are available or are pursued, risk assessor expertise should be sought. This framework is not intended to provide guidance on quantitative risk assessments.

Qualitative risk assessments, both proactive and retroactive, can be made using ISO (2012), as summarised below.

Proactive risk assessments can use the control banding approach to provide guidance on the selection of control strategies to manage risk. After assigning hazard band and exposure band rankings, the control banding matrix in ISO (2012) (reproduced in Table 5.10) can be used to determine the recommended control band to manage the risk of the nanomaterial in an occupational setting.

Table 5.10. **Control banding matrix**

Hazard band	Exposure band			
	EB1	EB2	EB3	EB4
A	CB1	CB1	CB1	CB2
B	CB1	CB1	CB2	CB3
C	CB2	CB3	CB3	CB4
D	CB3	CB4	CB4	CB5
E	CB4	CB5	CB5	CB5

Source: International Organization for Standardization (ISO) (2012), *Nanotechnologies – Guidelines for Occupational Risk Management Applied to Engineered Nanomaterials – Part 2: The Use of the Control Banding Approach in Occupational Risk Management*, ISO TC 229/SC N.

The control bands are defined in ISO (2012) as correlating to specific control strategies as follows:

- CB1: natural or mechanical general ventilation
- CB2: local ventilation: extractor hood, slot hood, arm hood, table hood, etc.
- CB3: enclosed ventilation: ventilated booth, fume hood, closed reactor with regular opening
- CB4: full containment: glove box/bags, continuously closed systems
- CB5: full containment and review by a specialist: seek expert advice.

Retroactive risk assessments can use the risk banding approach to qualitatively characterise the risk of an existing occupational setting. After assigning hazard band and exposure band rankings, the risk or priority banding matrix in ISO (2012) (reproduced in Table 5.11) can be used to determine the qualitative assessment of risk for the nanomaterial in an existing occupational setting, accounting for existing controls in place.

Table 5.11. **Risk or priority banding matrix**

Hazard band	Exposure band			
	EB1	EB2	EB3	EB4
A	Low	Low	Low	Medium
B	Low	Low	Medium	High
C	Low	Medium	Medium	High
D	Medium	Medium	High	High
E	Medium	High	High	High

Source: International Organization for Standardization (ISO) (2012), *Nanotechnologies – Guidelines for Occupational Risk Management Applied to Engineered Nanomaterials – Part 2: The Use of the Control Banding Approach in Occupational Risk Management*, ISO TC 229/SC N.

Additionally, retroactive risk assessments can use the exposure banding approach in the same manner as a proactive risk assessment. The exposures can be characterised without considering the exposure mitigation controls in place, and an exposure band ranking can be assigned per ISO (2012). A control band can then be assigned as described for the proactive risk assessment approach above (using Table 5.10). The assigned control band can then be compared to the existing mitigation controls in place. This comparison can be used to evaluate the effectiveness of the current controls in place.

General population and ecological risk assessment

This framework includes guidance for the evaluation of the entire life cycle in the assessment and management of risk. Therefore, it is acknowledged that risks posed to the general population and ecological endpoints should be evaluated and incorporated into the overall assessment and site-specific risk management strategies. At this point in time, limited data are available regarding the fate and transport and toxicity of nanomaterials in general, and even less is available in public literature regarding those used in tyres. Therefore, it may be difficult to complete a quantitative risk assessment – especially for specific nanomaterials used in specific applications. Additionally, a qualitative risk/control banding approach (similar to that used for assessing and managing worker exposures) is not presented, as one does not currently exist.

However, the steps discussed in this framework can be used to form the basis for an appropriate evaluation and conservative risk management strategy until additional information becomes available. As new data and information are developed, the results should be fed back into the aforementioned steps and the strategy should be revised as needed. This feedback step should be a formal part of the overall strategy such that continual improvement is achieved and potential risks are truly identified and minimised.

Additional guidance for evaluating risk to general population and ecological endpoints is presented below.

Exposure measurements can be used in a quantitative risk assessment. However, a quantitative risk assessment also requires quantitative toxicological data. If such data are available or are pursued, risk assessor expertise should be sought. This framework is not intended to provide guidance on quantitative risk assessments.

In the absence of quantitative toxicological data, risk can be evaluated through a qualitative risk assessment. To most conservatively protect general population and ecological health, it can be assumed that a nanomaterial may pose a severe hazard. Then, a comprehensive evaluation of exposure pathways can be used to look for areas where chemistry, fate and transport data are needed to further characterise the exposure pathway. For example, further data may be needed to determine the fate of a nanomaterial in an incinerator (e.g. is it destroyed or is it liberated from a cross-linked product and subsequently released in exhaust gas as a product of incomplete combustion?).

A nanomaterial or tyre manufacturing company can use this guidance to evaluate all potential exposure pathways over the entire life cycle of the nanomaterial and develop a risk management strategy that extends beyond the company fence line. For example, a nanomaterial or tyre manufacturer could use the exposure pathway evaluation to improve the facility or company-wide environmental stewardship plan by avoiding any wastewater discharges of nanomaterials and evaluating the efficacy of dust collector systems associated with air streams potentially containing nanomaterials. Recognising that exposure pathways during the use and end-of-life of tyres may be outside the control of these companies, it may be appropriate to implement public awareness and hazard communication programmes that recommend safe handling and disposal methods.

A tyre manufacturer pursuing research and development of a particular nanomaterial could use this framework to evaluate where more data are needed to evaluate the risk posed to the general population and ecological endpoints. For example, risks could be evaluated from the release and disaggregation of nanomaterials from rubber due to chemical and physical degradation of tyre particles during use and on the side of a road, or due to incineration of tyres in energy recovery processes.

Regulatory bodies can also use the exposure pathway evaluations to inform decision makers when determining where further research funding is needed to assess the level of risk posed to the general population and ecological endpoints.

Phase II, Stage 3 – Confirmation of utility of risk assessment

To confirm the utility of a risk assessment, certain questions must be asked, including the following:

- Do the assessment results include the attributes called for in planning?
- Do the assessment results provide sufficient information to discriminate among risk management options?
- Has the assessment been satisfactorily reviewed by others?

If the utility of the risk assessment cannot be confirmed, then the planning stage must be re-visited to evaluate what is necessary to appropriately characterise the risks. The level of uncertainty and variability must also be re-evaluated to determine if the risk results can be reported within an acceptable level of confidence. If confirmation of utility can be achieved, then Phase III of the framework (risk management) can begin.

Phase III – Risk management

The purpose of risk management is to reduce risks to an appropriate level and the process should follow the control hierarchy demonstrated by the STOP principle (as described in ISO [2012]) and the

United States Occupational Safety and Health Administration's (OSHA) hazard prevention and control guidance (OSHA, 2013). The STOP principle (substitution, technical measures, organisational measures, and personal protective equipment) and OSHA's hazard prevention and control guidance both follow the same hierarchy of first attempting to remove a hazard through design or redesign of industrial processes; then trying to minimise exposure to a hazard through controls and management practices; and finally to protect workers against any remaining exposure to the hazard.

When incorporating nanomaterials into tyres, this control hierarchy should be incorporated into the company- and site-specific risk management plan. The following key points should be integrated into the risk management plan:

1. Substitution: if the nanomaterial presents hazard concerns, determine if it can be substituted with a less hazardous material.
2. Process design: design the process such that exposures are minimised (e.g. enclosed process, using automation in place of manual activities).
3. Engineering controls: implement engineering controls to minimise exposures (e.g. barriers, local ventilation).
4. Safe work practices: implement company- or site-specific workplace rules to ensure workers take necessary precautions to minimise exposures (e.g. respiratory protection standards, laboratory chemical hygiene standards, protocols for cleaning spilled nanomaterials and fixing leaks).
5. Personal protective equipment: require the use of proper PPE to minimise exposures that remain after all of the above considerations. Include proper PPE training.
6. Systems to track hazard correction: develop a hazard tracking system to track the original discovery of a hazard to its correction.
7. Preventive maintenance systems: implement good scheduling and documentation of maintenance activities. For example, good maintenance scheduling of pressurised pneumatic transfer lines can prevent leaks, instead of relying on visual inspection of leaks before maintenance occurs.
8. Medical programmes and industrial hygiene monitoring: implement industrial hygiene monitoring programmes to regularly monitor exposures. Implement a medical programme to record and document employee health complaints and injuries.

The above key points focus on worker health within occupational settings. However, risks posed to the general population and ecological endpoints can also be considered as part of a company- or site-specific environmental stewardship plan. This plan can include provisions such as:

1. Avoid any discharge of nanomaterials to wastewater.
2. Treat nanomaterials and any wastes potentially containing nanomaterials as hazardous waste.
3. Where possible, handle nanomaterials in small quantities in controlled, laboratory settings.
4. Where possible, handle nanomaterials incorporated into a solid matrix instead of as a solid powder. For example, the laboratory incorporation of nanomaterials into

> rubber blocks for subsequent addition to the low-temperature mixer during tyre manufacturing could be considered a good practice, not only to minimise worker exposures, but also to reduce fugitive dust releases.

Review of available information on HD-HS silica and nanoclays for use within the risk management framework

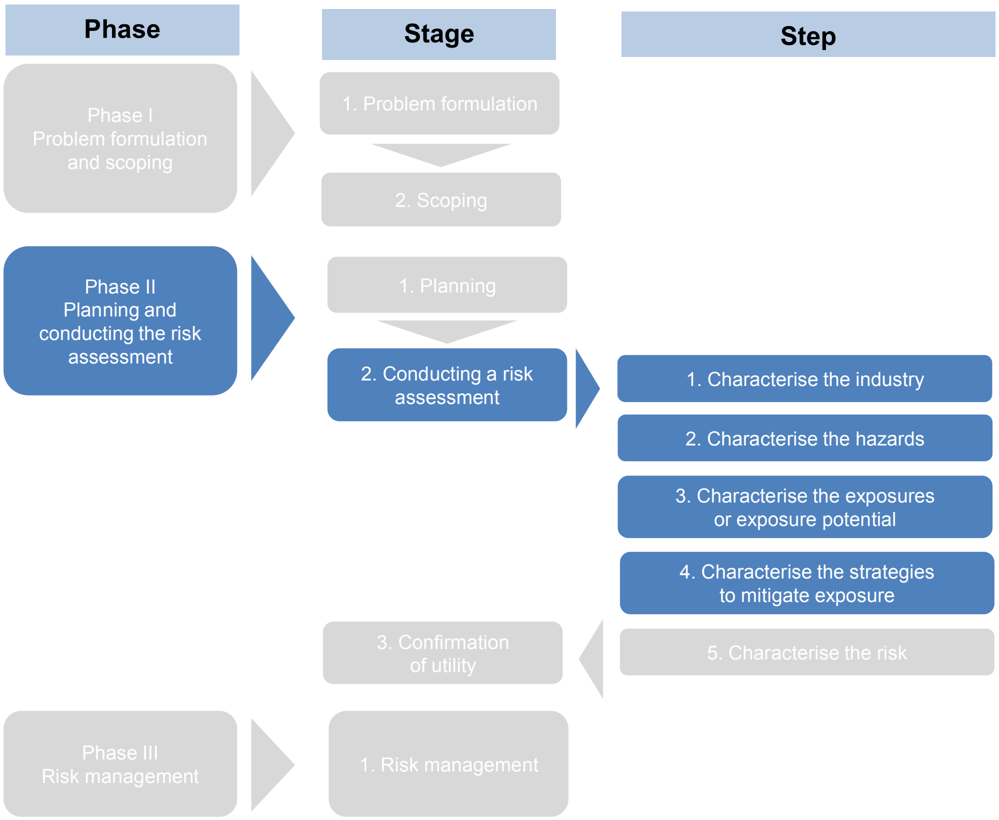
This section presents the information currently available for HD-HS silica and nanoclays that can be used within the risk management framework discussed in the previous sections. Multiple suppliers were contacted with requests for site-specific information that could be used to develop full case study examples. These contacts indicated the requested information was either not available (e.g. toxicity studies had not been conducted and industrial hygiene monitoring had not occurred) and/or information was considered to be confidential (e.g. detailed information pertaining to worker activities and process descriptions). Because information is not publicly available, there are numerous data gaps. Therefore, not enough information is available to complete a case study utilising the control banding (and other) approaches recommended in the framework. Nonetheless, publicly available information was gathered (and is presented below) such that it can be used in future evaluations along with company-specific, confidential data. The information presented below was obtained entirely from publicly available sources and interviews with tyre industry stakeholders.

The information search revealed that there is not enough publicly available information to characterise the risk of using HD-HS silica or nanoclays in tyres following the risk management framework. Therefore, this section instead presents a literature review of information obtained on HD-HS silica and nanoclays following the data elements required for risk assessment identified in Phase II, Stage 1 of the risk management framework. Since information specific to the use of these nanomaterials in tyres was not identified, this section focuses on characterising the industry, exposure potential and exposure mitigation strategies for nanomaterial manufacturing only. The risk management framework presented above already addresses these topics for nanomaterials in general for all other life-cycle stages. Figure 5.2 presents a flow diagram that illustrates the sections of the framework covered in this section for HD-HS silica and nanoclay. This section presents the information that is currently available and highlights the data gaps that must be addressed before the risks can be properly characterised.

HD-HS silica

The following subsections discuss the chemistry of HD-HS silica, the processes used to manufacture each nanomaterial, and potential sources of exposure or release, based on Phase II, Stages 1 and 2 of the risk management framework.

Figure 5.2. **Phases and stages of the risk management framework covered in this section**



Physical/chemical properties data

According to the Synthetic Amorphous Silica and Silicate Industry (SASSI) Association, there are two main polymorphs of synthetic amorphous silica: precipitated silica and pyrogenic silica (also known as fumed silica) (SASSI, 2008). Silicas used as reinforcing fillers are mainly obtained by precipitation (SASSI, 2008; Rodgers and Waddell, 2005). Precipitated silica is the most commonly produced synthetic amorphous silica and is widely used in Europe, with increasing demand in North America and Asia (Bergna and Roberts, 2006, as cited in SASSI, 2008). Pyrogenic silica does not appear to play a significant role in the tyre industry, based on west European consumption rates (European Commission, 2007).

Precipitated silicas can be grouped by dispersibility and surface area, as shown in Table 5.12. These groups include:

- conventional silica
- semi-high dispersion (semi-HD) silica
- high dispersion silica (HD) silica
- highly dispersable high surface area (HD-HS) silica.

Table 5.12 shows there is a correlation between surface area and application, where tyre casings incorporate silicas with low- to mid-range surface areas and tyre treads incorporate silicas with mid- to high-range surface areas. High-performance tyre treads are unique in that they only incorporate HD-HS silica.

Table 5.12. **Classification of silica groups used in rubber tyres**

Silica type	Surface area (m^2/g)		
	90-130	130-180	180-220
Conventional	Tyre casings	Tyre casings Tyre treads	Tyre treads
Semi-high dispersion	Tyre casings	Tyre casings Tyre treads	Tyre treads
High dispersion	Tyre casings Tyre treads	Tyre treads	--
Highly dispersible high surface area	--	--	High-performance tyre treads

Source: Rodgers, B. and W. Waddell (2005), "The science of rubber compounding", In: *The Science and Technology of Rubber*, 3rd ed., Elsevier, Burlington, MA; interviews with industry stakeholders.

There do not appear to be widely accepted standard distinctions between the four silica types listed above. Based on a review of product specification data from silica manufacturer websites, as well as discussions with tyre manufacturers, the key distinctions include surface area, elementary particle diameter and aggregate mean diameter. Table 5.13 summarises characteristic values associated with each type.

Table 5.13. **Characteristic properties of conventional, high dispersion and highly dispersible high surface area silica**

Physical property	Unit	Conventional silica	HD silica[1]	HD-HS silica[2]
CTAB surface area	m^2/g	~110	160	200
BET surface area	m^2/g	~115	165	215
Diameter of elementary particles	nm	25	20	10
Mean diameter of aggregates	nm	95	50	55-60

Notes: CTAB: cetyltrimethylammonium bromide; BET: brunauer–emmett–teller. 1. Rhodia Zeosil 1165 is used as representative of HD silica. 2. Rhodia Zeosil Premium 200 MP is used as representative of HD-HS silica.

Source: Rhodia (2011), "Safety data sheet. Zeosil Premium 200MP", Revision 4.00.

Previous work conducted in support of the Tyre Industry Project (TIP) indicates that precipitated amorphous silica meets the ISO definition of a nano-structured material. It does not meet the definition of a nano-object because the primary particles bind to form aggregates and agglomerates that are above the nanometre range. While the initial precipitation step yields primary particles that meet the ISO definition of nano-objects, they immediately bond covalently to form non-dissociable aggregates having diameters of approximately 100-500 nm. The aggregates then electrostatically bind together to form agglomerates with diameters ranging from 1-40 µm. The study notes that aggregate and agglomerate bonds are not broken during use (ChemRisk, 2011).

HD-HS silica manufacturing risk assessment

Phase II, Stage 2 of the risk management framework describes the assessment of risk per the characterisation of the following elements: the industry, hazards, exposures or exposure potential, and strategies or techniques to mitigate exposure. The following subsections characterise each of these elements for the manufacture of HD-HS silica. However, a risk assessment has not been completed at this time due to significant data gaps. Additional research to fill these gaps may allow for development of a risk assessment in the future.

Process description

Solvay submitted a patent application for a production process of an HD-HS silica product which is similar to the generic precipitated silica manufacturing process. The difference in Solvay's HD-HS silica production method is a different method of reacting the silicate solution with the acidifying agent. The remaining steps (precipitation, filtration, washing, etc.) are identical to conventional precipitated silica manufacturing operations as discussed in further detail below. The patent application recommends the use of a filter press and spray dryer to perform the solid-liquid separation (Valero, 2005).

