MASTER THESIS

Relevance and development of new rubber technology competences for a sustainable automotive industry

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List of abbreviations

BR	Butadiene Rubber
CBS	N-Cyclohexyl 2-BenzothiazylSulphenamide
Cd	Coefficient of drag
DPG	DiPhenylGuanidine
EC	European Commission
ELT	End-of-Life Tires
EPDM	Ethylene Propylene Diene Monomer
EQF	European Qualification Framework
ESE	Elastomer Science and Engineering (course)
ETE	Elastomer Technology and Engineering (chair)
EU	European Union
EV	Electric Vehicle
FPEC	Fleet-wide passenger car energy consumption
GHG	Greenhouse Gas
HNBR	Hydrogenated Nitrile Butadiene Rubber
ICCT	International Council of Clean Transportation
IP	Improvement Potential
MBT	2-Mercapto BenzoThiazole
NEDC	New European Driving Cycle
NR	Natural Rubber
OCT	Octadecylamine
PAH	Polycyclic Aromatic Hydrocarbons
PhD	Philosophiae Doctor
PHR	Parts per Hunderd Rubber
Project DRIVES	Development and Research on Innovative Vocational Educational Skills
R&D	Research and Development
R/P ratio	Reserves to Production ratio
RC	Reduction Contribution
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
RFL	Resorcinol Formaldehyde Latex
RP	Reduction Potential
RR	Rolling Resistance
RRC	Rolling Resistance Coefficient
RT	Rubber Technologist
SBR	Styrene Butadiene Rubber
SUV	Sport Utility Vehicle
TMTD	TetraMethylThiuram Disulfide
TPE	Thermoplastic Elastomers
TDAE	Treated Distillate Aromatic Extract
WETG	Wet Grip
WLTP	World harmonised Light-duty vehicles Test Procedure
WP	Work Package
ZnO	Zinc Oxide

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Keywords
rubber, sustainability, education, automotive, tire technology, renewable, contamination, greenhouse gas, CO_2 emission, EU project DRIVES, GEAR 2030

Abstract

Rubber is known for its unique elastic properties and provides irreplaceable functionality in automotive applications, for example in tires that account for roughly 60% of global rubber consumption. Tires and mechanical rubber goods are facing challenges in meeting performance and sustainability demands. The road transport sector emits 21% of total equivalent CO_2 emissions in the European Union and resistant force generated by tire rolling hysteresis accounts for roughly a third of the total energy consumption of a car. Fleet-wide rolling resistance reduction is expected to reduce passenger car energy consumption up to 3.4% in 2030. Further main challenges regard tire tread wear and the tire lifecycle. Each year 2.5 billion tires are produced worldwide whose treads are scrapped by 2-9 kg of rubber during the use-phase. These rubber particles are released and contribute to contamination of the environment, the depletion of resources and end-of-life tire waste. Project DRIVES, co-funded by the Erasmus+ program of the EU, has identified the field of rubber technology to require new competences. The rubber industry is interested in online educational programs that provide holistic education and new compounding and processing solutions to facilitate robust product design and sustainability solutions. The development of educational skill cards for two, Basic and Advanced, Rubber Technologist job roles was performed based on the know-how of the Elastomer Technology and Engineering group at the University of Twente as well as a study into the future needs of the automotive and rubber industry. A literature study succeeded by discussions with the rubber industry revealed four main objectives: rubber performance enhancement (tire magic triangle performance), REACH conscious compounding solutions, circular economy solutions and the replacement of non-renewable ingredients. These objectives were integrated into the Basic Rubber Technologist skill card and the Advanced Rubber Technologist skill card structure with new competences to facilitate a further transition to a more sustainable rubber and automotive future.

Contents

1. Introduction

This master's assignment is a contribution to project DRIVES (Development and Research on Innovative Vocational Educational Skills) that is co-funded by the Erasmus+ program of the European Union. (Figure 1) The European automotive sector is undergoing disruptive changes and transformation due to digitalization and low and zero emission mobility trends. This transformation affects the workforce and the industry needs to increase their capacity to deliver the expected in terms of digital technology, alternative powertrains and circular and sustainable economy concepts.[1] DRIVES is a Blueprint for Sectoral Cooperation on Skills in the automotive sector and has identified 60 future educational topics, or job roles, to support the transformation of the automotive industry.

Figure 1: DRIVES logo[2]

Multiple job roles are dedicated to polymeric materials to reduce CO_2 emissions and improve the overall driving performance. For example, thermoplastic composites are replacing aluminum for lightweight construction and the introduction of green tire rubber technology by Michelin has improved fuel economy of passenger car tires.[3,4] Elastomers are polymeric materials classified as amorphous polymers that, in contrast to thermoplastic materials, are in a rubbery state at room temperature. Elastomers are typically cross-linked, or vulcanized, forming a network of polymer chains and often referred to as rubber material.[5] (Figure 2) Rubber is known for unique elasticity and damping properties and provides irreplaceable functionality in automotive industry applications. (Figure 3)

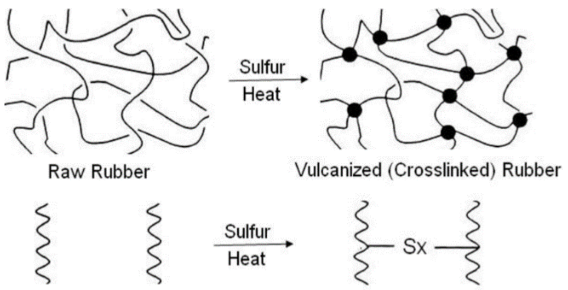


Figure 2: General process of elastomer vulcanization[6]

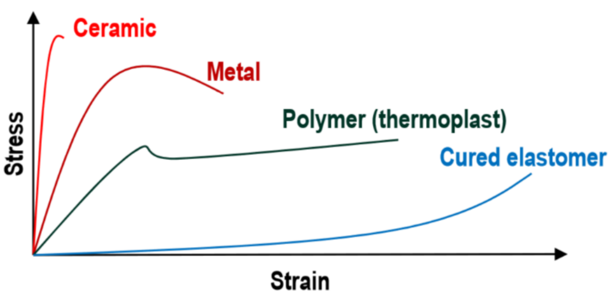


Figure 3: General comparison of materials[7]

Project DRIVES aims to contribute to innovation and education in the automotive rubber industry by offering job roles in the field of rubber technology. The fundament is the Rubber Technologist (RT) job role, which are developed by the Elastomer Technology and Engineering (ETE) group of the University of Twente. The rubber technologist provides general training on rubber material and the skills needed for producing rubber goods with additional emphasis on tire tread compound technology. Tires are highly engineered for optimal grip, but are subject to tread wear and energy losses due to rolling hysteresis of the tire. These factors are related to negative environmental impact of the automotive industry.[8] (Figure 4)

The scope of this project was to substantiate the relevance of rubber technology in a sustainable automotive future, assist in the development of the rubber technologist job role structures and acquire complete, future sound, educational competence skill sets. The gaps between currently available educational possibilities and future needs of the rubber industry were identified. These needs are two-fold, on the one hand needs to follow future trends in the automotive and rubber industry and on the other hand currently lacking educational possibilities in the rubber industry. The two are of equal importance and strengthen each other in the endeavor of amplifying the quality of rubber goods and innovation in the rubber industry. The future needs were examined by a literature study and interviewing sessions with various rubber industry partners. The results are integrated into the drafted rubber technologist skill sets, that are primarily based on the know-how of the ETE group of the University of Twente.

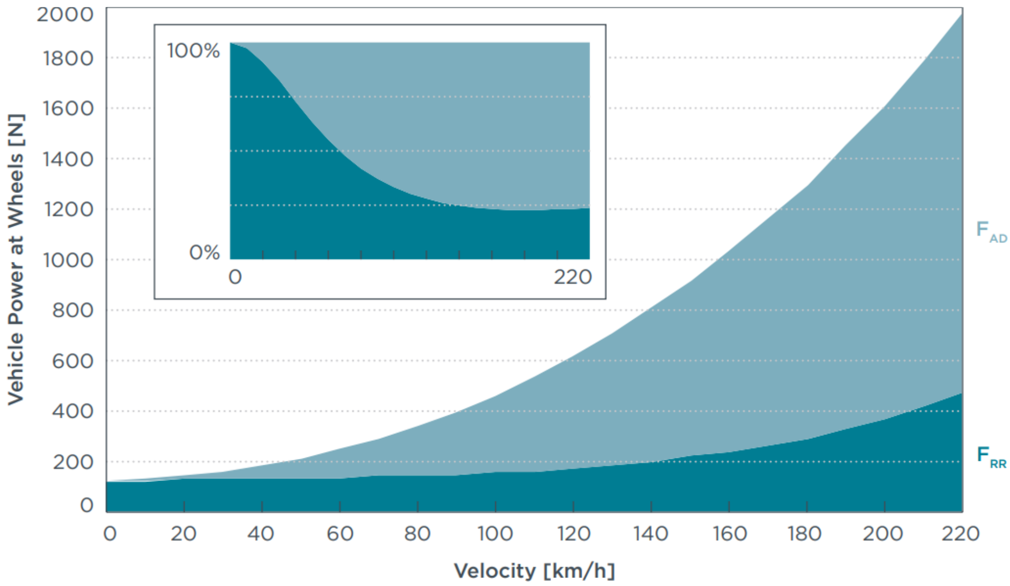


Figure 4: General comparison of total energy consumption by tire rolling resistance force (F_{RR}) and aerodynamic drag force (F_{AD}) over vehicle velocity[8]

1.1 Project DRIVES

The DRIVES project is a Blueprint for Sectoral Cooperation on Skills in the Automotive Sector and is funded by Erasmus+ Sector Skills Alliances Program. DRIVES is part of GEAR 2030 that addresses main challenges and opportunities for the automotive sector in the near and far future and focusses on connected, automated and zero emission driving. The purpose of DRIVES is to introduce new training possibilities to re-qualify employees to occupy new and emerging jobs within the company.