The manufacture of precipitated synthetic amorphous silicas usually comprises the following major unit operations: precipitation, filtering/washing, drying and granulation/milling (Luginsland, 2002). Packaging of the final product occurs during granulation/milling, where the granulised product is packaged into product containers (European Commission, 2007). According to European Commission (2007), only batch precipitation processes have attained economic importance; however, continuous precipitation techniques can also be employed. The general precipitated silica manufacturing process is described below, followed by a brief discussion of key process differences for manufacturing HD-HS silica.

During the initial step (i.e. precipitation), an aqueous alkali metal silicate solution (e.g. waterglass) is mixed with either concentrated sulfuric, hydrochloric or carbonic acids (European Commission, 2007; SASSI, 2008). The raw materials needed to produce waterglass are sand, sodium carbonate, sodium hydroxide and water (European Commission, 2007; SASSI, 2008). The molar ratio of silicon dioxide to sodium dioxide is kept to a range of 2 to 4 (European Commission, 2007; Hewitt and Ciullo, 2007; SASSI, 2008).

According to SASSI (2008), precipitated silicas are manufactured under neutral to alkaline conditions and result in primary particle, aggregate and agglomerate size ranges of 5-100 nm, 0.1-1 μm, and 1-250 μm, respectively.

The precipitation reaction produces not only a hydrated silica slurry, but also residual salts such as sodium sulfate, sodium chloride or sodium carbonate (Hewitt and Ciullo, 2007). The residual salts content is reduced by 1% or 2% by passing the slurry through a counter-current decantation system or by filtering (Hewitt and Ciullo, 2007). Filtration units consist of filter presses, rotary filters and belt/drum driers, and produce a solid wet cake containing 15-25% silica (European Commission, 2007; Hewitt and Ciullo, 2007). Immediately after filtration, the wet cake is washed to remove residual salts. This washing step typically occurs within the filtration section (European Commission, 2007). The salt content remaining in the product will vary depending on the intended application of the final silica product (European Commission, 2007).

In industrial scale operations, the resulting wet cake is dried by belt, turbine, recycling, rotary drum and spray dryers (European Commission, 2007). The specific equipment that is employed will depend on the desired structure and properties of the final silica product (European Commission, 2007). Shorter drying times are typical of HD silica production while longer drying times are typical of conventional silica production (as cited in Mihara, 2009).

After drying, the final silica product contains about 6% water (Hewitt and Ciullo, 2007) and is an irregular granulate that requires milling (European Commission, 2007). Milling establishes the particle size distribution of the final product (European Commission, 2007; SASSI, 2008). Milling requires air or steam and is energy intensive (European Commission, 2007). Hammer and jet mills are most typically used (European Commission, 2007).

For certain applications, a dust-free product is required. To fulfill this requirement, the spray-dried or milled products must be granulated, which is normally carried out with drum granulation equipment. Granulators are used to increase the particle size of silica, mainly for improved handling and to reduce dusting. The final product is then packaged using automatic or manual filling machines, which load the silica into paper or plastic bags of 5-25 kg, big bags of 100-1 000 kg, or silo containers. Inputs and outputs to mills and granulators are often handled by airway systems equipped with bag houses for product recovery and dust extraction. To minimise particulate emissions, bagging machines are always equipped with their own dust extraction and control systems (European Commission, 2007).

Hazard characterisation

The material safety data sheet (MSDS) for an HD-HS silica product contains information about toxicity and potential human health effects, as listed in Table 5.14, although the majority of results are from unpublished studies. The MSDS also indicates that the HD-HS silica is not bioaccumulative, based on published data (Rhodia, 2011). No other HD-HS silica-specific studies were identified.

Exposure or exposure potential characterisation

HD-HS silica is expected to be handled primarily in solid particulate form. However, there were no specific data available to characterise the amount of nanomaterial handled, duration and frequency of exposure, or any other data elements to quantify potential exposures.

Potential occupational exposure pathways associated with silica production include packaging and shipping activities (European Centre for Ecotoxicology and Toxicology of Chemicals, 2006; SASSI, 2008). For each of these exposure sources, the generation of airborne dusts represents a potential inhalation exposure route for workers. Dermal exposures also may occur through incidental contact. Refer to Table 5.4 for specific occupational exposure pathways from handling solid particles.

The environmental release media associated with precipitated silica manufacturing are air, water and landfill (European Commission, 2007; SASSI, 2008). According to European Commission (2007), air and water make up the two major release sources. The specific sources of environmental release include:

- Air: fugitive dust releases occur during drying operations. The level of particulates generated depends on the drying technology used. Fast-drying processes (e.g. flash or spray dryers) are typically used for precipitated silicas and result in fewer dust emissions than slow, indirect drying processes. Slow-drying processes rely on large volumes of air and are used in the manufacture of other silica types (European Commission, 2007).
- Water: releases occur during silica washing. Wastewaters generated during silica washing pass through wastewater treatment plants prior to direct release to surface waters (European Commission, 2007).
- Landfill: releases occur as a result of product spills and wet sludge from on-site wastewater treatment (European Commission, 2007).

Table 5.14. **Toxicological and ecological information for highly dispersible high surface area silica**

Category	Information available	Source
Acute oral toxicity	LD50 : > 5 000 mg/kg – rat	Unpublished reports
Acute inhalation toxicity	Risk of physical blockage of the upper respiratory tract. By analogy, an LC50/inhalation/4h/rat could not be determined because no mortality of rats was observed at the maximum achievable concentration.	Unpublished reports
Acute dermal toxicity	LD50 : > 5 000 mg/kg – rabbit	Unpublished reports
Acute toxicity (other routes of administration)	No data available.	
Aspiration toxicity	Not applicable.	
Skin irritation	Repeated or prolonged contact may cause slight irritation to the skin.	Unpublished reports
Eye irritation	Mild eye irritant.	Unpublished reports
Sensitisation	Humans: no cutaneous sensitisation reaction observed.	Unpublished reports
Repeated dose toxicity	If inhaled: no irreversible effect or symptom of silicosis was observed during the inhalation toxicity tests.	Unpublished reports
	Oral exposure: no irreversible effects were observed during chronic oral toxicity tests.	Unpublished reports
STOT – single exposure	The substance or mixture is not classified as specific target organ toxicant, single exposure.	Not listed
STOT – repeated exposure	The substance or mixture is not classified as specific target organ toxicant, repeated exposure.	Not listed
Carcinogenicity	Rat, oral exposure: animal testing did not show any carcinogenic effects.	Unpublished reports
	Mouse, oral exposure: animal testing did not show any carcinogenic effects.	Unpublished reports
Genotoxicity *in vitro*	*In vitro* tests did not show mutagenic effects.	Unpublished reports
Genotoxicity *in vivo*	*In vivo* tests did not show mutagenic effects.	Unpublished reports
Reproductive toxicity	Fertility and developmental toxicity tests did not reveal any effect on reproduction.	Unpublished reports
Neurological effects	No neurotoxic effects observed.	Not listed
Experience with human exposure: Inhalation	Mild respiratory irritant.	Unpublished reports
Toxicity to fish	LC50 – 96 h : > 10 000 mg/l – *Danio rerio* (zebra fish)	Unpublished reports
Toxicity to daphnia and other aquatic invertebrates	EC50 – 24 h : > 1 000 mg/l – *Daphnia magna* (water flea)	Unpublished reports
Ecotoxicity assessment	The product does not have any known adverse effects on the aquatic organisms tested.	

Notes: LD50: lethal dose, 50%; the dose required to kill half the members of a tested population after a specified test duration. LC50: lethal concentration, 50%; the concentration of the surrounding medium required to kill half the members of a tested population after a specified test duration; STOT – Specific Target Organ Toxicity.

Source: Rhodia (2011), “Safety data sheet. Zeosil Premium 200MP”, Revision 4.00.

According to SASSI (2008), most non-occupational exposures are likely to be from the ingestion of silica dissolved in water, although an MSDS for an HD-HS silica product describes the silica as “practically insoluble” in water, with an estimated solubility of 0.1 g/L.

Refer to Table 5.4 for additional guidance on potential exposure pathways for the general population or aquatic ecological endpoints.

In terms of fate and transport, the Rhodia MSDS for an HD-HS silica product indicates the ultimate destination of the product is to soil or sediment (Rhodia, 2011). No other HD-HS silica-specific studies were identified.

Strategies or techniques to mitigate exposure

The Rhodia MSDS for an HD-HS silica indicates that specific PPE should be used, including safety glasses, and a respirator with an approved filter if a risk assessment indicates that it is necessary (Rhodia, 2011). No other information was found concerning current specific strategies practised by industry to mitigate nanomaterial (including HD-HS silica) release or exposure during nanosilica manufacturing. As mentioned previously for certain silica products, bagging machines are equipped with dust extraction and control systems (European Commission, 2007).

Nanoclays

The following subsections discuss the chemistry and processes used to manufacture nanoclays, and potential sources of exposure or release, based on Phase II, Stages 1 and 2 of the risk management framework.

Physical/chemical properties data

Clays are classified as a group of minerals in the phyllosilicate subclass (sheet-like structures) of the silicate class. Clay minerals may be divided into four major groups, mainly in terms of the variation in the layered structure. These include the kaolinite group, the montmorillonite (MMT)/smectite group, the illite group and the chlorite group (Uddin, 2008). This section focuses on MMT and kaolinite nanoclays, which have applications in the tyre manufacturing industry.

MMT and kaolinite are aluminosilicates, which have a sheet-like (layered) structure, and consist of silica SiO_4 tetrahedra bonded to alumina AlO_6 octahedra in a variety of ways. A 2:1 ratio of the tetrahedra to the octahedra results in smectite clays, the most common of which is MMT (Hay and Shaw, 2000). The MMT has a typical chemical description of $(Ca,Na)(Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$. Kaolinite has a 1:1 structure consisting of one tetrahedral sheet bonded to one octahedral sheet, giving a typical chemical description: $Al_2Si_2O_5(OH)_4$. *In situ* additional mineral content is present in clay due to its geological formation. In most applications, these minerals are considered impurities and downstream processing is aimed toward removing the extraneous minerals setting the particle fineness (and distribution) (Uddin, 2008; Michelin, 2013).

Clay minerals used as fillers occur in two main varieties: non-expanding and expanding. Kaolin is a non-expanding mineral, which has a neutral surface and does not have any chemistry on the surface that promotes separation of platelets. The MMT is an expanding mineral, which has a negative surface charge that promotes easy dispersion in aqueous systems (Lopez, 2000).

The thickness of the MMT and kaolinite layers are similar: an MMT layer is approximately 1 nm (Lopez, 2000) while the thickness of a kaolinite layer is approximately 0.7 nm (Marquis et al., 2011). However, aspect ratios differ greatly. The MMT plates have aspect ratios (width to thickness) from 50 to over 1 000, while water-washed kaolins have ratios of 10-30. The size and shape of montmorillonite gives a surface area of approximately 800 m^2/gram (Lopez, 2000).

In terms of classification, each layer of the MMT and kaolinite can be considered a nanoplate. However, nanoclays normally exist as agglomerated bundles, consisting of thousands of platelets held together by van der Waals forces (Kang, 2010). Therefore, nanoclays primarily exist on their own as nanostructured materials.

In order to optimise the use of nanoclays in rubbers and plastics, the individual layers must be partially or fully separated (exfoliated) and dispersed into the polymer matrix (Kang, 2010). nanoclay, sheets primarily remain bound together and can be separated within a nanocomposite to form three main types of nanocomposite structures (Sengupta, 2007):

- conventional: nanostructured material is dispersed within the matrix
- intercalated: nanoplates are separated by polymer fillers
- exfoliated: nanoplates are completely dispersed within the polymer matrix.

Nanoclay manufacturing risk assessment

Phase II, Stage 2 of the risk management framework describes the assessment of risk per the characterisation of the following elements: the industry (process description), hazards, exposures or exposure potential, and strategies or techniques to mitigate exposure. The following subsections characterise each of these elements for the manufacture of nanoclays. However, a risk assessment has not been completed at this time due to significant data gaps. Additional research to fill these gaps may allow for development of a risk assessment in the future.

Process description

Clay processing is divided into two major groupings: dry state processing or wet. Clay from the dry process is used where purity and appearance characteristics are not critical to the end use. Alternatively, wet processing is conducted to allow further improvement of the clay properties, referred to as “beneficiation” (Michelin, 2013; USEPA, 1995).

Note that no specific information was found specifically concerning the manufacture of nanoclays. However, information from Brell (2000) of Rockwood additives and Tellaetxe et al. (2004) points to a wet processing method.

The wet process for “high grade kaolin products” is assumed to also be applicable to MMT processing until further information is obtained. Wet processing of kaolin begins with blunging to produce a slurry, which then is fractionated into coarse and fine fractions using centrifuges, hydrocyclones or hydroseparators. At this step in the process, various chemical methods, such as bleaching, and physical and magnetic methods, may be used to refine the material. Chemical processing includes leaching with sulfuric acid, followed by the addition of a strong reducing agent such as hydrosulfite. Before drying, the slurry is filtered and dewatered by means of a filter press, centrifuge, rotary vacuum filter or tube filter. The filtered dewatered slurry material may be shipped or further processed by drying in apron, rotary or spray dryers (USEPA, 1995).

Further beneficiation may include chemical treatments, delamination and calcination, depending on application requirements. Chemical treatments such as mercapto-silane coupling agents may be applied to the clay offer more functionality. Resulting rubber products exhibit improved compression set, permanent set and reduced heat build-up (Michelin, 2013).

Delamination is the process of separating the nanoclay stacks into finer platy particles by attrition grinding of slurries using sand or other media to facilitate the process. Such products can add benefit to certain rubber applications where products need higher stiffness, modulus, less die swell or reduced gas permeability (Michelin, 2013).

Hazard characterisation

Martin et al. (2008) found that there are very limited toxicological data available for nanoclays, with only acute (mostly *in vitro*) studies performed, which is consistent with the results of the literature search, as summarised in Table 5.15. Studies that examined ecotoxicity were not identified.

Table 5.15. **Nanoclay toxicity studies**

Source	Summary
Totuska et al. (2009)	Analysed *in vitro* genotoxic effects of kaolin microparticles on human cancer cell line (A549) cells. Results revealed increased micronuclei (MN) frequencies after treatment. Additionally, kaolin nanoparticles induced lung DNA damage and mutagenicity in mice (*in vivo*).
Lordan et al. (2010)	Evaluated the cytotoxicity of unmodified nanoclay, Cloisite® Na+ and the organically modified nanoclay, Cloisite 93A® in human hepatoma HepG2 cells. Data demonstrated nanoclays are highly cytotoxic and as a result pose a possible risk to human health.
Li et al. (2010)	Evaluated toxicity for nanosilicate platelets (NSP) derived from natural montmorillonite clay. The material had been previously shown to be effective for antimicrobial properties and tendency for adhering onto the biomaterial surface based on observations by a scanning electron microscope. Overall, the study demonstrated the safety of the NSP for potential uses in biomedical areas.
Sharma et al. (2010)	Investigated natural clay mineral montmorillonite (Cloisite) Na+ and an organo-modified montmorillonite (Cloisite 30B) for genotoxic potential as crude suspensions and as suspensions filtrated through a 0.2-micron pore-size filter to remove particles above the nanometre range. Filtered and unfiltered water suspensions of both clays did not induce mutations using the tests in the study, but both the filtered and the unfiltered samples of Cloisite 30B induced DNA strand-breaks in a concentration-dependent manner. Further study suggested that the genotoxicity of organo-modified montmorillonite was caused by the organo-modifier. The detected organo-modifier mixture was synthesised and comet-assay results showed that the genotoxic potency of this synthesised organo-modifier was in the same order of magnitude at equimolar concentrations of organo-modifier in filtrated Cloisite) 30B suspensions, and could therefore at least partly explain the genotoxic effect of Cloisite 30B.
Verma et al. (2012)	Investigated cytotoxic effects of platelet and tubular type nanoclays on cultured human lung epithelial cells A549. A low, but significant, level of cytotoxicity was observed at 25 µg/mL of platelet type nanoclays. Results indicate potential hazard of nanoclay-containing products at significantly higher concentrations.
Smirnova et al. (2012)	Analysed intragastric administration of nanoclay to rats. Exposure over 28 days led to reductions in the relative weight of the liver, the activity of its conjugating enzymes, the antagonistic activity of bifidoflora, and the hyperproduction of colonic yeast microflora. The findings lead to the conclusion that nanoclays that may be present in foods must be the object of sanitary regulation.
Lordan et al. (2012)	Investigated the effect of the commonly used growth supplement, fetal calf serum (FCS), concentration on the cytotoxic behaviour of the unmodified nanoclay, Cloisite® Na+ (*in vitro*). Human monocytic U937 cells in medium supplemented with 5% FCS, 2.5% FCS or serum-free medium were treated with 1 mg/mL Cloisite Na+. Cell growth in 2.5% FCS was significantly inhibited by Cloisite Na+ within 48 h, whereas little effect was seen with a supplement of 5% FCS. Without serum, cell growth was inhibited and Cloisite Na+ had a detrimental effect on these cells. In media supplemented with FCS, the nanoclays agglomerated together to form large bundles, whereas they were evenly dispersed throughout the medium in the absence of serum. Clay particles, therefore, have cytotoxic properties that may be linked to their dispersion pattern. These adverse effects seem to be masked by 5% FCS. Serum supplementation is an important consideration in the toxicological assessments of nanomaterials on cells, which needs to be addressed in the standardization of *in vitro* testing methods.

Exposure or exposure potential characterisation

Nanoclays such as MMT and kaolinite are expected to be handled primarily in solid particulate form. However, there were no specific data available to characterise the amount of nanomaterial handled, duration and frequency of exposure, or any other data elements to quantify potential exposures as discussed in the risk management framework.

No information was found concerning specific exposure points associated with nanoclay manufacturing. Particulate matter is emitted from all dry mechanical processes, such as crushing, screening, grinding, and materials handling and transfer operations (USEPA, 1995). Potential occupational exposure pathways associated with the wet production process for “high grade” nanoclay products include inhalation and dermal exposures from dry handling and transfer of clay particles. Specific activities may include, but are not limited to: loading/packaging, spill clean-up and maintenance. Additional exposure pathways listed in Table 5.4 involving solid particles may also be applicable.

Fugitive particulate emissions are potentially emitted from all dry mechanical processes; therefore, the main environmental release media is to air (USEPA, 1995). It is unclear whether there are significant water releases from dewatering operations. Exposure pathways for the general population or aquatic ecological endpoints are dependent on pollution control technologies or waste disposal methods, as illustrated in Table 5.4.

No specific information on nanoclays was found concerning fate and transport of nanoclays.

Strategies or techniques to mitigate exposure

No information was found concerning mitigation specifically for nanoclays. For most clay processing operations, cyclones, wet scrubbers and fabric filters are the most commonly used devices to control particulate emissions. Cyclones often are used for product recovery from mechanical processes. In such cases, the cyclones are not considered to be an air pollution control device. Electrostatic precipitators also are used at some facilities to control PM emissions (USEPA, 1995).

Concluding remarks

Phase II, Stage 1 of the risk management framework (Planning for the Risk Assessment) discusses the need to identify what data are needed and what data are available in order to conduct a risk assessment. There is a general lack of publicly available information pertaining to the hazard potential and the exposure potential associated with the nanomaterials of interest. In an attempt to acquire corporate industrial hygiene, human health, and fate and transport information, input was solicited from industrial stakeholders that manufacture HD-HS silica and nanoclays as well as tyre manufacturers that may use these and other nanomaterials in the future. These stakeholders provided information that was readily available and not considered confidential. However, after assessing the information, it was determined that too many information gaps remain to complete a full risk management plan, even as a case study. Therefore, rather than providing complete case studies, this report presents information that was identified such that it can be used by interested parties as a first step. This information can be used and supplemented by additional data as it becomes available to provide a detailed evaluation.

There are ongoing efforts by industrial stakeholders, academic entities and government organisations to characterise the risk associated with these and other nanomaterials. For example, tyre manufacturing stakeholders are actively trying to identify data that are needed to inform corporate decision makers for their internal product stewardship programmes. Also, some governments are in the process of developing regulations that require testing of certain nanomaterials. Table 5.16 summarises several key risk assessment data gaps that were identified (organised by life-cycle stage). Industrial, government and academic stakeholder decision makers can use this as a guide to help prioritise future research efforts. These could include industrial hygiene studies at nanomaterial manufacturing and tyre manufacturing facilities, toxicological and ecotoxicological studies by industry or academic institutions, and fate and transport studies.

Table 5.16. **Summary of key risk assessment data gaps for nanomaterial use in each life-cycle stage of the tyre industry**

Data required for risk assessment	Data availability
Nanomaterial manufacturing	
Characterisation and physical/chemical properties data	Basic chemical information is available to identify each nanomaterial, such as molecular structure and basic morphology, but there are not well-defined differences to be able to distinguish between certain types of silica, or even nanoclays. Data on physical and chemical properties for each compound at the nanoscale is practically non-existent.
Toxicological data	Only a few published studies have been performed to evaluate toxicological properties of nanosilica and nanoclay. More studies will need to be completed before a full risk assessment is possible.
Exposure data and information	Industrial manufacturing processes of bulk (macro- and microscale) silicas and clays are well characterised; however, information on manufacturing the nanoscale versions is limited. General process descriptions and unit operations can be deduced from literature, but detailed process operation, release and exposure data are not publicly available. Several of these data gaps could be filled with additional information from industry.
Tyre manufacturing	
Exposure data and information	Nanomaterial fillers have not yet been widely implemented for use in tyre manufacturing. Therefore, no specific exposure data are available. Some industry stakeholders expect that nanosilica will be a drop-in replacement for currently used silica (and use the same handling methods), while the method of handling nanoclays will be chosen based on the results of an exposure assessment.
Mounting of tyres on vehicles	
Exposure data and information	Potential exposures to and releases of the nanomaterials are expected to be less likely due to being bound in the polymer matrix. However, no specific studies were identified to verify this assumption.
Use of tyres on vehicles	
Exposure data and information	Tyre wear or blowouts may result in potential nanomaterial releases to the environment. However, no data were found on the release of nanomaterials from the vulcanised rubber and subsequent fate and transport in the environment.
End-of-life tyres	
Exposure data and information	End-of-life tyres may be recovered for reuse, material or energy recovery, or disposal. Therefore, potential exposures and releases will vary depending on the disposition method. No data were found on the exposure to or release of nanomaterials from the vulcanised rubber for any disposition method.
Fate and transport data	Studies to investigate potential leaching of nanomaterials from rubber under end-of-life scenarios (e.g. incineration, landfill) were not identified. Further, data on the fate and transport of nanomaterials after their release from the rubber under end-of-life scenarios is very limited (this data gap is also discussed under the section entitled “Use of tyres”).

NOTES

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[1] At the time of writing, the ISO document was still under development – the latest version available at the time (September 2012) was used.

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CHAPTER 6

ENVIRONMENT, HEALTH AND SAFETY: KNOWLEDGE AND BEST PRACTICE TRANSFER

This chapter examines some of the initiatives aiming to the transfer of best practice for addressing environmental, health and safety (EHS) concerns regarding the use of nanotechnology in general, and most specifically in the tyre industry. It reviews 24 initiatives at the national and international levels aiming to support knowledge transfer in the area of EHS. The chapter also highlights the nature of the challenges met by policy makers in developing and exchanging EHS best practices.

Whilst many governments are actively engaged in international collaboration, the rapidly evolving nature of nanotechnology poses several challenges to developing regulatory approaches. As such, a growing number of guidelines and voluntary approaches have emerged. Despite this growth, there appears to be some convergence as a small number of references were frequently referenced as being good resources. These include publications from the OECD, NIOSH resources, the DuPont/EPA Nano Risk Framework, standards development organisations such as the International Organization for Standardization (ISO).

This chapter aims to analyse how best practices for dealing with environment, health and safety (EHS) concerns are being shared. It reviews examples of knowledge-sharing initiatives at the national and international levels.

Analysis of knowledge-sharing initiatives

A list of knowledge and best practice transfer initiatives that could be relevant to the tyre industry is reviewed in Table 6.1. Due to the large number of initiatives globally, the most relevant were selected based on consultations with experts. The initiatives are categorised against each of the following aspects:

- Objectives:
    - Best practice: aim to develop or review the state-of-the-art in terms of dealing with EHS concerns.
    - Standardisation or harmonisation: aim to develop standardised approaches for managing the EHS concerns. In contrast to best practice, these initiatives tend to focus on “minimum consistent standards” rather than the best approaches available.
    - Guidelines: aim to outline approaches at high level and present information in a simplified way; they are not intended to be comprehensive.
    - Inventories: aim to collate existing approaches for dealing with the EHS concerns.
    - Research: aim to develop further knowledge and understanding of the EHS issues.
- Primary audience:
    - tyre industry: including closely related industry areas such as suppliers to the tyre industry
    - general industry: includes other industry areas such as general manufacturing
    - policy makers
    - academia.
- Life-cycle stage:
    - manufacturing
    - in-use
    - end-of-life: aspects relevant to the treatment of waste tyres.
- Nanomaterials:

- general nanotechnology
- specific materials: particularly those used in the tyre industry.

In terms of the primary audience (tyre industry, general industry, policy makers or academia), the majority of initiatives are relevant for general industry and/or policy makers. With the exception of the guidelines developed in this study, the only initiatives found that specifically targeted the tyre industry were led by industry.

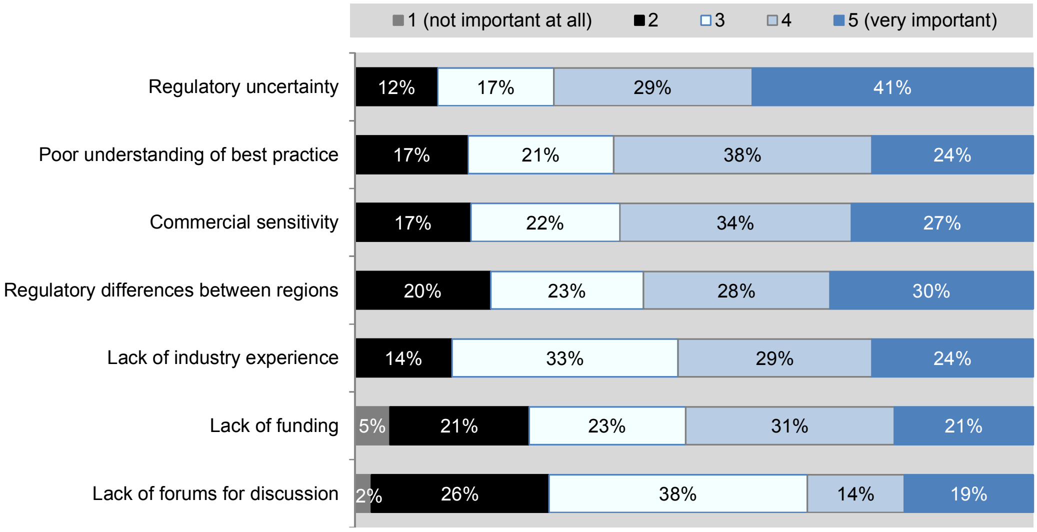
All life-cycle stages are covered by at least some initiatives, although the majority focus on the manufacturing stages. Specific guidance and information on end-of-life aspects specifically for nanotechnology applications in tyres was missing, although end-of-life issues were discussed in general terms by several publications. The Tire Industry Project/ChemRisk guidelines plan to eventually cover this aspect, but at the time of writing the guide was still under development.

Finally, there is a lack of guidance on specific nanomaterials, although as noted in the conclusions for Chapter 5, publicly available information on specific nanomaterials is generally scarce.

Analysis of stakeholder views

As part of a survey carried out for this study, stakeholders in government, academia and industry were sent questionnaires on various aspects of nanotechnology in tyres. A question on knowledge sharing asked: “How important do you feel each of the following are in terms of barriers to knowledge sharing?”, with answers provided on a scale of 1 (not important at all) to 5 (very important). The responses are shown in Figure 6.1. Regulatory uncertainty was perceived as being the biggest barrier to knowledge sharing. The current lack of regulatory clarity and the uncertainty around potential risks have a negative impact on the extent to which nanomaterials are developed. A lack of forums for discussion and a lack of funding were assigned the lowest average scores.

Figure 6.1. **Survey responses to the question: “How important do you feel each of the following are in terms of barriers to knowledge sharing?”**



Note: Total of 43 responses to this question (respondents were permitted to skip any question in the survey).

Table 6.1. **Review of knowledge and best practice-sharing initiatives for the tyre industry**

Responsible organisation and initiative	Objectives					Primary audience				Lifecycle stage			Nanotech	
	Best practice	Standardisation	Guidelines	Inventories	Research	Tyre industry	General industry	Policy makers	Academia	Manufacturing	In-use	End-of-life	General	Specific
International organisations														
OECD Working Party on Manufactured Nanomaterials: Series on the Safety of Manufactured Nanomaterials	(✓)		✓	✓	(✓)		✓	✓		✓	✓	✓	✓	(✓)
OECD Working Party on Manufactured Nanomaterials: *Database on Research into the Safety of Manufactured Nanomaterials*				✓			(✓)	✓	✓	(✓)	(✓)	(✓)	✓	✓
OECD Working Party on Manufactured Nanomaterials (OECD, 2012): "Planning guide for public engagement and outreach in nanotechnology"	✓		✓				✓	✓					✓	
OECD Working Party on Manufactured Nanomaterials (OECD, 2008): "Inventory of national science, technology and innovation policies for nanotechnology"				✓			✓	✓					✓	
International Council on Nanotechnology (ICON, 2013): *The Good Nano Guide*	(✓)		✓	✓			✓		✓	✓	(✓)	✓	✓	✓
International Organization for Standardization: ISO TS 12901-1 and TS 12901-2	✓	✓		(✓)			✓	✓		✓	✓	✓	✓	✓
United Nations Environment Programme (UNEP, 2011): "Technical guidelines addendum – Revised technical guidelines for the environmentally sound management of used and waste pneumatic tyres"	(✓)		(✓)			(✓)	(✓)	(✓)			(✓)	(✓)		
National and regional initiatives														
European Commission: Framework Programme research projects, e.g. ObservatoryNano and NANOSAFE, ENRHES			✓	✓	✓		✓	✓	✓	✓	(✓)	(✓)	✓	(✓)
European Commission (European Commission, 2008): "Recommendation on a code of conduct for responsible nanosciences and nanotechnologies (N&N) research"			✓				✓	✓	✓				✓	
European Commission (European Commission, 2012): "Working safely with engineered nanomaterials and nanoproducts"			✓				✓			✓	✓		✓	
Nanoscale Science and Engineering Forum (NSEF)				✓	✓		✓		✓				✓	✓
British Standards Institute (British Standards Institute, 2007): *Nanotechnologies – Part 2: Guide to Safe Handling and Disposal of Manufactured Nanomaterials*	✓	✓					✓		✓	✓		(✓)	✓	✓
Institut de recherche Robert-Sauvé en santé et en sécurité du travail (IRSST)	✓			✓			✓	✓	✓	✓	(✓)	(✓)	✓	✓
National Institute for Occupational Safety and Health (NIOSH)	✓	✓		✓	✓		✓	✓	✓	✓	✓	(✓)	✓	

Table 6.1. **Review of knowledge and best practice-sharing initiatives for the tyre industry** (*cont.*)

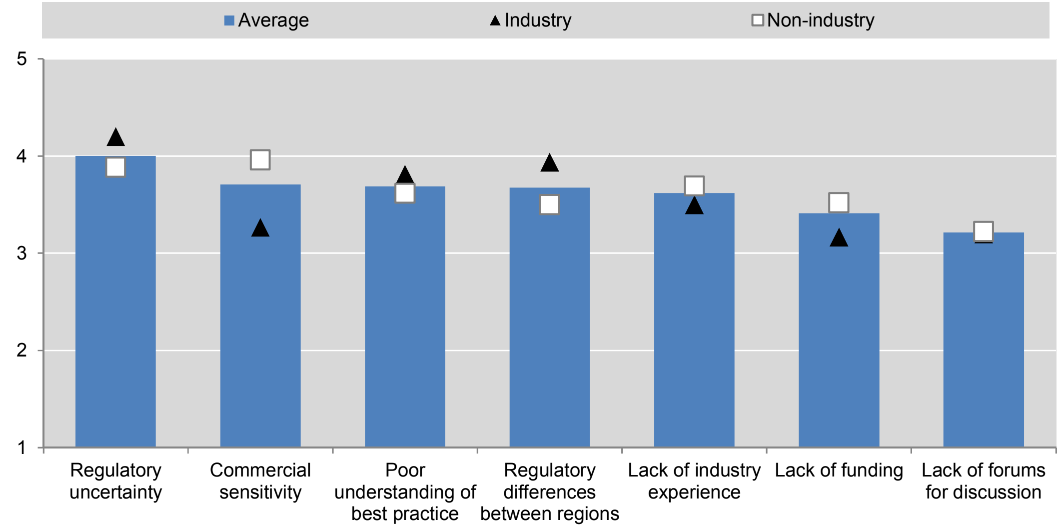
Responsible organisation and initiative	Objectives					Primary audience				Lifecycle stage			Nanotech	
	Best practice	Standardisation	Guidelines	Inventories	Research	Tyre industry	General industry	Policy makers	Academia	Manufacturing	In-use	End-of-life	General	Specific
German Federal Institute for Occupational Safety and Health and German Chemical Industry Association (BAuA/VIC, 2007): “Guidance for handling and use of nanomaterials at the workplace”			✓				✓			✓			✓	
NanoKommission (NanoKommission, 2010): “Guidelines for collecting data and comparing benefit and risk aspects of nanoproducts”			✓				✓	✓		✓	✓	✓	✓	
National Research Council (National Research Council, 2012): *A Research Strategy for Environmental, Health, and Safety Aspects of Engineered Nanomaterials*					✓			✓	✓	✓	✓	✓	✓	
Dutch Ministry of Social Affairs and Employment (Dutch Ministry of Social Affairs and Employment, 2011): “Guidance: Working safely with nanomaterials and nanoproducts”			✓				✓			✓	✓		✓	
European Committee for Standardisation (CEN): CEN/TC 352		✓					✓	✓		(✓)	(✓)	(✓)	✓	
Massachusetts Office of Technical Assistance (OTA, 2011): “Nanotechnology – Considerations for safe development”			✓				✓		✓	✓			✓	
Industry-led initatives														
Tyre Industry Project/ChemRisk (2011 version): “Framework for best practice guidelines for development and use of nanomaterials in the tyre industry”	✓	(✓)	✓		✓	✓				✓	✓	✓	✓	

European Chemical Industry Council (CEFIC, 2012): *Responsible Production and Use of Nanomaterials*	✓		✓	✓	✓	(✓)	✓	✓		✓	✓	✓	✓
Saint Gobain: EHS code of conduct applying to nanomaterials & related products			✓				✓			✓			✓
US Environmental Defense and DuPont (US Environmental Defense and DuPont, 2007): “Nano risk framework”	✓		✓				✓			✓	✓	✓	✓

Key: ✓ = aspect is directly covered by the initiative; (✓) = aspect is partially/indirectly covered. In terms of the objectives, the different initiatives include a mixture of best practice development, standardisation, guidelines, knowledge inventories and research. It is appropriate to encompass all of these objectives while knowledge in the field of nano-safety continues to develop, as they play different roles in ensuring dissemination of information. For instance, inventories are important resources to draw together the outputs of numerous and ongoing activities, but do not necessarily provide mechanisms to review quality or specifically interpret the information. International initiatives are important to develop a co-ordinated approach to deal with the regulatory challenges (e.g. due to uncertainties in the behaviour of nanomaterials, their application in many different industries and the lack of appropriate standards and validated testing procedures). Guidelines and voluntary approaches are therefore crucial in the interim. Other measures focus more on improving understanding of whether manufacturers choose to participate in voluntary schemes, for example the CEFIC (2012) publication “Responsible production and use of nanomaterials”, which aims to share information on what specific companies are doing in the area of nano-safety. These initiatives are not on their own sufficient to ensure best practice, but complement the use of guidelines and codes of conduct. Comprehensive reporting may be difficult to implement without internationally agreed standards, in order to avoid inconsistent requirements.