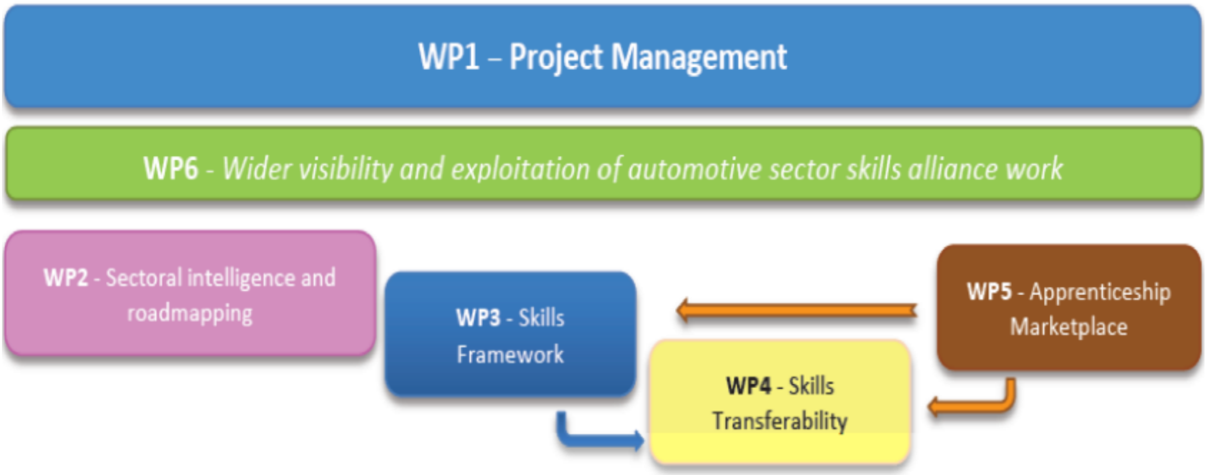


Figure 5: Overview of the DRIVES work package management structure[2]

The project's duration is 4 years, starting January 2018, and is divided into six work packages that are managed by different organizations. The project structure is visualized in Figure 5. The key objectives of DRIVES [2] are to:

- Map and assess future skills for the automotive industry
  - Based on trends and roadmap of the industry
- Improve existing and proven skills framework across the EU
- Implement a common European automotive skills umbrella
- Creation of a pool of 60 job roles for future use
- Create EU-wide recognition of those job roles in a apprenticeship marketplace

Work package 2 has identified future job-roles required in the automotive industry. From surveys and interviews with stakeholders a total of 60 job roles are compiled, of which 30 are under development in DRIVES and 30 are offered for development in subsequent projects. Important trends in the industry are related to electric, autonomous and sustainable mobility, finally resulting in job roles such as: IT Specialist in communicating cars, Artificial Intelligence Expert, Cybersecurity Engineer, Predictive Maintenance Engineer and Rubber Technologist.

The ETE group is co-leader of work package 3, which includes establishing the skill frameworks and integration of job roles into European Certification & Qualification Association (ECQA) system portals.[9] ECQA is a recognized certification body that can be used by DRIVES. A job role is a re-qualification possibility (1 week up to ½ year) for an employee to gain EU recognized and certified qualification to be used within/as part of his/her job. The job roles are European Qualification Framework (EQF) qualified and generally range from level 4 to level 7.[10] The educational trainings are usually executed by online courses, possibly supported by block courses and lab trainings. Finally, the trainee has to pass one or multiple tests to prove that the student has acquired the learning outcomes to a satisfactory level and subsequently he/she receives a certificate, DRIVES Badge and European Credit Transfer and Accumulation system (ECTS) credits.

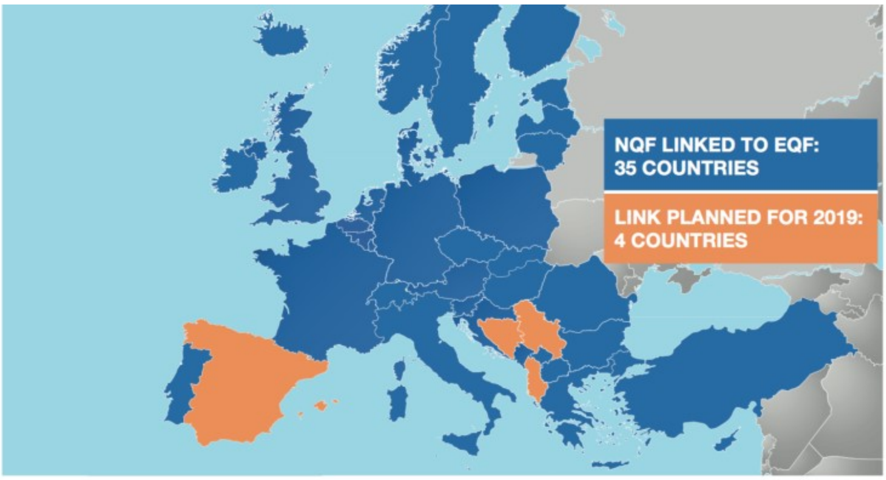


Figure 6: Countries linked to the EQF system[10]

1.1.1 Learning outcome qualification

Learning outcomes can be qualified by the EQF qualification and Bloom's taxonomy levels of competence.[10,11] EQF and Bloom's taxonomy are overlapping in their purpose, but in general the EQF describes competences on macro educational level and Bloom's taxonomy is more skill-based. The EQF has entered into force in 2012 and connects national qualification frameworks (NQF) for international recognition of acquired qualifications. (Figure 6) The EQF differs eight reference levels of learning outcomes that describe the general educational level and mastering of subjects within an educational program.[12] (Table 1) DRIVES job roles are EQF qualified and the Rubber Technologist is planned to be offered on three levels: applied (EQF 5), basic (EQF 6) and advanced (EQF 7) level. The content and workload of the ESE course offered by the University of Twente equals 5 ECTS points. The Basic and Advanced RT trainings aim for respectively 4 and 5 ECTS workload and reward.

EQF level	
1	Basic general knowledge
2	Basic factual knowledge of a field of work or study
3	Knowledge of facts, principles, processes and general concepts, in a field of work or study
4	Factual and theoretical knowledge in broad contexts within a field of work or study
5	Comprehensive, specialised, factual and theoretical knowledge within a field of work or study and an awareness of the boundaries of that knowledge
6	Advanced knowledge of a field of work or study, involving a critical understanding of theories and principles
7	Highly specialised knowledge, some of which is at the forefront of knowledge in a field of work or study, as the basis for original thinking and/or research
8	Knowledge at the most advanced frontier of a field of work or study and at the interface between fields

Table 1: Descriptors defining levels in the European Qualifications Framework[12]

The Bloom's taxonomy was invented by a group of educational psychologists led by Benjamin Bloom in 1956 and updated by a group led by Lorin Anderson in the 1990's.[11] The Bloom taxonomy describes six reference levels of learning outcomes and is the basis of many qualification frameworks and teaching methodologies. It focusses on skills rather than content and distinguishes lower level remembering, understanding and applying from higher levels of analyzing, evaluating and creating. (Figure 7) Lower levels are the foundation for higher levels of competence and accordingly the student should climb the mountain of Bloom levels, especially for educational purposes. Hereby, when the student is able to create, he or she can perform according to all levels. Accordingly, education and cognition require a holistic approach, which should be taken into account when categorizing cognitive processes in classification levels, but also in the development of the job roles.[13] The rubber technologist aims for higher levels of the bloom taxonomy by not only remembering, understanding and applying the knowledge, but also analyzing, evaluating and creating new materials.

The final skills or competences are related to Bloom levels and distinguish between general levels of intellectual behaviour. The learning outcomes are formulated according to frames of increasing competence, for example: "The student knows…", "The student has an understanding of … " and "The student is able to … ".

Figure 7: Bloom's taxonomy levels of intellectual behaviour[11]

1.1.2 Learning methodology

An effective teaching methodology contributes to acquiring competences and should be regarded in the development of the skill sets and training material. A learning environment that allows interaction with the lecturer is generally superior to passive education without opportunities for questions and interacting. Online education therefore poses challenges in order to substitute classroom interaction. A proven teaching method to support the learning process of students is called "scaffolding".[14] It includes breaking up learning elements into bits and providing tools and exercises per bit for better understanding and mastering of the learning concepts.[15] Studies show that especially online learning environments without scaffolding result in the failure to apply the acquired knowledge.[16] Furthermore, self-regulation is essential for an online distance learning environment to be successful and requires motivated students that are willing to participate.[17]

1.2 Rubber technology in DRIVES

Road transportation vehicles are assembled using numerous rubber components with a variety of applications. (Figure 8) For example, rubber bushings connect chassis, engine and transmission parts to provide damping and vibration isolation; rubber timing belts synchronize rotations and transfer power between shafts of engine and cooling systems; rubber sealings seal the interior of the car from moist; window wipers clear the front and back window vision; rubber tubes prevent leakage and support the transportation of fluids under the hood; et cetera. All applications require different rubber compounds for their operating conditions vary, although it is often hidden by the similar black appearance.

Figure 8: A selection of rubber applications in a passenger car[18–23]

Tires account for roughly 60% of global rubber consumption for both synthetic (petroleum-based) and natural "rubber tree" (Latex) rubber.[24] They connect vehicles to the road and provide grip and damping, which are highly related to safety, comfort and driving performance. But, although delivering critical performance for road transport, tires contribute to environmental impact of the automotive industry. In 2019, 2.5 billion tires were produced worldwide and numbers are growing roughly 3.4% each year, which contributes to the depletion of non-renewable resources and their disposal is a problematic source of waste.[25] The waste problem is two-fold: Firstly, the tire tread is worn off and rubber micro particles pollute the ground, water and air; secondly worn tires are difficult to recycle and often incinerated.[26] Finally, and often disregarded by costumers, tires contribute to fuel consumption of road vehicles by energy loss due to rolling hysteresis.[27]

1.2.1 Educational institutes in Europe

In European countries several governmental sponsored institutes offer rubber courses on practical and more theoretical level, such as IFOCA (France), Consorcio Caucho (Spain), DIK (Germany), TARRC (UK/Malaysia), ERT (The Netherlands) and more.[28–32] Well known is the German institute of rubber technology DIK (Deutsches Institut für Kautschuktechnologie), which is a publicly funded and non-university institution of the Lower Saxony Ministry of Economics, Labor, Transport and Digitalization in Germany. The institution aims to conduct applied research to stimulate understanding and innovation in rubber technology, especially by investigating the chemical and the physical behavior of rubber. The DIK offers several courses from theoretical to more practical education in the laboratory and is commonly known for high quality courses.[30] Other examples of institutes are Rubber Consultants in the

UK (TARRC) that offers tailor-made theoretical and practical education and the Elastomer Research Testing (ERT) in the Netherlands that offers two to three day basic trainings at the institute for introductions to compounding, mixing and product design, including non-linear modeling and FEA analysis methods. In addition, the University of Twente offers an annual five-day seminar into rubber compounding, processing and product design. This seminar is on a more theoretical level than the ERT trainings. Production and mixing related courses are offered by e.g. the DIK, DKG and Harburg-Freudenberger Maschinenbau GmbH (HF).[33] In general, these trainings are taught on location. In some cases, online courses are offered, but these include either livestreams of lectures or online exams for which content is delivered by paperback hand-outs or books.[34] Therefore the DRIVES project facilitates an undiscovered niche for rubber technology, exclusively online education and examination for the Basic and Advanced Rubber Technologist job roles.

1.2.2 Rubber Technologist job roles

The ETE group is, besides co-leader of work package 3 within the DRIVES project, responsible for the development of the Rubber Technologist job roles that are partly developed "in-house" based on material from the Elastomer Science and Engineering (ESE) course for master students at the University of Twente. ESE discusses a variety of topics in the rubber field, ranging from basic compounding skills to more advanced chemical and mechanical phenomena on macro and micro-level. The course requires basic chemical knowledge on high school degree (EQF 5) level and mechanical engineering background on bachelor (EQF 6) level.

The job roles aim to promote sustainability by improving the design, processing, design process and performance of rubber products. The general scope of the Rubber Technologist job roles is to teach thorough understanding of rubber material, processing methods, behavioral phenomena and compounding methodology. This will subsequently lead to an increasing first-time right mentality in rubber product development and decreasing degree of trial-and-error based design processes. Hereby the product quality and design process efficiency for rubber goods in Europe is improved. Additionally, specially designed "Sustainable Rubber Technology" elements are added in order to promote sustainable and wholesome compounding.

Figure 9: Rubber Technologist job role levels[35,36]

The Rubber Technologist is planned to be offered on Applied, Basic and Advanced level. The Applied RT offers a practical work-floor approach, the Basic RT offers a basic theoretical understanding for trainees without a background in rubber technology and the Advanced RT offers a deeper understanding for the development of new materials and products. The trainee can choose for any of the three job roles without required pre-knowledge, but in general the Basic RT is a beginners course and can be followed up by the Applied or Advanced RT. (Figure 9) The ESE course is the foundation for the development of the Basic RT, containing simplified content, and the Advanced RT. The Applied RT will be developed in a later stage. The skills cards were developed according to the DRIVES job role structure, top-down respectively comprised of units, 2-6 elements per unit and 2-6 skills per element. (Figure 10)

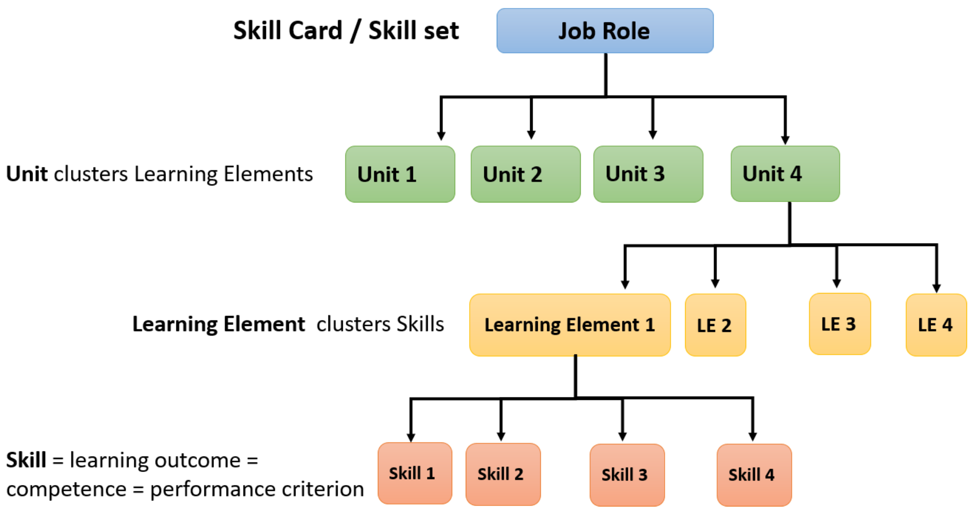


Figure 10: Skill Card model for project DRIVES in accordance with the ECQA

1.3 Aim and goal of the research

The goal of this thesis project was to substantiate the relevance of new rubber technology competences in a sustainable automotive industry future and to develop the Basic and Advanced RT job role skill cards. The skill sets were drafted by combining the ESE content with a study into future needs of the automotive rubber industry. These needs are two-fold, on the one hand needs following from future trends in the automotive rubber industry and on the other hand currently lacking educational needs. The future needs were examined by a literature study and evaluated further by discussions with various rubber industry respondents. The results are integrated into the ESE based rubber technologist skill sets. The content and general timeline of the research was divided in four main objectives:

- Perform a literature study in future trends in the automotive industry and the accompanying role of rubber technology
- Propose a preliminary job role skill card in accordance with the certification body ECQA, based on the Elastomer Science and Engineering course at the University of Twente and an executed literature study
- Investigate future needs of the industry by interviewing various companies and associations
- Implement the gained knowledge in the proposed skill cards

The role of rubber technology in future automotive was investigated with emphasis on trends driven by the reduction of greenhouse gas (GHG) emissions. The tire industry was expected to contribute to the emission of greenhouse gasses and in general to the overall environmental impact of the automotive industry. An all-inclusive summary that addressed major forms of environmental impact related to the automotive industry was written. The literature study primarily investigated the quantification of the impact related to the tire industry and concluded by the proposal of general solutions for tire and rubber technology challenges.