Figure 6.2 compares the average score given by industry and non-industry stakeholders for the above question. In general, it appears that industry stakeholders perceive regulatory issues (uncertainty and differences between regions) to be a bigger barrier compared to non-industry stakeholders (including policy makers and academia). Conversely, industry stakeholders appear to view commercial sensitivity as somewhat less of an issue compared to non-industry stakeholders, although it was emphasised that best practice transfer should not include intellectual property or confidential business information.

Figure 6.2. **Comparison between industry and non-industry responses: Average scores for responses to the question "How important do you feel each of the following are in terms of barriers to knowledge sharing?"**



Note: Total of 43 responses to this question, with 25 (58%) from industry.

Concluding remarks

This chapter reviewed 24 initiatives at the national and international levels. The need for international collaboration and co-ordination is well understood; however, whilst regulatory authorities have generally been proactive in developing approaches, the rapidly evolving nature of nanotechnology poses several challenges. As such, a growing number of guidelines and voluntary approaches have emerged.

Despite this growth, there appears to be some convergence in the recommended approaches. The reviewed guidelines typically refer the user to more detailed information in other publications, a small number of which were frequently referenced as being good resources. These include publications from the OECD Working Parties on Nanotechnology and Manufactured Nanomaterials, NIOSH resources, the DuPont/EPA Nano Risk Framework, and consensus-based standards published by national and international standards development organisations such as the International Organization for Standardization (ISO).

The review found that there were key data gaps relating to the following areas:

- There is a lack of industry-specific guidelines, which was also highlighted by stakeholders as a barrier to innovation in nanomaterials in the tyre industry. In an effort to close this gap, Chapter 5 sets out a general risk framework that can be used by industry, which should be supported by communication between stakeholders and dissemination of reliable information on nano-safety.

- There is a need for better coverage of end-of-life tyres. The only initiative that considers end-of-life tyres in a nano-safety context is the TIP/ChemRisk publication that was still under development at the time of writing.
- Finally, there is a lack of guidance on specific nanomaterials used in the tyre industry. This issue relates to the general state of nano-safety understanding, and is already the subject of much research effort globally.

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ANNEX A
STAKEHOLDER ENGAGEMENT

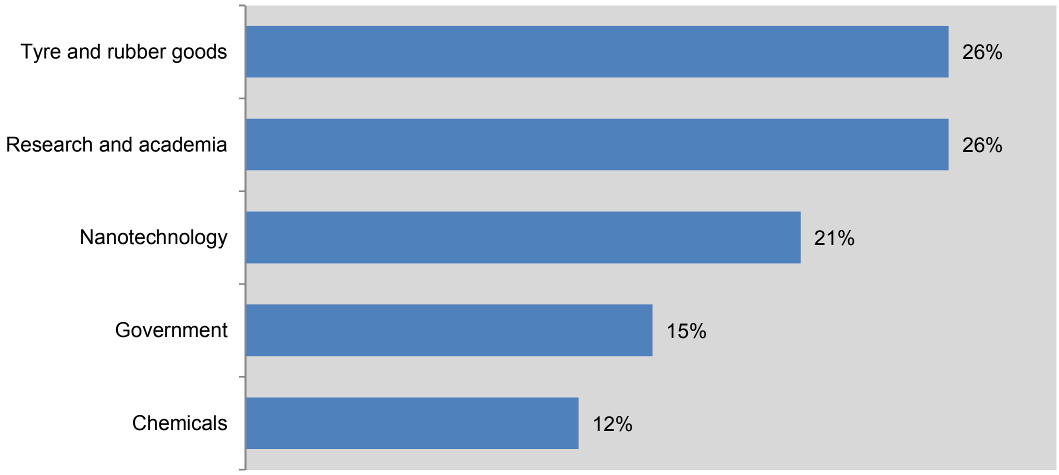
Methodology and limitations of stakeholder engagement

Stakeholders were engaged as part of this study via an online survey and interviews. To ensure broad coverage, the survey was sent to a list of stakeholders in industry, academia and government. It contained questions on the relative importance of different factors affecting innovation, commercialisation and knowledge sharing with respect to nanotechnology in tyre production. All questions were based on a 5-point Likehert scale, ranging from 1 (the factor is considered to be not important at all) to 5 (the factor is considered very important). The survey was followed up with interviews with selected participants to seek further input.

A total of 56 responses to the online survey were received (after screening the results for quality and relevance). Although large companies in the tyre and chemical industries are typically multinationals, the responses were grouped according to the location of the individual responding on their behalf. The majority of individuals identified themselves as being from Europe (32), with a smaller number being from the United States (10), Asia (7) and other world regions (7).

Individuals from most major tyre manufacturers participated, with respondents from companies representing almost two-thirds of global tyre market sales. Figure A.1 shows the percentage of survey respondents from different industry areas, with the majority being from the tyre and rubber goods industry (26%) and from research/academia (26%).

Figure A.1. **Percent of stakeholders from each industry area**



The aims of the stakeholder engagement task were to gather opinions on the relative importance of different factors and develop a deeper understanding of key issues specific to the tyre industry. The results cannot be generalised to all stakeholders as they are subject to well-understood limitations, namely that a relatively small sample was collected, that responses were entirely voluntary and that the opinions are subjective. In addition, some stakeholders co-ordinated responses from multiple parts of their organisations whereas others submitted responses based on their individual opinions. There was no attempt to weight the responses to account for this.

With these limitations in mind, the responses were used in the following way:

- To validate draft findings: the survey was compiled after initial research into the various factors was completed. Survey respondents were asked to rate the importance of these different factors and were also given an opportunity to suggest additional factors that might have been missed for each question.
- To gain a deeper understanding of different points of view: the distribution of responses to each question was examined to ascertain the level of agreement between stakeholders. The responses from different stakeholder groups (by region, by industry area, etc.) were compared to see if any differences emerged. It should be noted that splitting responses into subgroups further reduces the sample size, and therefore the results were interpreted as an indication only.
- To provide guidance for further research and interview topics: numerical results from the survey are not used in the main report. Rather, the responses were used to provide guidance for additional research and further explored some areas in interviews.

For each question, the overall distribution of answers was reviewed and responses were split by stakeholder type and region. Any interesting points were then explored further using literature review and interviews. Any results that were included in the main report are clearly shown as being from the stakeholder engagement task.

ANNEX B
DATA, ASSUMPTIONS AND RESULTS FROM THE SOCIETAL COST-BENEFIT MODEL

This annex provides an overview of the model inputs and assumptions relating to:

- baseline (without new nanotechnology) tyre market size and characteristics
- nano-enabled tyre market uptake scenarios
- cost-benefit model development.

The quantitative analysis in Chapter 3 considers only the passenger car market, as insufficient data were available to model the impacts on the truck market.

Baseline tyre market size and characteristics: Detailed method

This section summarises the sources for the data needed in the above described method.

Average reference tyre prices

Average retail prices for a premium tyre were estimated by taking the average price of ten tyres from major brands sold in each region and rounding to the nearest US dollar. An additional cost was added to account for mounting and balancing of each tyre.

Table B.1. **Current (2013) average retail prices for reference tyres**

In USD

Region	Tyre size	Premium tyre price including tax	Premium tyre price excluding tax	Cost to fit each tyre (mounting, balancing)	Assumed tax rate
Europe	195/65 R 15	139	111	15	20%
Europe	205/55 R 16	170	135	15	20%
United States	P265/70R17	182	173	15	5.6%
China	195/65 R 15	105	87	9	17%

Notes: Exchange rates assumed at CNY 1 = EUR 0.1259 and USD 1 = EUR 0.77; tyre fitting costs from TRB (2006) and inflated to 2013 prices and applied to United States and Europe; for China, tyre fitting costs were multiplied by a PPP conversion factor of 0.6 (World Bank: http://data.worldbank.org/indicator/PA.NUS.PPPC.RF).

Sources: For Europe, see www.national.co.uk; for the United States, see www.tirerack.com; for China, see www.tyrepac.com.cn.

Table B.2. **Summary of parameters and data sources for baseline tyre market model**

Parameter and definition		Source	Calculation
$TS_{r,k}$, $TSR_{r,k}$	Tyre sales in region *r* in time period *k*, respectively for original equipment manufacturers (OEM) and replacement market	(1)	The modelled tyre market consists of two parts: OEM tyre market and replacement tyre market. The replacement market is further split into premium and non-premium segments.
N, NR	Number of tyres on new vehicles and replacement vehicles	(2)	Represents the number of tyres on each new vehicle (average).
$VS_{r,k}$	Vehicle sales in region *r* for time period *k*	Calculated	From the OEM tyre market size, effective vehicle sales are calculated as follows: [1] $\forall r, \forall k, VS_{r,k} = TS_{r,k} / N_r$
P_i	Proportion of premium tyres in replacement market	(1)	The size of premium market segment *i* expressed in percent.
L_i	Average lifespan of tyres in market segment *i*	(1)	Average lifetime of tyres, expressed in km.
$LN_{r,k}$, $LR_{r,k}$ ($L_{r,k,i}$, & $P_{i,r,k}$)	Average lifespan of tyres on new vehicles for OEM and replacement market	Calculated	Represents the average lifespan of replacement tyres. Note that the resulting vehicle kilometres are not those driven in period *k*, but those associated with replacement tyres bought in period *k*. Average replacement tyre lifespan is a weighted average of the average lifetime of tyres in the premium and non-premium market segments as shown below: [2] $\forall r, \forall k, LR_{r,k} = \Sigma_i L_{i,r,k} * P_{i,r,k}$
$MN_{r,k,}$ $MR_{r,k}$	Vehicle kilometres associated with the OEM/ replacement tyres sold in year *k* in region *r*	Calculated	Average replacement tyre lifespan is a weighted average of the average lifetime of tyres in the premium and non-premium market segments. The average lifetime mileage associated with these OEM tyres using average OEM tyre lifespan as follows: [3] $\forall r, \forall k, MN_{r,k} = VS_{r,k} * LN_{r,k} \forall r, \forall k, MN_{r,k} = VS_{r,k} * LN_{r,k}$ Similarly, using the replacement market size, tyre lifespan and number of replacement tyres per vehicle, total vehicle-kilometres associated with replacement tyres sold in each year are calculated as follows: [3] $\forall r, \forall k, MR_{r,k} = TSR_{r,k} * LR_{r,k} / NR_r \forall r, \forall k, MR_{r,k} = TSR_{r,k} * LR_{r,k} / NR_r$
M	Total mileage associated with tyres over their lifetimes	Calculated	The total mileage, *M*, associated with the baseline tyre market is thus: [4] $\forall r, \forall k, M_{r,k} = MN_{r,k} + MR_{r,k}$ Where $MN_{r,k}$ and $MR_{r,k}$ are as calculated above, and $M_{r,k}$ is the total vehicle-kilometres (v-km) associated with the tyres sold in year *k* in region *r*.

$FP_{t,r,k}$	Proportion of total v-km driven by vehicles of powertrain type *t* in region *r* in period *k*	(3), (4)	Projections for the vehicle fleet composition in each region in terms of powertrains (gasoline, diesel, electric vehicles etc) were provided by the IEA, based on the Mobility Model (MoMo). The reference "4 degrees" scenario was taken as the baseline. The proportion of total v-km driven by vehicles of powertrain type *t* includes an adjustment factor for electric vehicles, which reflects the lower expected mileage of these vehicles compared to ICE vehicles. This starts at 60% in 2010 and rises to 100% by 2025.

Table B.2. **Summary of parameters and data sources for baseline tyre market model** (*cont.*)

Parameter and definition		Source	Calculation
$FE_{t,r,k}$	Fuel efficiency (MJ/km) of powertrain *t* in region *r* during period *k*	(3)	Fuel economy values represent average fuel consumption for different powertrains based on the average test cycle efficiency.
ΔFE	Adjustment factor to represent "real world" fuel efficiencies	(3)	To reflect observed differences between fuel efficiency achieved in real world driving conditions and those achieved in vehicle test cycles.
$BP_{r,k,}$ $BDP_{r,k}$	Proportion of biogasoline/biodiesel in blend	(3), (4)	The assumed source of the biogasoline/biodiesel affects the calculation of emission factors.
$EP_{r,k}$	% electricity assumed to be used by PHEVs	(3)	Assumed to remain at an average of 50%.
$FC_{t,r,k}$	Share of fuel consumption for each powertrain type	Calculated	Fuel consumption and associated emissions are calculated for each fuel type based on the share of v-km of each vehicle category. The calculations account for any improvement in vehicle fuel efficiency and/or tailpipe emissions (air pollution) over time, any changes in the mix of powertrain technologies and differences in the usage (annual v-km) of different powertrain types. First, fuel consumption, *FC*, is calculated for each powertrain type as follows: [5] $\forall t,\ \forall r,\ \forall k,\ FC_{t,r,k} = M_{r,k} * FP_{t,r,k} * FE_{t,r,k} * \Delta FE$ $\forall t, \forall r, \forall k, FC_{t,r,k} = M_{r,k} * FP_{t,r,k} * FE_{t,r,k} * \Delta FE$
F	Total consumption (MJ) of each fuel	Calculated	CNG consumption (MJ): [6] $\forall r,\ \forall k,\ F_{CNG,r,k} = FC_{CNG,r,k}$ $\forall r, \forall k, F_{CNG,r,k} = FC_{CNG,r,k}$ LNG consumption (MJ): [6] $\forall r,\ \forall k,\ F_{LNG,r,k} = FC_{LNG,r,k}$ $\forall r, \forall k, F_{LNG,r,k} = FC_{LNG,r,k}$ Hydrogen consumption (MJ): [6] $\forall r, \forall k,\ F_{Hydrogen,r,k} = FC_{Fuel\ cell,r,k}$ $\forall r, \forall k, F_{Hydrogen,r,k} = FC_{Fuel\ cell,r,k}$ For PHEV/hybrid vehicles, the proportion of energy that is taken from electricity versus the combustible fuel is taken into account when calculating final consumption of fuels. Similarly for gasoline and diesel

			ICE/hybrids, the percentage of biofuels and low sulphur fuel in the mix is considered. For each of the fuels considered the formulae are shown below. Gasoline: [6]$\forall r ,\forall k , F_{Gasoline , r , k} = (1 - BP_{r , k}) * (FC_{Gasoline\ ICE , r , k} + (1 - EP_{r , k}) * FC_{Gas\ PHEV , r , k}$ $\forall r,\forall k, F_{Gasoline,r,k} = (1 - BP_{r,k}) * (FC_{Gasoline\ ICE,r,k} + \left(1 - EP_{r,k}\right) * FC_{Gas\ PHEV,r,k})$ Ethanol: [6]$\forall r ,\ \forall k , F_{Ethanol , r , k} = BP_{r , k} * (FC_{Gasoline\ ICE , r , k} + (1 - EP_{r , k}) * FC_{Gas\ PHEV , r , k}$ $\forall r,\forall k, F_{Ethanol,r,k} = BP_{r,k} * (FC_{Gasoline\ ICE,r,k} + \left(1 - EP_{r,k}\right) * FC_{Gas\ PHEV,r,k})$ Diesel: [6] $\forall r ,\forall k , F_{Biodiesel , r , k} = (1 - BDP_{r , k}) * FC_{Diesel\ ICE , r , k} + (1 - EP_{r , k}) *FC_{Diesel\ PHEV , r , k}$ $\forall r,\forall k, F_{Biodiesel,r,k} = (1 - BDP_{r,k}) * FC_{Diesel\ ICE,r,k} + \left(1 - EP_{r,k}\right) * FC_{Diesel\ PHEV,r,k})$ Biodiesel: [6] $\forall r ,\forall k , F_{Biodiesel , r , k} = BDP_{r , k} * (FC_{Diesel\ ICE , r , k} + (1 - EP_{r , k}) * FC_{Diesel\ PHEV , r , k})$ Electricity: [6]$\forall r ,\forall k , F_{Electricity , r , k} = FC_{Electric , r , k} + EP_{r , k} * (FC_{GasPHEV , r , k} + FC_{Diesel\ PHEV , r , k})$ $\forall r,\forall k, F_{Electricity,r,k} = FC_{Electric,r,k} + EP_{r,k} * (FC_{Gas\ PHEV,r,k} + FC_{Diesel\ PHEV,r,k})$
$EF_{f,p}$	Emission factor of pollutant *p* for fuel *f*	(3)	Emission factors for CO_2 and SO_2 are based on the carbon and sulphur content of fuel, respectively. Emission factors for other air quality pollutants (NOx and tailpipe PM) are based on a weighted average of emission rates from vehicles in each emission standard category in each region and each year.
TTW E	Tank-to-wheel quantity of pollutant *p* from burning fuel *f*	Calculated	Tank-to-wheel (TTW) emissions are calculated as follows: [7] $\forall t,\forall a,\forall r,\forall k, TTW\ E_{t,p,r,k} = M_{r,k} * FP_{t,r,k} * TTW\ EF_{t,p}$
WTT E	Well-to-tank quantity of pollutant *p* from burning fuel *f*	Calculated	The well-to-tank (WTT) factor allows the calculation to include pollutants generated during fuel production, and accounts for changes in the electricity generation mix. Upstream pollutant emissions are calculated on a WTT basis as follows: [8]$\forall f ,\forall p ,\forall r ,\forall k ,WTT\ E_{f , p , r , k} = F_{f , r , k} * WTT\ EF_{f , p}$ $\forall f,\forall a,\forall r,\forall k, WTT\ E_{f,p,r,k} = F_{f,r,k} * WTT\ EF_{f,p}$
$Price_{f,r,k}$	Fuel *f* price per energy unit in region *r* in period *k*	(4)	Fuel prices for gasoline mix, diesel mix, electricity and hydrogen were given in USD/litre per gasoline equivalent. Prices have been converted to USD/MJ using the following conversion factors: 1lge = 31.944 MJ.
$C_{f,,r,.k}$	Costs of buying fuel *f* in region *r* during period *k*	Calculated	Fuel costs are calculated as follows: [9] $\forall f ,\forall r ,\forall k , C_{f , r , k} = F_{f , r , k} * Price_{f , r , k}$ $\forall f,\forall r,\forall k\ C_{f,r,k} = F_{f,r,k} * Price_{f,r,k}$
$RTP_{r,k}$	Average reference tyre price	Calculat	Detail provided below

	in region *r* in period *k*	ed	
$RTC_{r,k}$	Total costs of purchasing reference tyres in the replacement market	Calculated	Tyre purchase costs: [10] $\forall r, \forall k \; RTC_{r,k} = TSR_{r,k} * \sum_i RTP_{i,r,k} * P_{i,r,k}$