The rubber technologist skill sets were prepared based on the ESE course and analyzed on completeness with respect to the content and structure for anybody unfamiliar with rubber technology. The solutions of the executed literature study were integrated into the drafted RT skill sets. Hereby, preliminary skill sets were prepared for presentation to rubber industry partners.

The project and skillsets were proposed to the industry respondents to investigate the demand for the project and completeness of the skill sets. The educational gap was investigated together with the future needs of the company. Future needs from the perspective of the automotive industry and educational needs of the rubber industry were expected to overlap and complement one another. Finally, outcomes of the discussions were integrated within the RT skill sets. Appendix A discloses the complete questionnaire structure that elaborates on the main topics:

- Type and frequency of internal and external rubber technology trainings within the company
- Challenges and trends in the operating field(s) of the company
- Wishes or lacking content in trainings with respect to sustainable rubber technology
- Skill set evaluation of topics addressed in the RT job roles
- The company's interest in project DRIVES and the RT job roles

After discussions with the respondents, the skill sets were adjusted based on feedback from the industry. The Basic Rubber Technologist skill set was fully developed up to skill level and the Advanced rubber technologist skill set was partly developed up to element level, according to the DRIVES skill set mind map visualized in Figure 10.

2. Future trends in the automotive sector

Future trends inside the automotive industry are heavily investigated by consultancy firms and summarized by catchy abbreviations, such as EASCY – *Electrified, Autonomous, Shared, Connected and Yearly updated* – by PricewaterhouseCoopers and ACES – *Autonomous, Connectivity, Electrification and Ride Sharing* – by McKinsey.[37,38] Firms are essentially observing similar trends and the future holds self-driving cars – *autonomous* – , that communicate with each other and infrastructure assets – *connectivity* – , that are powered by electric powertrains – *electrification* – and are shared among users – *ride sharing* – . (Figure 11) These trends are driven by the desire to improve either the driver experience, the infrastructure network and/or the reduction of environmental impact related to the automotive industry. Negative environmental impact mainly regards the emission of greenhouse gas (GHG), toxics and pollutants and the depletion of natural resources. Chapter 2.1 describes the status-quo of the highly debated and regulated GHG emissions.

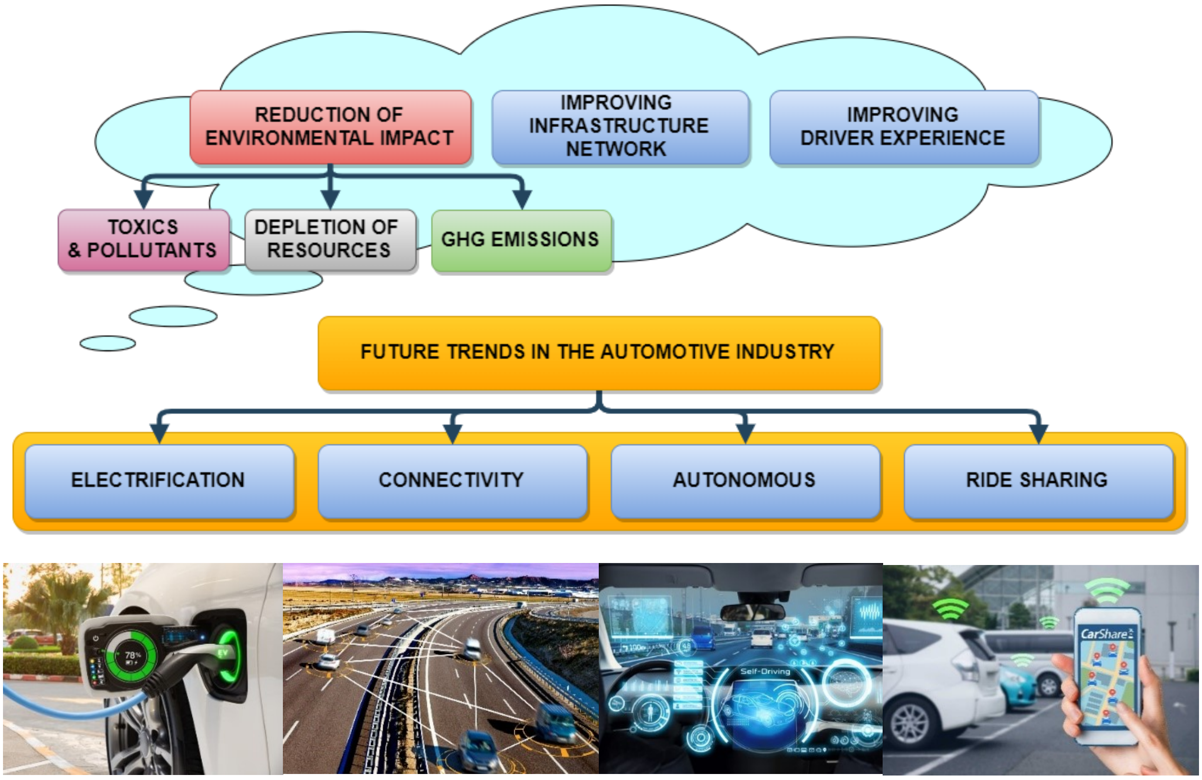


Figure 11: Future trends in the automotive sector (bottom) and key drivers (top)[37,39–42]

2.1 GHG emissions and regulations in road transport

The Paris Agreement (2015) states the goal to limit global temperature rise, stimulated by the greenhouse effect, to well below two degrees Celsius above pre-industrial levels.[43] Main greenhouse gas CO_2 is the final product of combustion fossil fuel in traditional automotive engines and 27% of total CO_2 equivalent GHG in the EU is emitted by the transport sector, including road, maritime and aviation transport of passengers and goods. Road transport contributes with 72% to transport CO_2 equivalent emissions, subsequently contributing with 21% to EU total CO_2 equivalent emissions.[44] (Figure 12) Globally, road transport accounts for 74% of transport emissions and 17% of the total emissions.[45,46] The EU road transport sector can be divided into three main categories: Passenger cars, light duty trucks and heavy duty trucks and busses. Passenger cars contribute by roughly 61% to the total road transport emissions, followed by heavy duty trucks and busses with 27% and light duty trucks with 12%.[47] (Figure 12)

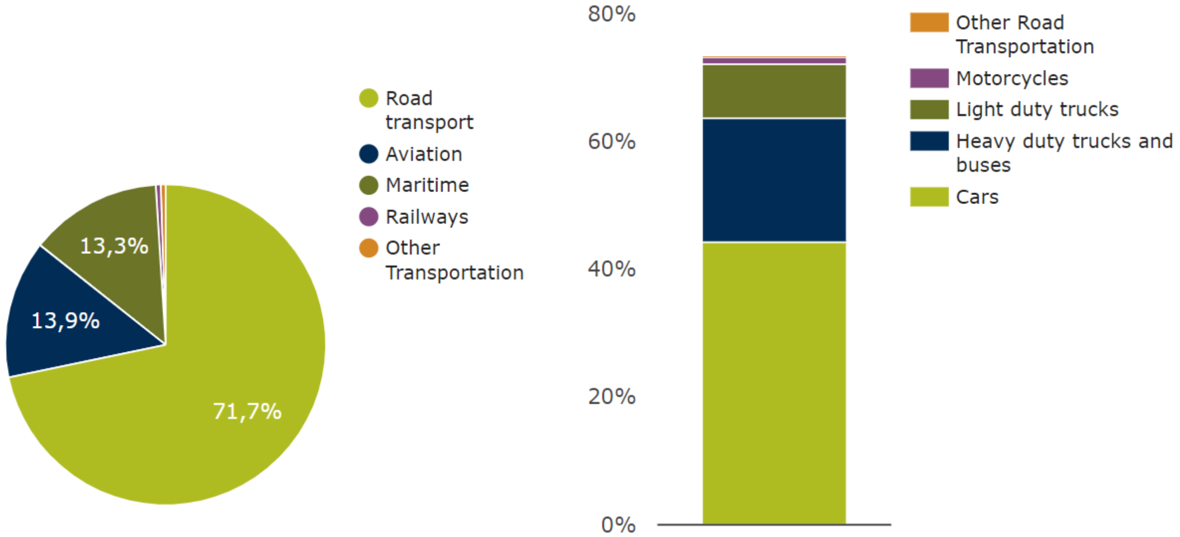


Figure 12: Share of EU transport GHG emissions in 2017 (left: Industries, right: Road transport)[47]

The reduction of GHG emissions is a prime topic in the road transport sector and electrification, in other words E-mobility, is a direct result of innovations led by this endeavour. The government and industry focus on reducing emissions and replacing combustion engines by non-emitting electric engines. But even though E-mobility places the location of energy production outside of the vehicle, gross GHG emissions do not necessarily change, as energy from renewable sources, excluding energy derived from biomass, accounts for only 7% of EU gross inland energy consumption and roughly 25% of electricity generation.[48] The majority of energy and electricity is still derived from fossil fuels, therefore the lifecycle emissions of Electric Vehicles (EVs) are close to those of traditional combustion engine vehicles. (Figure 13)

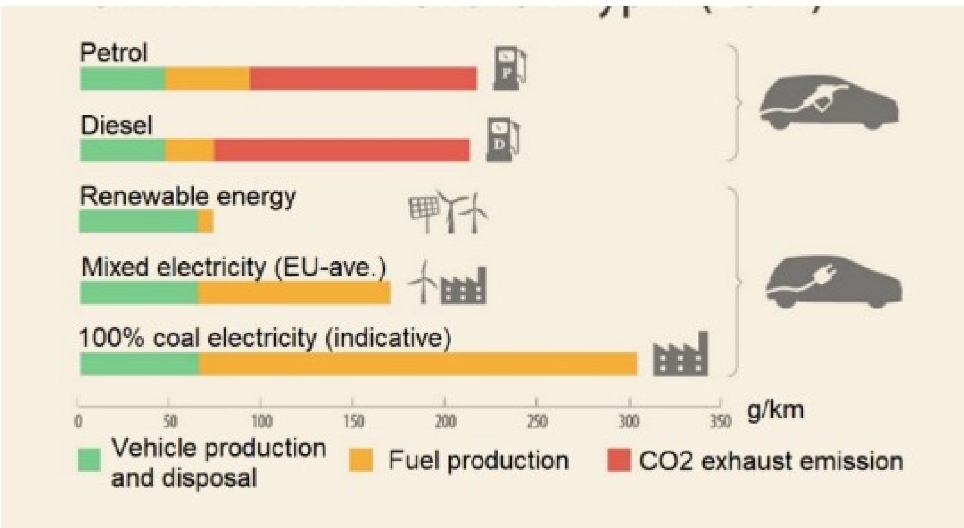


Figure 13: Life-cycle $C0_2$ emissions for different vehicle and fuel types (EU-2014)[49]

2.1.1 Future perspective of GHG emissions

Global GHG emissions continue to grow +0.5% annually.[45] (Figure 14) First world countries show reversion, but Asian countries show growth up to 6%, of which road transport is accountable for 10% of total emissions.[50] The global energy and automotive sector are expanding as welfare and car sales in emerging economies are expected to grow similarly to China's in the past decades, hereby further elevating road transport emissions.[51]

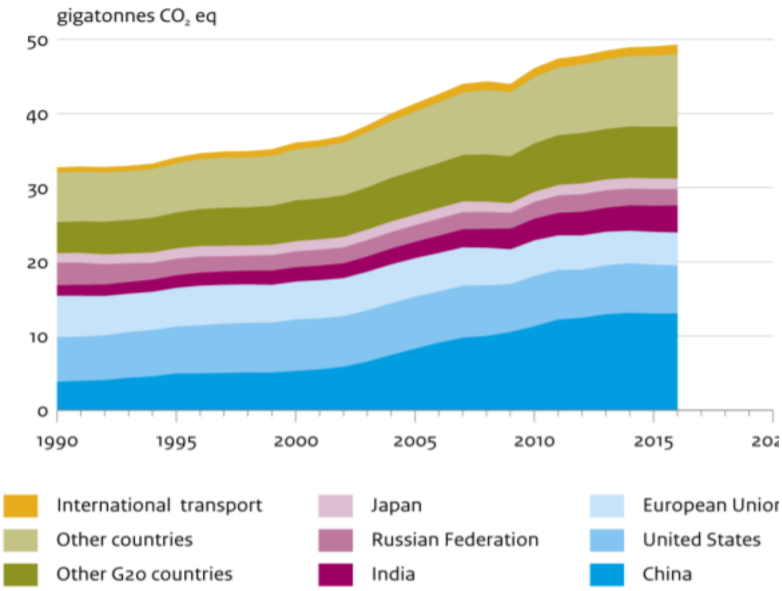


Figure 14: Global GHG emissions, per country or region[45]

In the EU, total GHG emissions have reversed to below 80% compared to 1990. However, the road transport sector fails to join this EU-wide trend and its emissions have grown of 25%. (Figure 15) The EU aims to reduce road transport emissions to levels below those of 1990 and continue towards zero emission driving.[49,52]

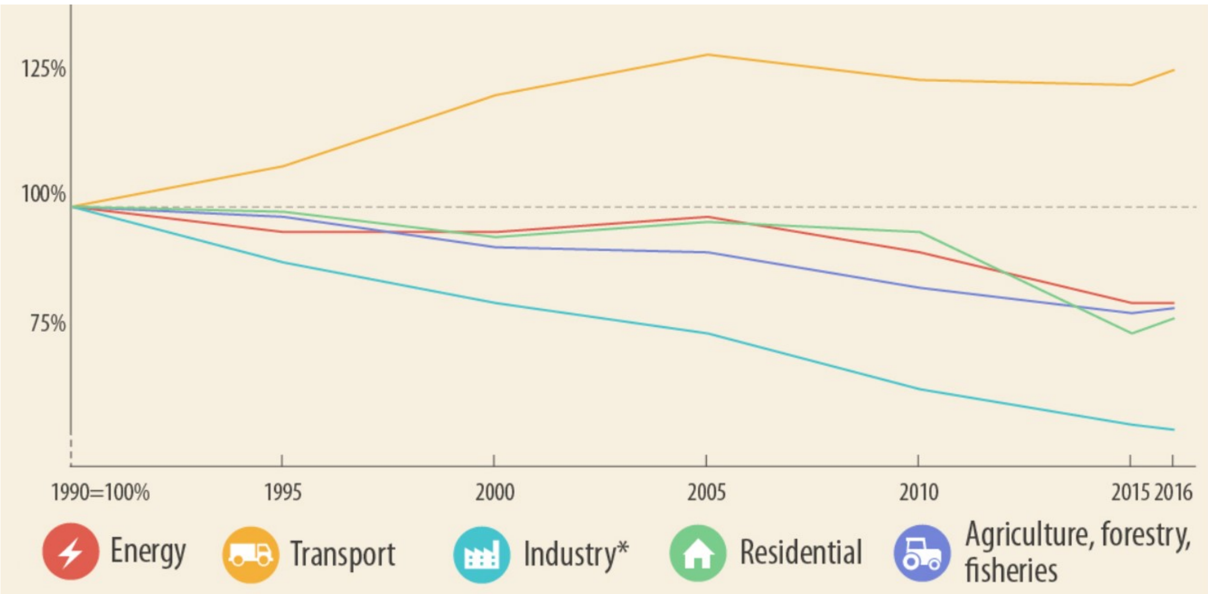


Figure 15: Evolution of CO_2 emissions by sector in the EU (1990-2016)[49]

2.1.2 Future perspective of GHG regulations

GHG regulations are imposed globally by fleet-wide average CO_2 emission targets for new vans and cars supported by tire performance labels that disclose the grade of fuel economy. (Figure 16) The EU is ambitious by imposing a fleet-wide newly registered passenger car target of 95 grams of CO_2 per kilometre (g/km) in 2021 and adopting regulations for up to 37.5% reduction in 2030. For diesel engine vehicles, having a quickly decreasing market segment of 47% in the EU, additional regulations apply for emitting NO_x gasses.[53] The automotive industry is struggling to meet the 2021 target for passenger cars and emissions increased to 120.4 g CO_2/km in 2018 partly due to sport utility vehicle (SUV) segment growth.[54] Historical data show fleet-wide emissions in Europe are flattening out, even though the European commission has high expectations for future reductions. (Figure 16)