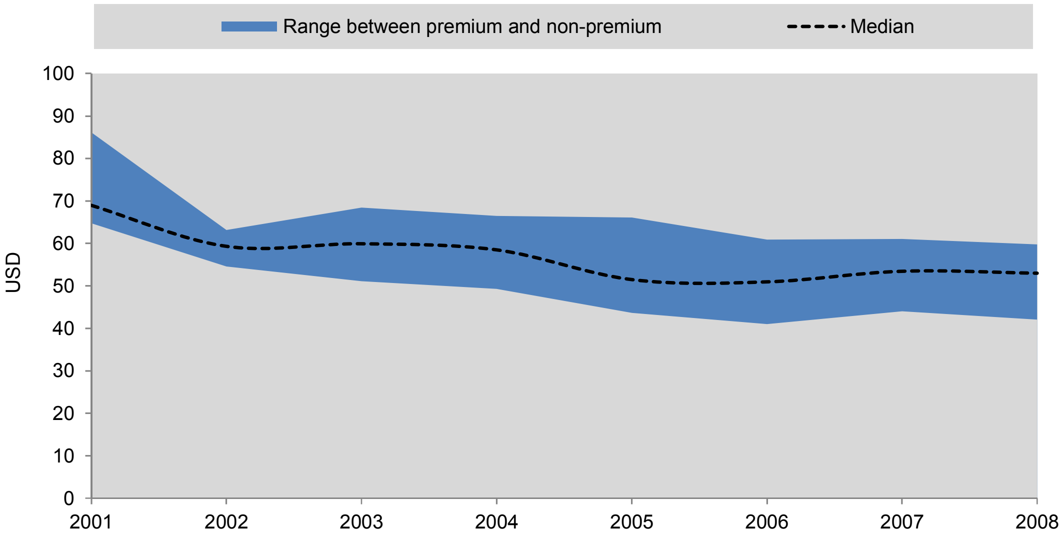
Sources: 1. Based on information from the Tyre Industry Project. 2. Based on *National Highway Traffic Safety Administration* (NHTSA) (2005), “Tire pressure monitoring system”, FMVSS No. 138, Final Regulatory Impact Analysis, Office of Regulatory Analysis and Evaluation National Center for Statistics and Analysis, US Department of Transportation, Washington, DC; Auto Express (2012), “Car manufacturers ditch spare tyres”, *Auto Express*, www.autoexpress.co.uk/car-news/61152/car-manufacturers-ditch-spare-tyres. 3. International Council on Clean Transportation (ICCT) (2012), “Influence of rolling resistance on CO_2”, Series: Worldwide Harmonized Light Vehicles Test Procedure (Wltp), Working Paper 2012-6, ICCT, www.theicct.org/sites/default/files/publications/ICCT_work_rollingresistance_nov2012.pdf. 4. Based on data from the IEA Mobility Modelling.

To find the price difference between premium and non-premium tyres, typical prices for major brands and low-cost replacement tyres of the same size were analysed from Modern Tyre Dealer. The most recent data (2006-08) were used to calculate the average price premium. Only limited data were available for the tyre size being investigated in the US market, so average price premiums for other tyre sizes were used as a guide.

Since the absolute price difference between premium and non-premium tyres appears to increase with tyre size, only the larger tyre sizes were used in the analysis (P235/75R15 and P225/60R16). Combined with the limited data available for P265/70R17 (only for 2006 and 2007), it was found that the average price difference between a premium and non-premium passenger car tyre was around USD 35 (2012 prices), although there was significant variation (from USD 25-60). Similarly, the average percentage increase in price was 46% (26-68%). When these figures were compared to market averages that include smaller tyre sizes, it was found that the percentage increase in price was very similar (average of 46%). Therefore the difference in price between a premium and non-premium passenger car tyre is assumed to be 46%.

Figure B.1 shows that that difference between premium and non-premium prices has remained relatively steady over time; therefore, it is assumed that the figure of 46% can be applied across the time period considered in this study. The same percentage has been assumed for the People’s Republic of China and Europe.

Figure B.1. **Difference in price for premium and non-premium tyre (P195/75R14)**



Source: Based on data from Modern Tyre Dealer, “Tire sales and prices”, for more information see: www.moderntiredealer.com/stats.

Market uptake scenario development

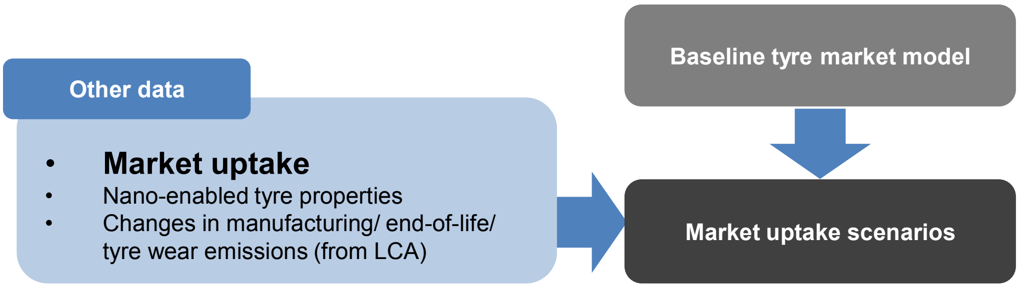
The baseline tyre market model described above was then used to inform the calculations in the different market uptake scenarios. Further data inputs are required to define:

- levels of market uptake
- nano-enabled tyre properties.

This section provides an overview of the calculations and assumptions used to derive these data inputs.

Levels of market uptake

Figure B.2. **Development of the market uptake scenarios**



Experience with tyre technology uptake in the past can provide some indication of feasible penetration rates. Two examples are analysed here:

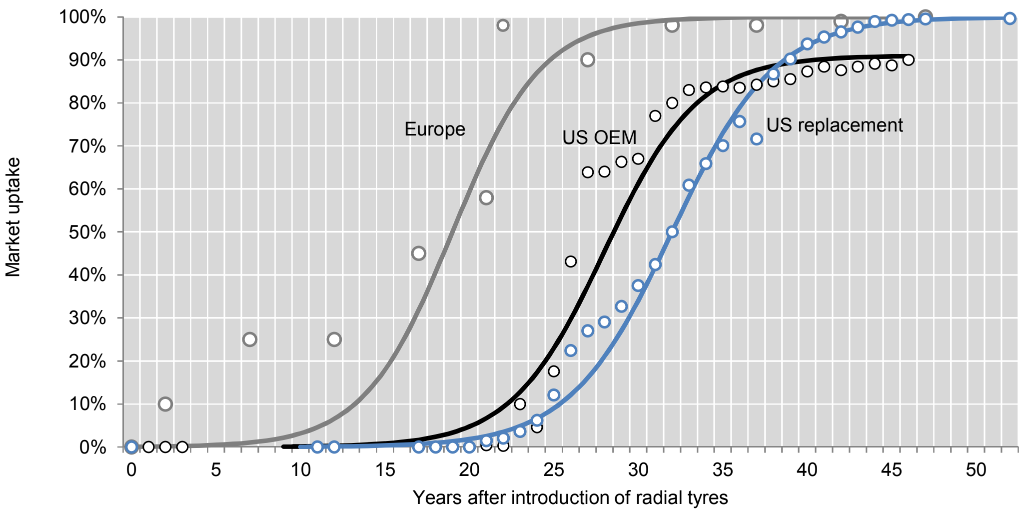
- Transition from bias ply tyres to radial tyres. In radial tyres, the carcass ply cords run mainly perpendicular to the direction of rotation whereas in bias tyres the plies are oriented diagonally. The radial construction provides a more stable tread foundation and a more flexible sidewall. This translates into longer tread life, improved fuel efficiency (25% reduction in rolling resistance), better high speed performance and better traction (Myers, 2006).
- Uptake of silica-containing tyres. Silica-containing tyres were first introduced by Michelin around two decades ago for cars and trucks. Most manufacturers have now developed their own silica-containing tyres.

Historical uptake of new tyre technologies has generally been faster in Europe compared to the United States. For example, Michelin first commercially produced radial tyres in France in 1946 and by 1970, 98% of tires sold in France were radials. The rest of Europe followed a similar path (Rajan et al., 1997). There was a significant delay in the transition to radial tyres in the United States, where in 1970 they represented less than 2% of sales (Myers, 2006), despite the technology being well-known to manufacturers in the United States, who were using it in their European subsidiaries. After the 1970s, uptake in the United States was very rapid.

Only various point estimates of historical market uptake for radial tyres could be found (i.e. market uptake in a specific year). Simple technology uptake curves were developed by combining the point estimates from different sources and fitting a normal distribution through them.[1] Data were differentiated between original equipment manufacturers (OEM) and replacement markets where possible. The results are shown in Figure B.3, where the lines represent data points found in the literature and the curves show the assumed market uptake.

The parameters used to develop the market uptake curves are shown Table B.3. The delay represents the estimated number of years for the market to start taking up the technology after it was first introduced and the diffusion rate shows the estimated number of years taken to reach 50% market penetration.

Figure B.3. **Uptake of radial tyres in Europe and the United States**



Notes: Circles represent data points for market penetration; lines represent an assumed market uptake curve based on a normal distribution. OEM: original equipment manufacturers.

Sources: Myers, A. (2006), "Improved fuel efficiency from nanocomposite tire tread", TDA Research Inc., Final Scientific Report, #DE2006-875756, US Department of Energy, Office of Science, www.osti.gov/scitech/biblio/875756; Modern Tyre Dealer (MTD) (2004), "Consumer tire construction", MTD, www.moderntiredealer.com/stats/viewer.aspx?file=http%3a%2f%2fwww.moderntiredealer.com%2ffiles%2fstats%2ffacts%25202004_p14.pdf; Tata SMG (2008), "Will the MHCV tyre industry finally go radial?", Tata Strategic Management Group, www.tsmg.com/download/article/Radialisation%20in%20CV%20Tyres%20-%20Final.pdf.

Table B.3. **Parameters for market uptake curves (estimates) for radial tyres**

Region	Market	Delay (years)	Diffusion rate (number of years to reach 50% penetration)	Main source
Europe	All	0	20	Myers (2006); Modern Tyre Dealer (2004)
United States	Original equipment manufacturers	8	21	
United States	Replacement	10	23	

This suggests that the main difference between uptake in Europe and the United States was the delay in reaching the US market (as opposed to a slower overall rate of market transformation). The available information also suggests that uptake in the replacement market is slower compared to the OEM market. This intuitively makes sense, as consumers generally have a lower awareness of different tyre technologies compared to the OEMs.

The factors causing the delay in uptake of radial tyres in the United States appear to be unlikely to affect the nano-enabled tyres considered in this study. The delay has been attributed mainly to resistance from US car manufacturers as radials required the suspension system to be redesigned (Rajan et al., 1997). By the 1970s, diffusion of radial tyres from Europe, combined with the oil crisis, helped to stimulate consumer demand for the more fuel-efficient radial tyres. Since the new nanotechnologies considered in this study do not require redesign of the vehicle, and also since the tyre industry is more globalised today, delays in uptake are not considered in the market uptake scenarios used in this study.

Specific data on the market uptake of silica-containing tyres is sparse and the terminology used in the literature is ambiguous. For example, silica-containing tyres are sometimes marketed as “green” tyres, but this term also includes non-silica tyres manufactured with sustainable materials. Similarly, tyres referred to as “energy-saving” or “low rolling resistance” do not necessarily contain silica. Finally, sources do not typically specify whether they refer to the total market or just the OEM/replacement segments. As shown in Table B.4, the resulting overview is rather fragmented, with only a few point estimates obtained for each region and market segment.

Table B.4. **Summary of literature sources on uptake of silica-containing tyres**

Region	Vehicle	Market	Year	Uptake	Terminology	Source
Europe	Car	Unspecified	1998	67%	Silica-containing tyres	Myers (2006)
		Unspecified	2009	70%	Silica-based	Tire Review (2009)
		Replacement	2007	50%	Referring to their own low rolling resistance or green tyres	Michelin (2007)
		Original equipment manufacturers	2011	80%	Based on silica treads	Malaysian Rubber Board (2011)
United States	Car	Unspecified	1998	17%	Silica-containing tyres	Myers (2006)
		Unspecified – assumed to be all	2009	30%	Silica-based	Tire Review (2009)
China	Unspecified	Unspecified	2012	2%	Low rolling resistance	Barclays Capital (2011)
			2020	50%	Low rolling resistance	Barclays Capital (2011)
United Kingdom	Car	Unspecified	2010	20%	Low rolling resistance	AEA (2012)
			2020	100%	Low rolling resistance	AEA (2012)

The various sources appear to indicate that uptake has been faster in Europe compared to the United States. In China, uptake is currently very low, but expected to increase significantly in the next decade. The significant delay seen in uptake could be expected to decrease given China’s emergence as a major automotive market. Table B.5 shows estimated parameters for market uptake curves for silica-containing tyres; however, given the uncertainties outlined above they should be interpreted with caution.

Table B.5. **Parameters for market uptake curves for silica-containing tyres (passenger cars)**

Region	Market (cars)	Delay (years)	Diffusion rate (number of years to reach 50% penetration)	Main source
Europe	Original equipment manufacturers	1 (est.)	~16 (est.)	Malaysian Rubber Board (2011)
Europe	Replacement	1 (est.)	~17 (est.)	Michelin (2007)
China	All	19 (est.)	9 (est.)	Barclays Capital (2011)

Source: Ricardo-AEA estimates.

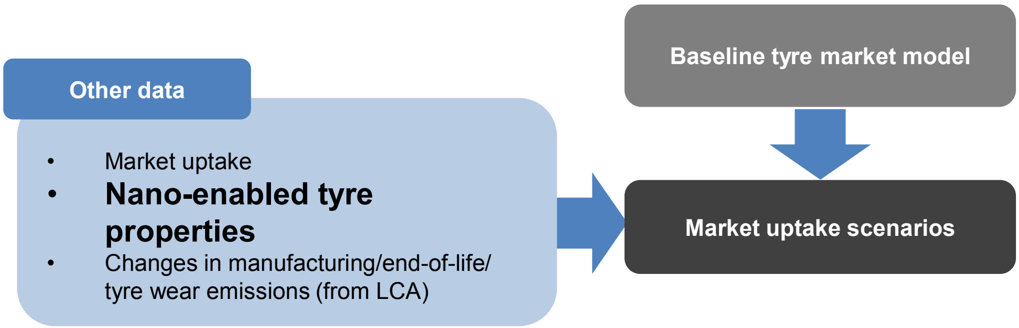
High and low scenarios for market penetration were developed based on the literature review (see Table B.6) and reviewed by tyre industry stakeholders. These are assumed to apply to the new nanomaterials and in all regions, as suitable data were not available to inform more disaggregated estimates. Delays in uptake are not considered to be significant for the nanotechnology uptake scenarios.

Table B.6. **Indicative uptake scenarios for uptake of nano-enabled tyres (passenger cars)**

Market	Diffusion rate (number of years to reach 50% penetration)	
	High	Low
Original equipment manufacturers	16	21
Replacement (premium)	17	23

Performance of nano-enabled tyres: Data and assumptions

Figure B.4. **Performance of nano-enabled tyres**



Performance of HD and HD-HS silica tyres

The performance of highly dispersible (HD) and highly dispersible high surface area (HD-HS) silica tyres was defined as an improvement relative to carbon black tyres, as shown in Table B.7. Note that the different tyre properties can be balanced against each other and manufacturers will design tyres with different combinations for specific purposes.

Table B.7. **Typical performance of highly dispersible and highly dispersible high surface area silica tyres relative to carbon black**

	Rolling resistance	Wear resistance	Wet grip
Carbon black	100	100	100
Highly dispersible silica (“conventional”)	125	95	110
Highly dispersible high surface area silica (“new generation”)	128	118	110

Source: consensus estimates made from interviews with industry stakeholders.

Performance of nanoclay inner liners

Direct improvements from tyres containing nanoclay inner liners cannot be measured, as the benefits arise indirectly due to maintaining tyre air pressure. Under-inflation is one of the most important factors affecting rolling resistance coefficient (RRC) in a tyre (TNO, 2006). In addition, sub-optimal tyre pressure can reduce tyre life and result in poorer vehicle handling.