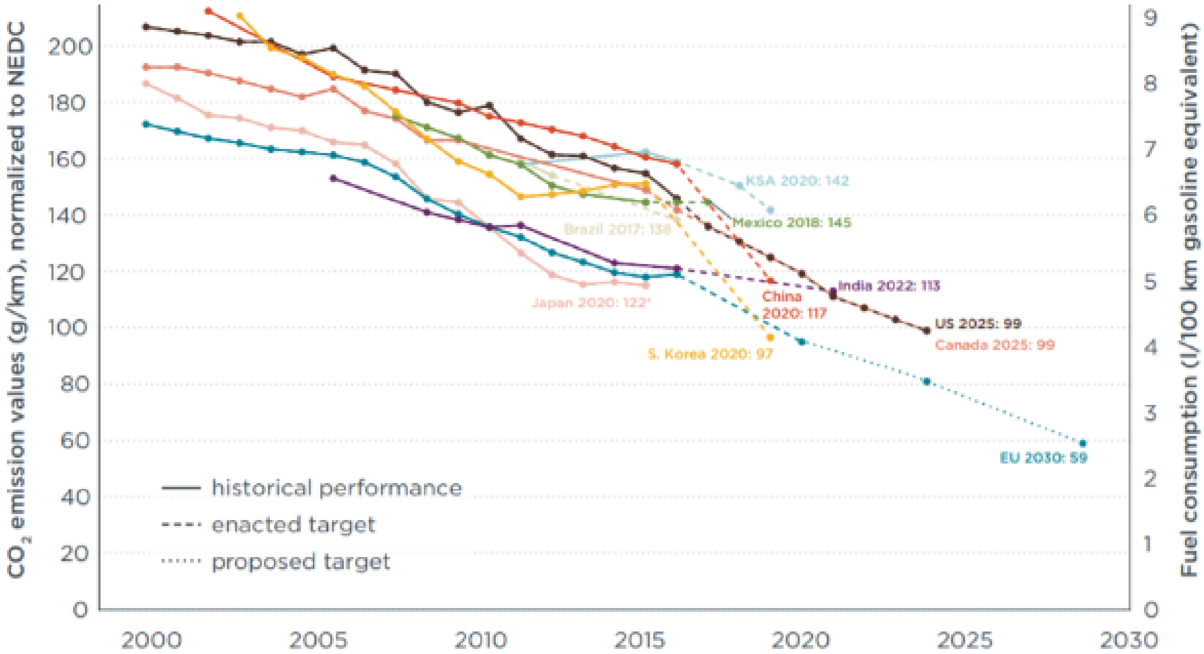
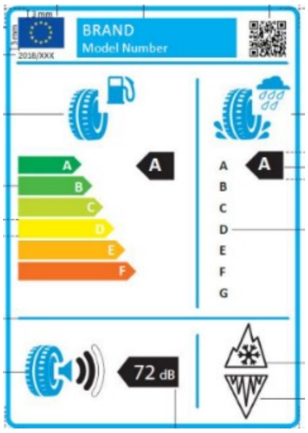


Figure 16: Overview of global CO_2 regulations for new passenger cars[55]

In 2012, the EU started informing consumers on tire performance by grading and labelling tires on noise, wet grip and fuel economy.[56] (Figure 17) The tire's use-phase accounts for 85% of the total carbon footprint of the tire by energy losses due to rolling hysteresis. The other 15% is mostly related to tire production that emits the equivalent of 5 g/km $C0_2$ in the use-phase.[57,58] The tire industry characterizes tire performance by three main criteria referred to as the "Magic triangle of tire performance": rolling resistance, abrasion resistance and wet grip. The magic triangle is commonly referred to as a zero-sum game where improving one property negatively affects others. Rolling resistance quantifies the fuel economy of the tire, abrasion resistance quantifies the life-time and wet grip quantifies grip on the road in wet conditions. Tire fuel economy, or rolling resistance, is one of the main energy dissipation phenomena in road transportation.[44] Rolling resistance accounts for roughly 25-35% of total energy consumption of a road vehicle.[27]



Passenger car tire (C1) RRC labels (2012-2020)	
RRC in kg/t	**Energy Efficiency class**
RCC ≤ 6.5	A
6.6 ≤ RCC ≤ 7.7	B
7.8 ≤ RCC ≤ 9.0	C
Empty	D
9.1 ≤ RCC ≤ 10.5	E
10.6 ≤ RCC ≤ 12.0	F
RCC ≥ 12.1	G

Figure 17: Tire performance label (left) and rolling resistance label categories (right)[56]

The rolling resistance coefficient (RRC) quantifies energy loss due to repetitive deformation of the tire structure, tire tread and road surface. Multiple factors influence the RRC, such as the dimensions of the tire, materials types and interaction phenomena between materials.[27] The majority of energy loss (44%) is caused by tire tread deformation hysteresis and slip between tread and road surface.[59] (Figure 18) RRC limits are introduced in 2012, and lowered in 2020, to phase out high rolling resistant tires and stimulate production and use of low rolling resistant tires. Passenger car, light commercial vehicle and heavy duty vehicle tire RCC limits tightened in 2020 from respectively 12.0, 10.5 and 8.0 kg/t to 10.5, 9.0 and 6.5 kg/t, according to ISO28580.[60] Safety related characteristics, such as wet grip, design integrity and handling, should be kept on a sufficiently high level when reducing RCCs.

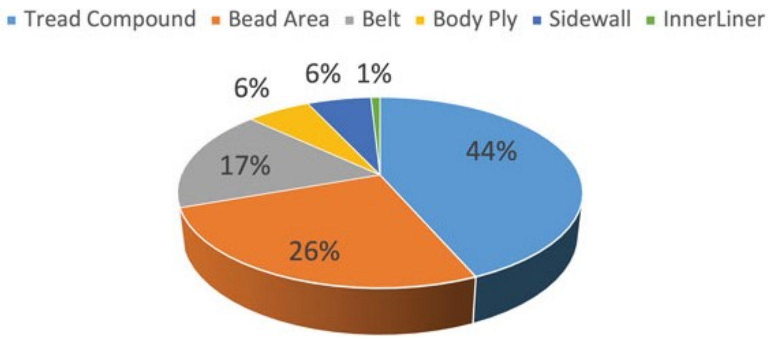


Figure 18: Rolling resistance contributions of main tire components[61]

2.2 Tire technology in environmental goals

The EU is aiming, but up to now failing, to reduce road transport GHG emissions and is struggling to meet future emission targets for newly registered vehicles. What is the reason behind stagnating road transport emissions in Europe in the past fifteen years and how should the regulators and society proceed to successfully meet future climate goals? GHG emissions and fuel economy are one-on-one correlated and tires contribute to a large extent to fuel economy by hysteresis energy losses due to the rolling of the tire, named rolling resistance. The tire industry can be regarded as a stakeholder for the environmental impact of the automotive industry. Can the contribution of tires to fuel economy improvement be qualified and quantified in comparison to other main energy consuming factors? And to what extent do, or potentially can, these factors contribute to short term (5-10 years) reductions? Apart from contribution to fuel economy, the overall lifecycle of especially passenger car tires is under investigation due to tire tread wear and end-of-life tire (ELT) disposal. In Chapter 3 all major forms of impact and the relevance of tire and rubber technology for the future automotive industry are discussed.

3. Environmental impact related to tire technology

In Chapter 3 the environmental impact related to the tire industry is discussed. In Chapter 3.1 the main drivers of vehicle energy consumption are addressed and the relevance of tire fuel economy is substantiated; in Chapter 3.2 the depletion of non-renewable resources is addressed; in Chapter 3.3 contamination by wear and disposal of end-of-life tires is addressed and in Chapter 3.4 the results are conclusively summarized.

3.1 Relevance of rolling resistance in fleet-wide energy consumption reduction

Energy consumption of road vehicles is quantified by the World harmonised Light-duty vehicles Test Procedure (WLPT), which has replaced the New European Driving Cycle test (NEDC) in 2019.[62] The WLPT is regarded to be more representative for real driving conditions and accordingly measures higher CO_2 emission values. Three factors are highly determinant for energy consumption: vehicle mass, aerodynamic drag and the rolling resistance coefficient (RRC), inducing energy losses by acceleration, air friction and rolling hysteresis. These factors are optimized by vehicle manufacturers for reducing energy consumption, which is directly related to GHG emission. [3,59] Additionally, secondary factors that indirectly affect energy consumption are optimized by e.g. power train efficiency improvement and emerging smart mobility technology.

Power train efficiency is the efficiency in conversion of (thermal) energy to actual power delivered to the vehicle's driving shafts. Energy loss occurs due to friction in the power train and (thermal) in-engine efficiency. Internal combustion engines typically have an efficiency of 30% due to energy dissipation by heat and friction between moving parts in the engine and transmission.[63] Electric engines are highly efficient by reaching >90% due to little moving parts and the absence of high temperature combustion. Other (tertiary) types of energy losses, such energy losses in transport of electricity/fuel from the grid/source to the vehicle, could be considered as well. For example, the charging efficiency of electric cars batteries is typically 80-90%.[64] Smart mobility includes mobility related IT solutions and increasing synergy between vehicles and infrastructure assets, e.g. bridges and traffic lights. Pilots on smart mobility concepts are in progress, such as the smart mobility grid pilot in Amsterdam and Truck Platooning pilot in co-operation with China.[65] They aim to improve traffic flow and reduce energy consumption. The average fuel consumption is reduced up to 16% by truck platooning due to reduced aerodynamic friction.[66] (Figure 19)

Figure 19: Truck platooning[67]

Secondary and tertiary factors are disregarded in this research in order to focus on primary factors contributing to energy consumption of road vehicles. The degree to which mass, drag and the RRC can reduce fleet-wide passenger car energy consumption (FPEC) up to 2030 is investigated and accordingly named the factor's "Reduction Potential" (RP) for future energy consumption. RPs are compiled of the factor's "Relative Contribution" (RC) and the factor's "Improvement Potential" (IP). RCs quantify the factor's relative contribution to FPEC reduction. IPs describe the factor's likelihood of improvement in the near future, which is calculated using the average of the factor's current trend line and maximum percentage of improvement based on current technology.

3.1.1 Relative Contribution to FPEC reduction

In the NEDC a 10% reduction of mass, aerodynamic drag and rolling resistance respectively reduces FPEC with 4, 1.7 and 1.7%.[59] (Table 2) Mass contributes by accelerating, according to the second law of Newton, and by increased load on the tires which results in extra rolling resistant force, according to the tire rolling resistance quantified by the RRC in resistant force per ton. At constant speed, rolling resistance dominates at lower driving speeds and aerodynamic drag at higher driving speeds, for drag increases quadratically with the airflow velocity (Equation 1). Aerodynamic drag and RRC equally reduce FPEC in the NEDC driving cycle. With a higher average driving speed in the WLTP driving cycle, a 10% reduction of mass, drag and RCC respectively reduces FPEC with 4, 3 and 1.5%.[8] (Table 2) The tire's RCC is least significant and vehicle mass reduction is most significant in terms of relative contribution to energy consumption reduction.

$$Force_{Aerodynamic\ Drag} = \frac{1}{2}\rho C_D A \cdot velocity^2 \quad \text{(Equation 1)}$$

Driving cycle	-10% Mass	-10% Aerodynamic drag	-10% Rolling Resistance Coefficient (RRC)
NEDC	-4.0% FPEC	-1.7% FPEC	-1.7% FPEC
WLTP	-4.0% FPEC	-3.0% FPEC	-1.5% FPEC

Table 2: Factor's Relative Contribution to FPEC reduction[8,59]

3.1.2 Improvement Potential of energy consuming factors

Vehicle mass

The increasing safety requirements, demand for comfort and higher sales in SUV and more luxury segments have led towards increasing fleet-wide average vehicle mass.[53] The average mass of light-duty road vehicles has increased over the last decades and stabilized at 1400 kg. (Figure 20)

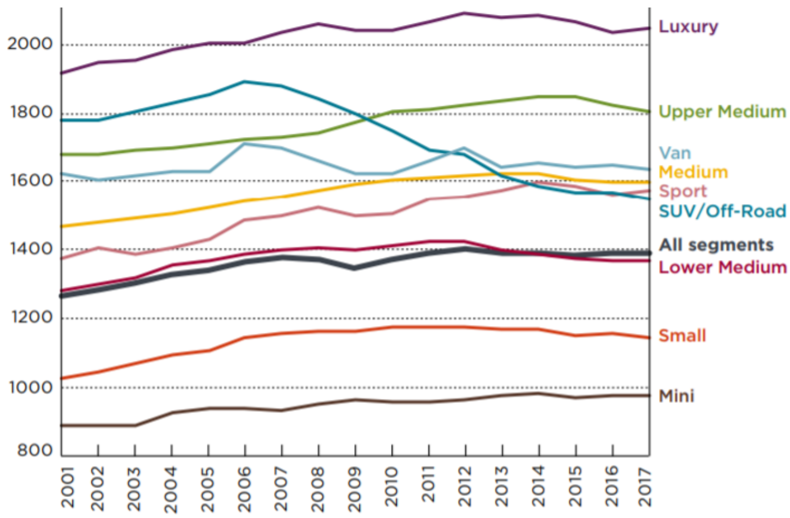


Figure 20: Vehicle mass in running order per segment in the EU[53]

In contrast, weight reduction by application of high strength steel, aluminium and fibre reinforced plastics has gained attention in the industry; and has been realised by optimizing the vehicle frame and replacing steel or aluminium parts with short fibre reinforced plastic parts, such as seat frames, oil pans, intercoolers and pedal boxes. (Figure 21) Chassis applications of continuous fibre reinforced plastic can promote further reductions, but the industry is struggling to improve cost-effectiveness in mass production manufacturing technology.[3] It is estimated that a 10% reduction of vehicle mass can be achieved by the application of high strength to weight ratio materials and smart solutions for reducing the number of luxury components. [8,68] It should be noted that the introduction of EVs may increase vehicle mass due to heavy battery packs. The Tesla model S for example has a 540 kg battery pack and weighs more than 2000 kilograms. [69] However, a benefit of EVs would be that braking energy is stored by regenerative braking, which reduces the influence of vehicle mass on energy consumption and the WLTP driving cycle.

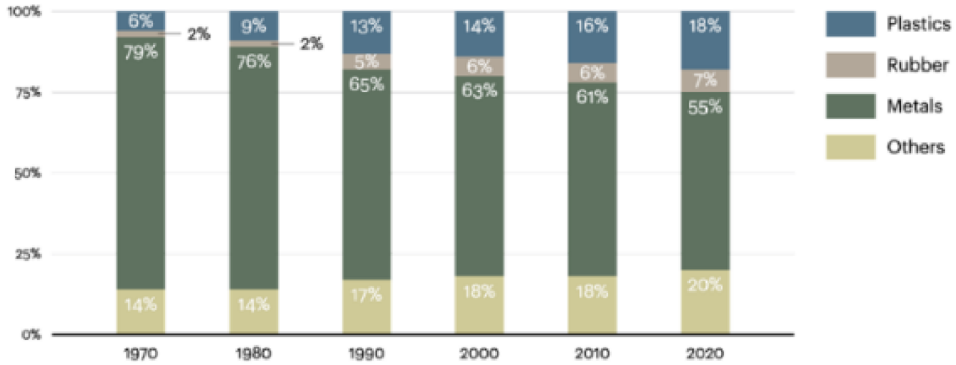


Figure 21: Application of materials as percentage of total vehicle weight[70]

Aerodynamic drag

Passenger car design is a compromise of costumer wishes, safety regulations and aerodynamic resistance. Typical drag values for passenger cars are $C_d = 0.25 - 0.4$. Drag resistance declined between 1970's and 1990's by increased focus on fuel consumption due to the oil crisis. From 1990's on, fleet-wide average drag coefficient of passenger cars stabilized around $C_d = 0.31$ and total drag (C_d multiplied with vehicle frontal area) has increased due to the greater frontal area of new vehicles. [8] (Figure 23) In the last decade, manufacturers have given aerodynamic drag reduction an impulse. Electric cars from Tesla for example have low drag coefficients of $C_d = 0.23 - 0.25$, as well as some newer series from brands like Volkswagen, Mercedes, Audi and BMW. [71] C_d is roughly 0.3-0.35 in the lower-medium passenger car segment. [72] Depending on the popularity of aerodynamic car design, the average drag coefficient can be reduced up to 25% (from $C_d = 0.31$ to $C_d = 0.23$), whilst maintaining the fleet-wide average vehicle frontal area. The overall trend between 2004 and 2013 was +0.4 % annual increase in fleet-wide average aerodynamic drag, which is likely to continue due to SUV segment growth. [8] (Figure 22)

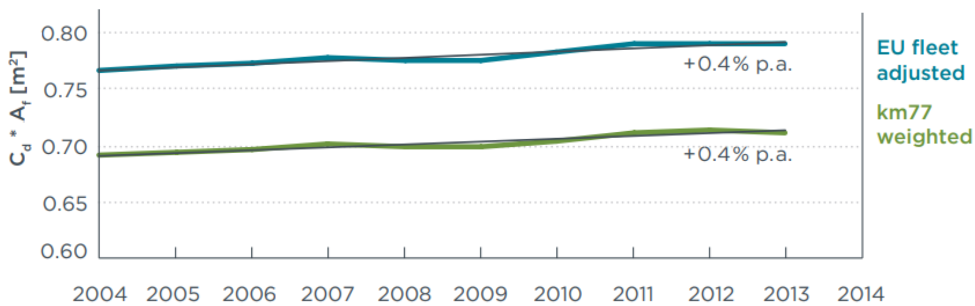


Figure 22: Fleet-wide average trend of aerodynamic drag of in the EU (km77 database & fleet adjusted)[8]