A simple model was built to assess the performance benefits deriving from improved air retention. The model calculates the impact on fuel consumption and tyre lifetime, accounting for the effect of tyre maintenance habits.

The tyre performance parameters affected by under-inflation include fuel economy and expected tyre life. Impacts on these aspects were calculated as follows:

[11] Impact on fuel economy =$(\Omega_T - \Omega_{NC}) * \rho$

[12] Impact ontyre life = $(\Omega_T - \Omega_{NC}) * \gamma$

Where:

- Ω represents the average percent under-inflation of tyres with traditional inner liner materials (T) and tyres with nanoclay inner liners (NC)
- ρ is the fuel economy coefficient, which gives the percent change in fuel economy for each percent change in average under-inflation
- γ represents the tyre life reduction coefficient, which gives the percent reduction in expected tyre life due to each percent under-inflation.

Since nanoclay inner liners provide an improvement in pressure retention compared to traditional tyres, Ω_{NC} can be expressed in terms of Ω_T as follows:

[13] $\Omega_{NC} = \Omega_T(1-\propto)$

Where α is the reduction in permeability of the nanoclay inner liner compared to the traditional liner materials. Therefore equations [21] and [22] can be reduced to the following:

- [14] Impact on fuel economy = $\alpha * \Omega_T * \rho$
- [15] Impact on tyre life = $\alpha * \Omega_T * \gamma$

The impact of changes in average under-inflation on tyre performance was calculated by assuming a linear relationship between under inflation and tyre performance (constant ρ and γ). Although the relationship is actually more complex, for the modest changes in average under-inflation (as in this case), the difference is not significant.

Average under-inflation for passenger cars

The average rate of under-inflation for passenger cars is affected by several market characteristics:

- average rate of traditional tyre air loss
- consumer behaviour (frequency of checking and inflating their tyres)

- penetration of tyre pressure monitoring systems (TPMS) in the fleet
- the sensor level for TPMS.

Average under inflation for a consumer with no TPMS system, $\Omega_{\text{no-TPMS}}$, is defined as follows:

- [16] $\Omega_{no-TPMS} = \frac{IPLR*m}{2}$

Where IPLR is the monthly inflation pressure loss rate (in percent), m is the number of months elapsed between autonomous (not prompted by tyre failure or other events) tyre pressure refills.

For consumers with a TPMS installed, assuming 100% of consumers respond to the signal by refilling their tyres, Ω_{TPMS}, is defined as follows:

- [17] $\Omega_{TPMS} = \begin{cases} \frac{IPLR*m}{2}, & \sigma * m < \lambda \\ \frac{\lambda}{2}, & \sigma * m \geq \lambda \end{cases}$

Where λ is the TPMS threshold (the level of under inflation at which the sensor is triggered). However, the response of drivers to the TPMS signal is not 100%, i.e. some drivers will ignore the signal. Therefore, average under-inflation for traditional tyres, Ω_{T}, is given by:

- [18] $\Omega_{\text{T (cars)}} = \Omega_{\text{TPMS}} * \theta + \Omega_{\text{no − TPMS}} * (1 - \theta)$

$$\Omega_{T(cars)} = \Omega_{TPMS} * \theta + \Omega_{no-TPMS} * (1 - \theta)$$

Where θ represents the percentage of drivers who respond to the TPMS signal. A summary of the parameters used to calculate the impacts of nanoclay inner liners on the passenger car market is shown in Table B.8.

Summary of nanoclay inner liner impacts

Table B.9 shows how the performance benefits from nanoclay inner liners vary depending on the market characteristics. In Europe, performance benefits are much smaller for cars with TPMS because the threshold is set at 20% compared to 25% in the United States. In China, the potential benefits are higher because of the higher inflation pressure loss rates in this region (2.81% per month on average compared to 2.34% in the United States). In the cost-benefit analysis model, the average improvement for passenger cars is a weighted average of TPMS/no TPMS figures, which is calculated based on the year of mandatory introduction and new vehicle sales. For trucks, lack of data availability meant that only a single estimate of performance impacts could be made for all regions.

Cost-benefit model: Data and assumptions

The cost-benefit model aims to monetise the main environmental impacts, using damage costs per tonne of pollutant and discounting the costs to net present value. Table B.10 summarises the data sources used for these inputs.

Inputs on the cost and price of nano-enabled tyres are also required in order to calculate changes in consumer and producer surplus. Since this information is confidential, several assumptions have been made to calculate these inputs. These are outlined in the following sections.

Manufacturing cost and retail price for HD and HD-HS tyres

Literature sources estimate the additional manufacturing cost of silica-containing low rolling resistance tyres to be around USD 1 (TRB, 2006)[2] and between USD 2 and USD 6 (*National Highway Traffic Safety Administration*, 2010). Interviews with tyre manufacturers suggested that, while initially, the manufacturing cost of conventional HD silica tyres was higher, these costs have reduced over time and are no longer significant. Given this, the additional cost for manufacturing conventional HD silica tyres is assumed to be USD 2 per tyre (EUR 1.60), in line with the lower-bound estimate in *National Highway Traffic Safety Administration* (2010).

Table B.8. **Summary list of parameters and sources for passenger cars**

	Parameter	Value	Assumption	Sources
α	Permeability improvement of nanoclay inner liner compared to traditional liner materials	30%	Final value chosen in collaboration with tyre industry stakeholders to be representative of typical performance.	Alipour (2011); TNO (2013); Suchiva and Siririttikrai (2013); Krishanamoorti (2010); Thomas and Stephen (2010)
ρ	Fuel economy coefficient for passenger cars	0.308	The relationship between under-inflation and fuel consumption, although not perfectly linear, can be considered so for under-inflation values below 30%. A large number of studies were consulted and estimates gathered vary between 0.1% and 0.4%. A value of 0.308% decrease in fuel economy for each 1% reduction in tyres pressure (based on Sivinski, 2012) was used for the model.	Sivinski (2012) for final value. Other sources included: Rouckhout (2013); Wadell (2008), NHTSA (2005), Booz Allen Hamilton Inc. (2003), Energy and Environmental Analysis INC. (2001)
γ	Tyre life reduction coefficient for passenger cars	0.56	Average of Goodyear (2013) and NHTSA (2005) taken.	Goodyear (2013) states that a 1% drop in pressure will reduce tyre mileage of 0.53%, while NHTSA (2005) states that a 1psi under-inflation will reduce tyre life by 1.78%. As typical car tyre placard pressure in psi is 30, a 1% under-inflation is equivalent to 0.3psi and relative life reduction is 1.78/3 = 0.59%.
m	Number of months elapsed between autonomous (not prompted by tyre failure or other events) tyre pressure refills	12	Tyres will be periodically checked by users. We estimate an average of 12 months between checks for passenger cars, in line with annual servicing of the vehicle. In general, it is very difficult to tell if a tyre is under-inflated by visual inspection and/or by the feel of driving the vehicle, so these types of checks are considered ineffective in the model.	NHTSA (2005) provides survey data for US consumers, showing a distribution of frequency in checking tyres.
λ	Tyre pressure monitoring system (TPMS) threshold	20-25%	In the United States, TPMS are mandatory for all new light vehicles (since September 2007) and the under-inflation detection threshold is 25%. In Europe, TPMS are mandatory for all new types of passenger vehicle (since November 2012) and for all new passenger	NHTSA (2005); EC Regulation No. 661/2009; International Council on Clean Transportation (2011)

			vehicles from November 2014. The detection threshold is initially set at 20%, with a second-stage threshold of 15% under consideration. In China, a voluntary standard has been drafted with a 25% under inflation detection threshold.	
IPRL	Inflation pressure loss rates	2.3-2.8%	Average values depend on region.	Rouckhout (2013) provides average values for IPRL in different geographic areas, derived from a survey carried out on 58 sets of tyres purchased in the United States, Europe and Asia Pacific.
θ	Proportion of drivers responding to TPMS signal	50%	The model is set with a TPMS effectiveness at 50%, based on *ex post* estimates of user response to TPMS.	While NHTSA (2005) estimates this reaction to be 90% (*ex ante*), Sivinski (2012), in a study for the NHTSA, concludes that TPMS are only 55.6% effective in preventing severe under-inflation (*ex post*).

Table B.9. **Summary of nanoclay inner liner performance impacts compared to traditional liner materials**

	Passenger cars				
	With tyre pressure monitoring system		No tyre pressure monitoring system		
	United States	Europe	United States	Europe	China
Impact on fuel consumption	+1.06%	+1.00%	+1.3%	+1.94%	+2.17%
Impact on tyre life	+1.84%	+1.73%	+2.25%	+3.37%	+3.76%

Table B.10. **Summary of parameters and data sources for the cost-benefit model**

Parameter	Data source	Notes
External cost – CO_2	CE Delft (2008)	In general, there are two main approaches to the valuation of the cost of greenhouse gas emissions. The first is the damage cost approach, which can intuitively be explained as an evaluation of total costs under the assumption that no efforts are taken to reduce the pace of climate change. It implies the incorporation of various effects connected to changes in sea level, landscape, fresh water availability, vegetation, etc. The second is the abatement cost approach, which evaluates the cost of achieving a given amount of emissions reduction. The estimation of full damage costs is desirable from a scientific point of view (as it allows for full quantification of the external effects). However, this approach suffers from extremely high uncertainty due to the complex global pathways of various effects and long time horizons involved. On the other hand, the use of abatement cost figures is a theoretically sound alternative – we have used the central abatement costs given in the IMPACT (2008) reference (CE Delft, 2008).
Damage cost – air pollutants (NOx, PM, SO_2)	PRIMES Transport Module; *National Highway Traffic Safety Administration* (2010)	Damage costs estimate the reductions in health damage costs per tonne of emissions of each pollutant that is avoided. These savings represent the estimated reductions in the value of damages to human health resulting from lower atmospheric concentrations. Values are different for different regions and for urban and inter-urban areas (due to differences in the baseline incidence rate, the size of the potentially affected population).
Discount factor	*National Highway Traffic Safety Administration* (2010)	A social discount rate (3%) is assumed for the main analysis (other discount rates will be applied in the sensitivity analysis).
Rebound effect	Maxwell et al. (2011)	Based on studies in OECD countries, the rebound effect is estimated to be between 10-30% (20% used in default scenario, which 10% and 30% are used in the sensitivity analysis.
Manufacturer margin on reference tyres	Barclays Capital (2011)	Assumed to be around 10%, based on five-year average margins on passenger car tyres for Continental, Pirelli and Michelin.

The manufacturing process used for HD-HS silica tyres is similar to that used for standard HD silica tyres. Furthermore, interviews with industry experts indicated that the additional cost of HD-HS silica as a raw material could be at least partially offset because the mixing step would be easier although actual cost estimates were considered confidential. Therefore, it was assumed that the additional cost of manufacturing HD-HS silica tyres is in line with the upper estimate of USD 6 (EUR 4.80) additional cost per silica-containing tyre given in *National Highway Traffic Safety Administration* (2010).

High estimates of the additional retail price for these technologies were based on a mark-up on the additional material cost of 500% (California Air Resource Board, 2008). Low estimates of additional retail price for these technologies were based on figures from European Policy Evaluation Consortium (2008), which indicated a price premium of EUR 7 (USD 9.10) for a tyre (unspecified technology) moving from labelling band B to band A for RRC under the European labelling system. This was applied to HD silica, and a further price premium of EUR 7 (USD 9.10) per tyre added for HD-HS silica. The resulting assumptions for additional cost and retail price are shown in Table B.11.

Table B.11. **Additional cost and price for highly dispersible silica and highly dispersible high surface area silica tyres**

In USD

	Conventional HD silica	New generation HD-HS silica
Additional cost per tyre	2.0	6.0
High additional retail price	12.0	36.0
Low additional retail price	8.9	17.8
Mid additional retail price	10.5	26.9

Material cost estimates for nanoclay inner liners

The change in material cost due to the use of nanoclay was also calculated. Nanoclay is more expensive per kilogramme compared to conventional inner liner materials, and it was assumed that nanoclay will replace carbon black in the inner liner composition. Due to limitations on tyre manufacturing process capability, it was assumed that the liner thickness would remain unchanged. Cost of materials and typical compositions in car inner liners were taken from Waddell (2008) and the cost of nanoclay was taken from NanoWerk (2012).

A typical composition for a reference passenger car liner is shown in Table B.12, along with the material costs. The total cost for such a liner is USD 2.64 (EUR 2.03) to achieve an inflation pressure loss rate of 2.1%.

Overall, the materials for the nanoclay liner are USD 0.36 more expensive compared to the reference liner, in order to achieve a performance improvement of 30%. An alternative way of improving permeability of the liner by 30% is to add an additional 20phr of halobutyl, although the technical limitations of this method are being reached. The additional cost of this is USD 0.12 (EUR 0.09) per liner. The cost estimate for nanoclay was obtained from NanoWerk (2012), which indicated a cost per kilogramme much greater than that for carbon black. However, a nanoclay supplier indicated that their products were cheaper than carbon black, although they were not able to reveal the price charged to their customers. Nevertheless, it appears that in terms of material costs, using nanoclay to improve the permeability of the tyre inner liner is of comparable cost to other available technology options, but may be capable of achieving higher performance per unit of liner thickness.

As a low retail price estimate, it is assumed that manufacturers would charge consumers the same retail price as the next-best alternative (i.e. for an additional 20phr halobutyl, since increasing the thickness of the liner is less cost-effective). Assuming a retail mark-up factor of five on this additional material cost (California Air Resource Board, 2008), the price of the improved liner would be 5x USD 0.12 = USD 0.59 (regardless of whether the improved performance was achieved using nanoclay or halobutyl). As a high retail price, it is assumed that the mark-up factor is applied to the additional cost of the nanoclay liner, i.e. 5 * USD 0.36 = USD 1.82.

Table B.12. **Cost and compositions for different liners (passenger cars)**

Compound ingredient	List price	Reference liner		Nanoclay liner		Additional 20phr halobutyl liner	
	USD/kg	phr	USD/liner	phr	USD/liner	phr	USD/liner
Halobutyl rubber	4.45	80	1.64	80	1.64	100	2.04
Natural rubber	3.16	20	0.29	20	0.20	x	-
Nanoclay	7.00	x	x	15	1.39	x	x
Carbon black	1.72	60	0.48	45	0.36	60	0.48
Naphthenic oil	*1.43*	*8*	*0.05*	*8*	*0.05*	*8*	*0.05*
Adhesive resin	*2.29*	*7*	*0.07*	*7*	*0.07*	*7*	*0.07*
Tackifying resin	*3.57*	*4*	*0.06*	*4*	*0.06*	*4*	*0.06*
Stearic acid	*2.23*	*1*	*0.01*	*1*	*0.01*	*1*	*0.01*
Sulphur	*1.01*	*0.5*	*0.00*	*0.5*	*0.00*	*0.5*	*0.00*
Zinc oxide	*2.18*	*1*	*0.01*	*1*	*0.01*	*1*	*0.01*
Accelerators	*4.52*	*1.25*	*0.03*	*1.25*	*0.03*	*1.25*	*0.03*

	Reference liner	Nanoclay liner	Additional 20phr halobutyl liner
Inflation pressure loss rate (%)	2.1	1.47	1.5
Compared to reference		-30%	-30%
Total liner cost (USD)	2.64	3.00	2.76
Compared to reference		USD 0.36	USD 0.12

Note: x: not applicable.

Source: NanoWerk (2012), “Polymer nanocomposites drive opportunities in the automotive sector”, www.nanowerk.com/spotlight/spotid=23934.php for nanoclay cost; California Air Resource Board (CARB) (2008), “Tire pressure regulation to reduce climate change emissions”, presentation at the Public Workgroup Meeting, 8 October, CARB, California Environmental Protection Agency, www.arb.ca.gov/cc/tire-pressure/meetings/031808/031808presentation.pdf for list prices of other materials and reference tyre composition.

Table B.13 shows the calculated material costs for the nanoclay inner liners compared to tyres with traditional liner materials.

Table B.13. **Summary of nanoclay inner liner cost and price compared to traditional liners**

	Passenger cars
Cost (materials)	USD 0.36
Price (retail)	USD 0.59-1.82

Some limitations of this approach must be highlighted at this point. Firstly, the composition of inner liners varies a lot between manufacturers; the values provided refer to a real case study provided by Exxon, so they cannot be considered to represent the whole market. Secondly, the model does not account for production costs, but is limited to assessing the cost for materials input.

NOTES

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[1]. The normal distribution was used so that the speed of uptake in different markets could be compared based on the half-diffusion rate. Although a more precise fit could be obtained using more complex S-curve functions, this would also make comparison in different markets more difficult.

[2]. Based on the following assumptions: reference prices are USD 45 per 100 pounds of carbon black (EUR 0.8/kg) and USD 60 per 100 pounds of silica (EUR 1.02/kg). About 5 pounds of silane, which costs about USD 3 per pound (EUR 5.01/kg), is used for every 100 pounds of silica. For an average passenger tyre weighing 26.6 pounds, the full tread band accounts for about 25% of the weight, or 6.7 pounds and the filler makes up 35% of this. Replacing one-third of carbon black with silica-silane leads to an increase in filler cost of USD 0.22 per tyre. Additional processing costs add a further USD 0.22 per tyre. To be conservative, the committee doubled the cost and rounded up to USD 1.

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ANNEX C
DATA, ASSUMPTIONS AND DETAILED RESULTS FOR THE LIFE-CYCLE ANALYSIS

Data sources

Summaries of the primary data modules and data sources used for the life-cycle inventory of reference and nano-enabled tyre product systems are presented in Tables C.1, C.2 and C.3 for the European Union, United States and the People's Republic of China geographic scopes, respectively.

Table C.1. **Summary of life-cycle inventory data sources: EU geographical scope**

	Temporal information	Geographical coverage	Technological coverage	Data sources
Electrical and energy sources	Energy source data from 2000. Electricity grid is 2000 average	Based on average ecoinvent v2.2 electricity grids for Europe (country and region specific)	The most representative technologies	Adapted from ecoinvent v.2.0 *LCI Database*
Raw materials (natural gas and oil)	Data from 1989-2000	Natural gas and crude oil based on average for Europe; represents average amounts of domestic and foreign oil	The most representative technologies	Adapted from ecoinvent v.2.0 *LCI Database*
SBS rubber and plastic resins	Data from 2005-07	European average	The most representative technologies	Boustead (2005-7) via the ecoinvent v.2.0 *LCI Database*
Natural rubber	Data from late 1990s	Malaysian production (literature estimate)	Production from field latex	ERG *Private LCI Database*
Chemicals, ancillary components	Data from 2000-06	European average	The most representative technologies	Adapted from ecoinvent v.2.0 *LCI Database* and ERG *Private LCI Database*
Nanoscale carbon black	Data from 2000-10	Global literature and stoichiometric estimate (no geographical origin); European inputs	Oil-furnace process; from crude oil feedstock	Based on unit process data from ecoinvent (v.2.0 *LCI Database*); ERG *Private LCI Database*; Keller et al. (2013)
Highly dispersible silica	Data from 2008	Synthetic Amorphous Silica & Silicate (SASSI) Association average	Precipitated silica from water glass with sulphuric acid	Adapted from SASSI; ERG *Private LCI Database*; Keller et al. (2013)
Next generation, high surface area silica	Data from 2008	SASSI HD-Si average proxy	Precipitated silica from water glass with sulphuric acid	SASSI HD-Si proxy adapted to reflect HD-HS Si releases per estimates of Keller et al. (2013)
Nanoclay	Data from 2008-12	LAVIOSA (Italian) manufacturing process	MMT from bentonite suspension, centrifugation and refining	Qualitative data from the LAVIOSA process adapted with SASSI HD-Si proxy, ERG *Private LCI Database*, and emission estimates per Keller et al. (2013)
Reference tyre production	Data from 2010	European average	The most representative technologies	Adapted from ETRMA
Nano-enabled tyre production	Data from 2010	Adapted from European baseline	Baseline data as proxy; modified to reflect difference in filler inputs	Adapted from ETRMA using filler weight composition data from TIP and literature
Transport	Data from	European average;	The most representative	LCI data for transport

processes	2000-10	distance industry specific	technologies	modes adapted from ecoinvent v.2.0 *LCI Database*

Table C.1. **Summary of life-cycle inventory data sources: EU geographical scope** (*cont.*)

	Temporal information	Geographical coverage	Technological coverage	Data sources
Tyre end-of-life treatment	Data from 2008	European industries	Ambient-temperature mechanical processing for material recycling; average waste incineration process for energy recovery	Adapted from Schmidt et al. (2009); Keller et al. (2013)
Landfilling	Data from 2000-10	EU average	The most representative technologies	Adapted from Doka (2007)

Table C.2. **Summary of life-cycle inventory data sources: US geographical scope**

	Temporal information	Geographical coverage	Technological coverage	Data sources
Electrical and energy sources	Energy source data from late 1990s to 2008. Electricity grid is 2009 US average	Based on average US grid (and NERC region specific)	The most representative technologies	Energy sources are publicly available in the US *LCI Database* (from ERG). Electricity grid has been updated to E-Grid 2009
Raw materials (natural gas and oil)	Data from late 1990s to 2011	Natural gas and crude oil based on US data; transport represents average amounts of domestic and foreign oil	The most representative technologies	Publicly available in the US *LCI Database* from ERG
SBS rubber and plastic resins	Data from 2003-07, updated in 2010	US average	The most representative technologies	ERG virgin resin data compiled for the American Chemistry Council (2010)
Natural rubber	Data from late 1990s	Malaysian production (literature estimate)	Production from field latex	ERG *Private LCI Database*
Chemicals, ancillary components	Data from 2006	US average	The most representative technologies	ERG *Private LCI Database;* US *LCI Database*; or adapted from ecoinvent
Nanoscale carbon black	Data from 2000-10	Global literature and stoichiometric estimate (no geographical origin); European inputs	Oil-furnace process; from crude oil feedstock	Based on unit process data from ecoinvent (v.2.0 *LCI Database*); ERG *Private LCI Database*; and Keller et al. (2013)
Highly dispersible silica	Data from 2008	Synthetic Amorphous Silica & Silicate (SASSI) Association average	Precipitated silica from water glass with sulphuric acid	Adapted from SASSI; ERG *Private LCI Database*; and Keller et al. (2013)
Next generation, high surface area silica	Data from 2008	SASSI HD-Si average proxy	Precipitated silica from water glass with sulphuric acid	SASSI HD-Si proxy adapted to reflect HD-HS Si releases per estimates of Keller et al. (2013)
Nanoclay	Data from 2008-12	LAVIOSA (Italian) manufacturing process	MMT from bentonite suspension, centrifugation and refining	Qualitative data from the LAVIOSA process adapted with SASSI HD-Si proxy; ERG *Private LCI Database*; and emission estimates per Keller et al. (2013)
Reference tyre production	Data from 2010	Adapted from European baseline to reflect US formulation and inputs	Baseline data as proxy; modified to reflect difference in filler inputs	Adapted from ETRMA to reflect US formulation data per ERG (2010) and Rubber Manufacturers Association (2011)
Nano-enabled tyre production	Data from 2010	Adapted from European baseline	Baseline data as proxy; modified to reflect difference in filler inputs	Adapted from ETRMA using filler weight composition data from TIP

				and literature
Transport processes	Data from 2000-10	US average; distance industry specific	The most representative technologies	LCI data for transport modes from ERG data compiled for the US *LCI Database*[1]
Tyre end-of-life treatment	Data from 2009	European industry adapted to US context for material recycling; US average for energy recovery	Ambient-temperature mechanical processing for material recycling; average cement kiln technology for energy recovery	Adapted from ERG (2010) and Keller et al. (2013)
Landfilling	Data from 2000-10	US average	The most representative technologies	ERG *Private LCI Database* and/or US *LCI Database*

Note: See: www.nrel.gov/lci.

Table C.3. **Summary of life-cycle inventory data sources: China geographical scope**

China	Temporal information	Geographical coverage	Technological coverage	Data sources
Electrical and energy sources	Energy source data from 2000. Electricity grid is 2009 average	Based on average ecoinvent v2.2 electricity production; grid mix for China per International Energy Agency	The most representative technologies	Adapted from ecoinvent v.2.0 *LCI Database*
Raw materials (natural gas and oil)	Data from 1989-2000	Natural gas and crude oil based on average for China; represents average amounts of domestic and foreign oil	The most representative technologies	Adapted from ecoinvent v.2.0 *LCI Database*
SBS rubber and plastic resins	Data from 2005-07	European average	The most representative technologies	Boustead (2005-7) via the ecoinvent v.2.0 *LCI Database*
Natural rubber	Data from late 1990s	Malaysian production (literature estimate)	Production from field latex	ERG *Private LCI Database*
Chemicals, ancillary components	Data from 2000-06	European average	The most representative technologies	Adapted from ecoinvent v.2.0 *LCI Database* and ERG *Private LCI Database*
Nanoscale carbon black	Data from 2000-10	Global literature and stoichiometric estimate (no geographical origin); European inputs	Oil-furnace process; from crude oil feedstock	Based on unit process data from ecoinvent (v.2.0 *LCI Database*); ERG *Private LCI Database*; and Keller et al. (2013)
Highly dispersible silica	Data from 2008	Synthetic Amorphous Silica & Silicate (SASSI) Association average	Precipitated silica from water glass with sulphuric acid	Adapted from SASSI; ERG *Private LCI Database*; and Keller et al. (2013)
Next generation, high surface area silica	Data from 2008	SASSI HD-Si average proxy	Precipitated silica from water glass with sulphuric acid	SASSI HD-Si proxy adapted to reflect HD-HS Si releases per estimates of Keller et al. (2013)
Nanoclay	Data from 2008-12	LAVIOSA (Italian) manufacturing process	MMT from betonies suspension and centrifugation and refining	Qualitative data from the LAVIOSA process adapted with SASSI HD-Si proxy; ERG *Private LCI Database*; and emission estimates per Keller et al. (2013)
Reference tyre	Data from 2010	European average	The most representative	Adapted from ETRMA

production		adapted to China formulations and inputs	technologies	
Nano-enabled tyre production	Data from 2010	Adapted from European baseline	Baseline data as proxy; modified to reflect difference in filler inputs	Adapted from ETRMA using filler weight composition data from TIP and literature
Transport processes	Data from 2000-10	European average adapted for China; distance industry specific	The most representative technologies	LCI data for transport modes adapted from ecoinvent v.2.0 *LCI Database*
Tyre end-of-life treatment	Data from 2008	European industries adapted to China inputs	Ambient-temperature mechanical processing for material recycling; average cement kiln technology for energy recovery	Adapted from Schmidt et al. (2009); Keller et al. (2013)
Landfilling	Data from 2000-10	EU average adapted to China inputs	The most representative technologies	Adapted from Doka (2007)

Detailed numerical results for life-cycle inventory and life-cycle analysis

Though the potential releases are not characterised in terms of environmental impacts, this life-cycle analysis (LCA) framework includes a separate inventory of nanoscale substances such that they may be characterised and assessed in future work. Implications of nanoscale releases of the tyre fillers are discussed qualitatively in Chapter 5. Quantitative estimates for these potential releases are presented here in Tables C.4-C.6 by material and life-cycle stage for each passenger tyre scenario on the basis of the functional unit of this analysis, i.e. 10 000 kilometres travelled by the tyre in each region.

Table C.4. **Potential nanoscale releases to air by material and life-cycle stage**

		LC stage	kg/40 000 km average passenger tyre							
			Carbon black LOW	Carbon black HIGH	HD-Si LOW	HD-Si HIGH	HD-HS Si LOW	HD-HS Si HIGH	MMT LOW	MMT HIGH
United States	Baseline	NM mfg.	2.0E-04	0.016	9.3E-05	0.0074	x	x	x	x
		Tyre use	0	0	0	0	x	x	x	x
		Tyre EOL	3.8E-04	8.1E-04	1.8E-04	3.8E-04	x	x	x	x
	HD-HS Si	NM mfg.	2.0E-04	0.016	x	x	9.3E-05	0.0074	x	x
		Tyre use	0	0	x	x	0	0	x	x
		Tyre EOL	0	8.1E-04	x	x	1.8E-04	3.8E-04	x	x
	MMT	NM mfg.	1.9E-04	0.015	8.8E-05	0.0070	x	x	1.0E-05	8.0E-04
		Tyre use	0	0	0	0	x	x	0	0
		Tyre EOL	3.7E-04	7.9E-04	1.7E-04	3.6E-04	x	x	2.0E-05	4.0E-05
European Union	Baseline	NM mfg.	1.5E-04	0.012	7.6E-13	7.6E-13	x	x	x	x
		Tyre use	0	0	0	0	x	x	x	x
		Tyre EOL	3.3E-04	7.0E-04	2.3E-17	2.3E-17	x	x	x	x
	HD-HS Si	NM mfg.	1.5E-04	0.012	x	x	7.6E-13	7.6E-13	x	x
		Tyre use	0	0	x	x	0	0	x	x

		Tyre EOL	3.3E-04	7.0E-04	x	x	1.1E-17	2.2E-17	x	x
	MMT	NM mfg.	1.5E-04	0.012	7.2E-13	7.2E-13	x	x	8.6E-06	6.9E-04
		Tyre use	0	0	0	0	x	x	0	0
		Tyre EOL	3.2E-04	6.9E-04	2.3E-17	2.3E-17	x	x	1.9E-05	3.9E-05
China	Baseline	NM mfg.	1.4E-04	0.011	9.0E-05	0.0072	x	x	x	x
		Tyre use	0	0	0	0	x	x	x	x
		Tyre EOL	0	8.7E-06	0	5.7E-06	x	x	x	x
	HD-HS Si	NM mfg.	1.4E-04	0.011	x	x	9.0E-05	0.0072	x	x
		Tyre use	0	0	x	x	0	0	x	x
		Tyre EOL	0	8.8E-06	x	x	0	5.7E-06	x	x
	MMT	NM mfg.	1.4E-04	0.011	8.6E-05	0.0069	x	x	7.8E-07	6.2E-05
		Tyre use	0	0	0	0	x	x	0	0
		Tyre EOL	0	8.5E-06	0	5.4E-06	x	x	0	4.9E-07

Note: EOL: end-of-life; x: not applicable.

Table C.5. **Potential nanoscale releases to water by material and life-cycle stage**

		LC stage	kg/40 000 km average passenger tyre							
			Carbon black LOW	Carbon black HIGH	HD-Si LOW	HD-Si HIGH	HD-HS Si LOW	HD-HS Si HIGH	MMT LOW	MMT HIGH
United States	Baseline	NM mfg.	2.0E-04	0.016	9.3E-05	0.0074	x	x	x	x
		Tyre use	0	0.043	0	0.021	x	x	x	x
		Tyre EOL	0	0	0	0	x	x	x	x
	HD-HS Si	NM mfg.	2.0E-04	0.016	x	x	9.3E-05	0.0074	x	x
		Tyre use	0	0.036	x	x	0	0.018	x	x
		Tyre EOL	0	0	x	x	0	0	x	x
	MMT	NM mfg.	1.9E-04	0.015	8.8E-05	0.0070	x	x	1.0E-05	8.0E-04
		Tyre use	0	0.041	0	0.020	x	x	0	0.0022
		Tyre EOL	0	0	0	0	x	x	0	0
European Union	Baseline	NM mfg.	1.5E-04	0.012	1.0E-04	0.0080	x	x	x	x
		Tyre use	0	0.058	0	0.037	x	x	x	x
		Tyre EOL	0	0	0	0	x	x	x	x
	HD-HS Si	NM mfg.	1.5E-04	0.012	x	x	1.0E-04	0.0080	x	x
		Tyre use	0	0.048	x	x	0	0.031	x	x
		Tyre EOL	0	0	x	x	0	0	x	x
	MMT	NM mfg.	1.5E-04	0.012	9.5E-05	0.0076	x	x	8.6E-06	6.9E-04
		Tyre use	0	0.055	0	0.035	x	x	0	0.0032
		Tyre EOL	0	0	0	0	x	x	0	0
China	Baseline	NM mfg.	1.4E-04	0.011	9.0E-05	0.0072	x	x	x	x
		Tyre use	0	0.033	0	0.021	x	x	x	x
		Tyre EOL	0	0	0	0	x	x	x	x
	HD-HS Si	NM mfg.	1.4E-04	0.011	x	x	9.0E-05	0.0072	x	x
		Tyre use	0	0.027	x	x	0	0.018	x	x
		Tyre EOL	0	0	x	x	0	0	x	x
	MMT	NM mfg.	1.4E-04	0.011	8.6E-05	0.0069	x	x	7.8E-07	6.2E-05
		Tyre use	0	0.031	0	0.020	x	x	0	0.0018
		Tyre EOL	0	0	0	0	x	x	0	0

Note: EOL: end-of-life; x: not applicable.

Table C.6. **Potential nanoscale releases to soil by material and life-cycle stage**

			kg/40 000 km average passenger tyre							
		LC stage	Carbon black LOW	Carbon black HIGH	HD-Si LOW	HD-Si HIGH	HD-HS Si LOW	HD-HS Si HIGH	MMT LOW	MMT HIGH
United States	Baseline	NM mfg.	0.0016	0.0078	7.4E-04	0.0037	x	x	x	x
		Tyre use	0	0	0	0	x	x	x	x
		Tyre EOL	0.076	0.10	0.036	0.050	x	x	x	x
	HD-HS Si	NM mfg.	0.0016	0.0078	x	x	7.4E-04	0.0037	x	x
		Tyre use	0	0	x	x	0	0	x	x
		Tyre EOL	0.076	0.10	x	x	0.036	0.050	x	x
	MMT	NM mfg.	0.0015	0.0076	7.0E-04	0.0035	x	x	8.0E-05	4.0E-04
		Tyre use	0	0	0	0	x	x	0	0
		Tyre EOL	0.074	0.10	0.034	0.047	x	x	0.0039	0.0054
European Union	Baseline	NM mfg.	0.0012	0.0062	8.0E-04	0.0040	x	x	x	x
		Tyre use	0	0	0	0	x	x	x	x
		Tyre EOL	0.067	0.073	0.043	0.047	x	x	x	x
	HD-HS Si	NM mfg.	0.0012	0.0062	x	x	8.0E-04	0.0040	x	x
		Tyre use	0	0	x	x	0	0	x	x
		Tyre EOL	0.067	0.073	x	x	0.043	0.047	x	x
	MMT	NM mfg.	0.0012	0.0060	7.6E-04	0.0038	x	x	6.9E-05	3.4E-04
		Tyre use	0	0	0	0	x	x	0	0
		Tyre EOL	0.065	0.071	0.041	0.045	x	x	0.0037	0.0041
China	Baseline	NM mfg.	0.0011	0.0056	7.2E-04	0.0036	x	x	x	x
		Tyre use	0	0	0	0	x	x	x	x
		Tyre EOL	0	0.15	0	0.094	x	x	x	x
	HD-HS Si	NM mfg.	0.0011	0.0056	x	x	7.2E-04	0.0036	x	x
		Tyre use	0	0	x	x	0	0	x	x
		Tyre EOL	0	0.15	x	x	0	0.095	x	x
	MMT	NM mfg.	0.0011	0.0054	6.9E-04	0.0034	x	x	6.2E-06	3.1E-05
		Tyre use	0	0	0	0	x	x	0	0
		Tyre EOL	0	0.14	0	0.090	x	x	0	0.0082

Note: EOL: end-of-life; x: not applicable.

For each geographic scope, the overview of average life-cycle impacts for 40 000 kilometres of travel on each tyre type is presented in Tables C.7-C.18.

Table C.7. **LCIA result details by life-cycle stage for US baseline tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	490	10.1	22.0	458	0.0012
Cumulative energy demand	MJ	45 659	269	431	44 959	0.0064
Ozone depletion	kg CFC-11 eq	8.4E-07	2.1E-08	1.4E-07	6.9E-07	2.2E-12
Water consumption	m^3	5.60	0.027	0.10	5.47	1.8E-06
Terrestrial acidification	kg SO_2 eq	8.30	0.027	0.13	8.14	2.6E-06
Freshwater eutrophication	kg P eq	0.021	1.1E-04	0.0023	0.019	1.6E-08
Photochemical oxidant formation	kg NMVOC	11.4	0.014	0.11	11.2	2.0E-06
Solid waste generation	kg SW	6.69	0.26	0.21	6.20	0.023

Table C.8. **LCIA result details by life-cycle stage for US HD-HS silica-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	469	5.41	22.0	442	0.0012
Cumulative energy demand	MJ	43 937	96.8	431	43 409	0.0064
Ozone depletion	kg CFC-11 eq	8.2E-07	2.1E-08	1.4E-07	6.6E-07	2.2E-12
Water consumption	m^3	5.40	0.011	0.10	5.29	1.8E-06
Terrestrial acidification	kg SO_2 eq	8.00	0.016	0.13	7.86	2.6E-06
Freshwater eutrophication	kg P eq	0.021	5.6E-05	0.0023	0.018	1.6E-08
Photochemical oxidant formation	kg NMVOC	11.0	0.0097	0.11	10.9	2.0E-06
Solid waste generation	kg SW	6.43	0.21	0.21	5.98	0.023

Table C.9. **LCIA result details by life-cycle stage for US MMT-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	484	9.97	22.0	452	0.0012
Cumulative energy demand	MJ	45 131	263	431	44 437	0.0064
Ozone depletion	kg CFC-11 eq	8.3E-07	2.0E-08	1.4E-07	6.8E-07	2.2E-12
Water consumption	m^3	5.54	0.027	0.10	5.41	1.8E-06
Terrestrial acidification	kg SO_2 eq	8.20	0.026	0.13	8.05	2.6E-06
Freshwater eutrophication	kg P eq	0.021	1.1E-04	0.0023	0.019	1.6E-08
Photochemical oxidant formation	kg NMVOC	11.2	0.014	0.11	11.1	2.0E-06
Solid waste generation	kg SW	6.61	0.25	0.21	6.13	0.023

Table C.10. LCIA result details by life-cycle stage for EU baseline tyres

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	411	9.57	19.1	383	0.0011
Cumulative energy demand	MJ	35 394	248	469	34 678	0.0059
Ozone depletion	kg CFC-11 eq	2.9E-06	5.1E-08	2.1E-07	2.6E-06	2.0E-12
Water consumption	m^3	0.0033	0	0.0033	0	1.7E-06
Terrestrial acidification	kg SO_2 eq	9.10	0.036	0.10	8.96	2.4E-06
Freshwater eutrophication	kg P eq	0.015	1.1E-04	0.0023	0.012	1.5E-08
Photochemical oxidant formation	kg NMVOC	8.64	0.019	0.094	8.52	1.8E-06
Solid waste generation	kg SW	18.5	0.38	2.16	16.0	0.021

Table C.11. **LCIA result details by life-cycle stage for EU HD-HS silica-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	396	5.79	19.1	371	0.0011
Cumulative energy demand	MJ	34 171	113	469	33 590	0.0059
Ozone depletion	kg CFC-11 eq	2.8E-06	4.6E-08	2.1E-07	2.5E-06	2.0E-12
Water consumption	m^3	0.0033	0	0.0033	0	1.7E-06
Terrestrial acidification	kg SO_2 eq	8.80	0.021	0.10	8.68	2.4E-06
Freshwater eutrophication	kg P eq	0.014	6.1E-05	0.0023	0.012	1.5E-08

Photochemical oxidant formation	kg NMVOC	8.35	0.011	0.094	8.25	1.8E-06
Solid waste generation	kg SW	18.0	0.32	2.16	15.5	0.021

Table C.12. **LCIA result details by life-cycle stage for EU MMT-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	405	9.39	19.1	376	0.0011
Cumulative energy demand	MJ	34 792	243	469	34 080	0.0059
Ozone depletion	kg CFC-11 eq	2.8E-06	5.0E-08	2.1E-07	2.6E-06	2.0E-12
Water consumption	m^3	0.0033	0	0.0033	0	1.7E-06
Terrestrial acidification	kg SO_2 eq	8.94	0.035	0.10	8.80	2.4E-06
Freshwater eutrophication	kg P eq	0.015	1.0E-04	0.0023	0.012	1.5E-08
Photochemical oxidant formation	kg NMVOC	8.49	0.019	0.094	8.37	1.8E-06
Solid waste generation	kg SW	18.3	0.38	2.16	15.7	0.021

Table C.13. LCIA result details by life-cycle stage for Chinese baseline tyres

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	496	9.67	22.3	464	0.0012
Cumulative energy demand	MJ	39 915	214	418	39 282	0.0067
Ozone depletion	kg CFC-11 eq	9.8E-07	2.7E-08	1.4E-07	8.1E-07	2.3E-12
Water consumption	m^3	0.77	0.032	0.11	0.63	1.9E-06
Terrestrial acidification	kg SO_2 eq	11.8	0.047	0.13	11.6	2.7E-06
Freshwater eutrophication	kg P eq	0.0061	9.5E-05	0.0023	0.0037	1.7E-08
Photochemical oxidant formation	kg NMVOC	11.8	0.023	0.10	11.7	2.0E-06
Solid waste generation	kg SW	7.62	0.18	0.44	6.98	0.024

Table C.14. **LCIA result details by life-cycle stage for Chinese HD-HS silica-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	478	6.16	22.3	450	0.0012
Cumulative energy demand	MJ	38 561	93.5	419	38 049	0.0067
Ozone depletion	kg CFC-11 eq	9.5E-07	2.5E-08	1.4E-07	7.9E-07	2.3E-12
Water consumption	m^3	0.75	0.029	0.11	0.61	1.9E-06
Terrestrial acidification	kg SO_2 eq	11.4	0.032	0.13	11.3	2.7E-06
Freshwater eutrophication	kg P eq	0.0060	5.4E-05	0.0023	0.0036	1.7E-08
Photochemical oxidant formation	kg NMVOC	11.4	0.015	0.10	11.3	2.0E-06
Solid waste generation	kg SW	7.36	0.14	0.44	6.76	0.024

Table C.15. **LCIA result details by life-cycle stage for Chinese MMT-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	486	9.32	22.3	455	0.0012
Cumulative energy demand	MJ	39 107	207	419	38 482	0.0067
Ozone depletion	kg CFC-11 eq	9.6E-07	2.6E-08	1.4E-07	8.0E-07	2.3E-12
Water consumption	m^3	0.76	0.031	0.11	0.62	1.9E-06
Terrestrial acidification	kg SO_2 eq	11.6	0.045	0.13	11.4	2.7E-06
Freshwater eutrophication	kg P eq	0.0061	9.1E-05	0.0023	0.0037	1.7E-08
Photochemical oxidant formation	kg NMVOC	11.6	0.022	0.10	11.5	2.0E-06
Solid waste generation	kg SW	7.47	0.17	0.44	6.84	0.024

Table C.16. **Summary of LCIA results for tyres in the US geographical scope**

Impact category	Unit	United States baseline	United States HD-HS Si	United States MMT
Climate change	kg CO_2 eq	2 079	2 004	1 890
Cumulative energy demand	MJ	182 548	176 101	178 655
Ozone depletion	kg CFC-11 eq	4.4E-06	4.2E-06	2.9E-06
Water consumption	m^3	2.45	2.36	2.29
Terrestrial acidification	kg SO_2 eq	42.2	40.8	32.9
Freshwater eutrophication	kg P eq	0.051	0.049	0.077
Photochemical oxidant formation	kg NMVOC	39.1	37.9	45.0
Solid waste generation	kg SW	40.3	39.3	25.0

Table C.17. **Summary of LCIA results for tyres in the EU geographical scope**

Impact category	Unit	EU baseline	EU HD-HS Si	EU MMT
Climate change	kg CO_2 eq	1 559	1 508	1 533
Cumulative energy demand	MJ	139 432	134 942	137 025
Ozone depletion	kg CFC-11 eq	1.1E-05	1.0E-05	1.1E-05
Water consumption	m^3	1.77	1.52	1.60
Terrestrial acidification	kg SO_2 eq	36.7	35.5	36.0
Freshwater eutrophication	kg P eq	0.052	0.050	0.051
Photochemical oxidant formation	kg NMVOC	34.3	33.2	33.7
Solid waste generation	kg SW	66.4	64.9	65.3

Table C.18. **Summary of LCIA results for tyres in the CN geographical scope**

Impact category	Unit	China baseline	China HD-HS Si	China MMT
Climate change	kg CO_2 eq	1 891	1 829	1 853
Cumulative energy demand	MJ	157 787	152 730	154 576
Ozone depletion	kg CFC-11 eq	3.4E-06	3.3E-06	3.4E-06
Water consumption	m^3	2.66	2.22	2.64
Terrestrial acidification	kg SO_2 eq	46.8	45.4	45.9
Freshwater eutrophication	kg P eq	0.017	0.017	0.017
Photochemical oxidant formation	kg NMVOC	47.7	46.2	46.7
Solid waste generation	kg SW	28.6	27.9	28.1

The following sections detail the process contribution LCIA analysis for each tyre type in each region and give the relative discrepancy of impacts for use of nano-enabled tyres relative to baseline tyres in each life-cycle stage. In Tables C.19-C.27, quantitative results are displayed for each scenario by the following life-cycle stages: *i)* nanomaterial production; *ii)* tyre production; *iii)* tyre use; and *iv)* tyre end-of-life.

Table C.19. **LCIA result details by life-cycle stage for US baseline tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	2 079	10.3	22.7	2 046	0.0012
Cumulative energy demand	MJ	182 548	269	434	181 845	0.0064
Ozone depletion	kg CFC-11 eq	4.4E-06	2.1E-08	1.4E-07	4.2E-06	2.2E-12
Water consumption	m^3	2.45	0.027	0.10	2.33	1.8E-06
Terrestrial acidification	kg SO_2 eq	42.2	0.028	0.13	42.0	2.6E-06
Freshwater eutrophication	kg P eq	0.051	1.1E-04	0.0023	0.048	1.6E-08
Photochemical oxidant formation	kg NMVOC	39.1	0.015	0.12	39.0	2.0E-06
Solid waste generation	kg SW	40.3	0.27	0.21	39.7	0.025

Table C.20. **LCIA result details by life cycle-stage for US HD-HS silica-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	2 004	5.49	22.7	1 975	0.0012
Cumulative energy demand	MJ	176 101	97.1	434	175 571	0.0064
Ozone depletion	kg CFC-11 eq	4.2E-06	2.1E-08	1.4E-07	4.1E-06	2.2E-12
Water consumption	m^3	2.36	0.011	0.10	2.25	1.8E-06
Terrestrial acidification	kg SO_2 eq	40.8	0.017	0.13	40.6	2.6E-06
Freshwater eutrophication	kg P eq	0.049	5.6E-05	0.0023	0.047	1.6E-08
Photochemical oxidant formation	kg NMVOC	37.9	0.010	0.12	37.7	2.0E-06
Solid waste generation	kg SW	39.3	0.66	0.21	38.4	0.025

Table C.21. **LCIA result details by life-cycle stage for US MMT-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	1 890	10.1	22.7	1 857	0.0012
Cumulative energy demand	MJ	178 655	264	434	177 957	0.0064
Ozone depletion	kg CFC-11 eq	2.9E-06	2.0E-08	1.4E-07	2.7E-06	2.2E-12
Water consumption	m^3	2.29	0.027	0.10	2.17	1.8E-06
Terrestrial acidification	kg SO_2 eq	32.9	0.028	0.13	32.7	2.6E-06
Freshwater eutrophication	kg P eq	0.077	1.1E-04	0.0023	0.075	1.6E-08
Photochemical oxidant formation	kg NMVOC	45.0	0.015	0.12	44.8	2.0E-06
Solid waste generation	kg SW	25.0	0.26	0.21	24.5	0.025

Table C.22. LCIA result details by life-cycle stage for EU baseline tyres

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	1 559	9.57	19.1	1 531	0.0011
Cumulative energy demand	MJ	139 432	248	469	138 716	0.0059
Ozone depletion	kg CFC-11 eq	1.1E-05	5.1E-08	2.1E-07	1.0E-05	2.0E-12
Water consumption	m^3	1.77	0.020	0.0033	1.74	1.7E-06
Terrestrial acidification	kg SO_2 eq	36.7	0.036	0.10	36.5	2.4E-06
Freshwater eutrophication	kg P eq	0.052	1.1E-04	0.0023	0.049	1.5E-08
Photochemical oxidant formation	kg NMVOC	34.3	0.019	0.094	34.2	1.8E-06
Solid waste generation	kg SW	66.4	0.39	2.16	63.9	0.023

Table C.23. **LCIA result details by life-cycle stage for EU HD-HS silica-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	1 508	5.79	19.1	1 483	0.0011
Cumulative energy demand	MJ	134 942	113	469	134 360	0.0059
Ozone depletion	kg CFC-11 eq	1.0E-05	4.6E-08	2.1E-07	1.0E-05	2.0E-12
Water consumption	m^3	1.52	0.0077	0.0033	1.51	1.7E-06
Terrestrial acidification	kg SO_2 eq	35.5	0.021	0.10	35.4	2.4E-06
Freshwater eutrophication	kg P eq	0.050	6.1E-05	0.0023	0.048	1.5E-08
Photochemical oxidant formation	kg NMVOC	33.2	0.011	0.094	33.1	1.8E-06
Solid waste generation	kg SW	64.9	0.82	2.16	61.9	0.023

Table C.24. **LCIA result details by life-cycle stage for EU MMT-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO$_2$ eq	1 533	9.39	19.1	1 504	0.0011
Cumulative energy demand	MJ	137 025	243	469	136 314	0.0059
Ozone depletion	kg CFC-11 eq	1.1E-05	5.0E-08	2.1E-07	1.0E-05	2.0E-12
Water consumption	m^3	1.60	0.020	0.0033	1.58	1.7E-06
Terrestrial acidification	kg SO$_2$ eq	36.0	0.035	0.10	35.9	2.4E-06
Freshwater eutrophication	kg P eq	0.051	1.0E-04	0.0023	0.048	1.5E-08
Photochemical oxidant formation	kg NMVOC	33.7	0.019	0.094	33.6	1.8E-06
Solid waste generation	kg SW	65.3	0.39	2.16	62.8	0.023

Table C.25. LCIA result details by life-cycle stage for Chinese baseline tyres

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO$_2$ eq	1 891	9.68	22.3	1 859	0.0012
Cumulative energy demand	MJ	157 787	214	419	157 154	0.0067
Ozone depletion	kg CFC-11 eq	3.4E-06	2.7E-08	1.4E-07	3.3E-06	2.3E-12
Water consumption	m^3	2.66	0.032	0.11	2.52	1.9E-06
Terrestrial acidification	kg SO$_2$ eq	46.8	0.047	0.13	46.6	2.7E-06
Freshwater eutrophication	kg P eq	0.017	9.5E-05	0.0023	0.015	1.7E-08
Photochemical oxidant formation	kg NMVOC	47.7	0.023	0.10	47.5	2.0E-06
Solid waste generation	kg SW	28.6	0.18	0.44	28.0	0.027

Table C.26. **LCIA result details by life-cycle stage for Chinese HD-HS silica-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO$_2$ eq	1 829	6.16	22.2	1 800	0.0012
Cumulative energy demand	MJ	152 730	93.6	417	152 218	0.0067
Ozone depletion	kg CFC-11 eq	3.3E-06	2.5E-08	1.4E-07	3.2E-06	2.3E-12
Water consumption	m^3	2.22	0.0038	0.11	2.11	1.9E-06
Terrestrial acidification	kg SO$_2$ eq	45.4	0.032	0.13	45.2	2.7E-06
Freshwater eutrophication	kg P eq	0.017	5.4E-05	0.0023	0.015	1.7E-08
Photochemical oxidant formation	kg NMVOC	46.2	0.015	0.10	46.1	2.0E-06
Solid waste generation	kg SW	27.9	0.36	0.44	27.1	0.027

Table C.27. **LCIA result details by life-cycle stage for Chinese MMT-enabled tyres**

Impact category	Unit	Total life cycle	Nano-material	Tyre mfg.	Use stage	End-of-life stage
Climate change	kg CO_2 eq	1 853	9.32	22.2	1 821	0.0012
Cumulative energy demand	MJ	154 576	207	417	153 950	0.0067
Ozone depletion	kg CFC-11 eq	3.4E-06	2.6E-08	1.4E-07	3.2E-06	2.3E-12
Water consumption	m^3	2.64	0.029	0.11	2.50	1.94E-06
Terrestrial acidification	kg SO_2 eq	45.9	0.045	0.13	45.7	2.7E-06
Freshwater eutrophication	kg P eq	0.017	9.1E-05	0.0023	0.015	1.7E-08
Photochemical oxidant formation	kg NMVOC	46.7	0.022	0.10	46.6	2.0E-06
Solid waste generation	kg SW	28.1	0.18	0.44	27.4	0.027

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