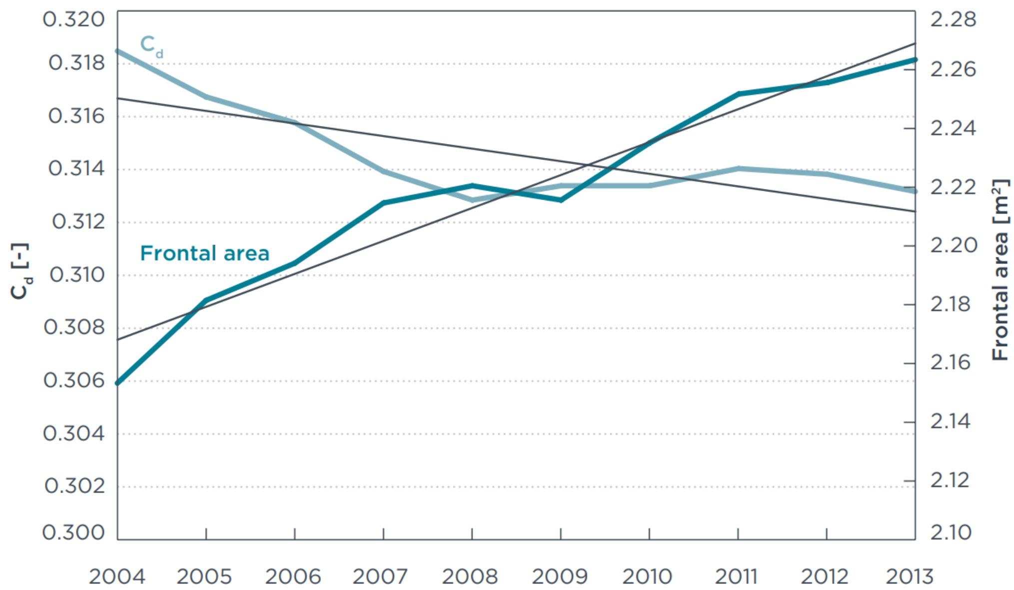


Figure 23: Drag coefficient and frontal area trends of new passenger cars in the EU (km77 database)[8]

Rolling resistance

Rolling resistance has reduced by approximately 50% since 1975.[8,73] From 2004 to 2013, the market average RRC in the EU was predicted to decrease of 1.3% annually.[8] From 2013 onwards, data based on the German market has predicted flattening around 9.6 kg/t (label E), but EU-wide research from the European tire and rubber manufacturers association (ETRMA) has predicted a shift towards better rolling resistant and wet grip label tires. (Figure 24, Figure 25) The most popular tire label in 2017 was "E" for fuel consumption and "C" for wet grip, but a promising shift towards fuel economy label "C" has been realised (from 19% to 26 % market share).[74] One should be aware that rolling resistance can compete with wet grip performance, but the two can actually be improved simultaneously, e.g. with silica-silane technology.[75]

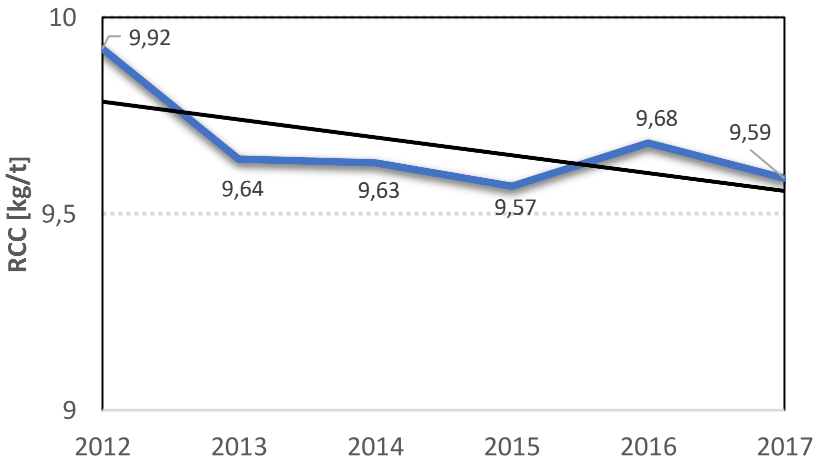


Figure 24: Market average RRC estimate in Germany (Tire on-line Germany)[74]

Market in 2012

C1 2012 2013	RR A	RR B	RR C	RR E	RR F	RR G
WETG A	0.1%	0.3%	1.7%	2.3%	0.8%	0.1%
WETG B	0.0%	0.7%	4.6%	9.8%	4.4%	0.6%
WETG C	0.0%	0.4%	8.8%	22.9%	12.9%	2.0%
WETG E	0.0%	0.1%	3.0%	10.4%	6.2%	1.0%
WETG F	0.0%	0.2%	0.7%	2.1%	3.5%	0.2%
RR	**0.2%**	**1.7%**	**18.9%**	**47.5%**	**27.8%**	**4.0%**

Market in 2017

	RR A	RR B	RR C	RR E	RR F	RR G
WETG A	0.1%	0.6%	3.4%	2.4%	0.6%	0.0%
WETG B	0.1%	1.2%	8.0%	10.3%	2.8%	0.3%
WETG C	0.1%	0.6%	11.0%	26.7%	9.6%	1.0%
WETG E	0.0%	0.2%	2.9%	8.7%	4.0%	0.6%
WETG F	0.0%	0.2%	0.7%	2.1%	2.0%	0.1%
RR	**0.2%**	**2.6%**	**26.0%**	**50.3%**	**18.9%**	**2.0%**

Figure 25: Tire market label shift in the EU[74]

The overall fuel economy of tires has been improved with the introduction of the "Green Tire" silica-silane technology by Michelin.[75] Silica silane technology is known for improved rolling resistance and breaking the rules of the magic triangle zero-sum game.[76] In 2015, roughly 30% of the EU market were silica-silane tires. It is expected that this market share will further increase and contribute to market average RRC reduction.[77] Due to newly imposed limits for tire fuel economy and emissions, the shift from NEDC to WLTP driving cycle, the tire labelling system and available tire technology further fleet-wide average RRC reduction is realisable. In 2016, the international council of clean transportation (ICCT) estimated that original equipment tires were characterized by RCC = 8 kg/t in 2019 and 7 kg/t in 2025. By 2025, a 75% market share for label A/B tires (RRC < 7.8 kg/t) was predicted, corresponding to an average annual reduction of 2%.[8] (Figure 26) The low amount of label A/B tires on the market in 2017 does not reconcile with the predictions for 2017 or 2019. Therefore, the prediction for 2025 is questionable as well as the estimated trend line of minus 2%. The previously achieved 1% annual reduction is considered to be more realistic. The lowest rolling resistant tires available (RRC ≈ 6 - 6.5 kg/t) enable a maximum market average reduction of roughly 35% compared to RCC = 9.5 kg/t.[78]

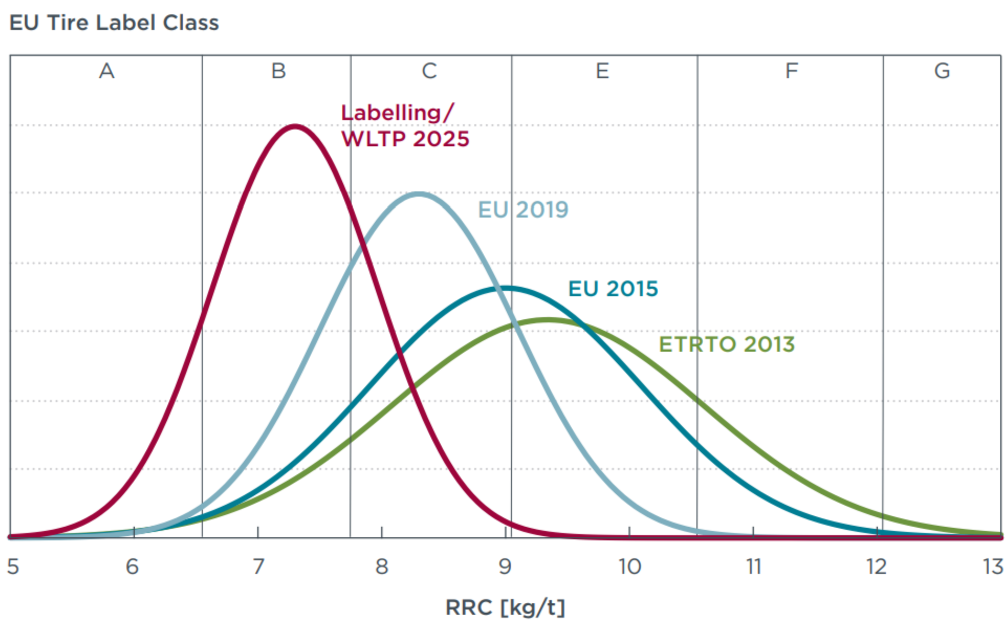


Figure 26: Forecast of rolling resistance distribution for original equipment tires in the EU[8]

3.1.3 Reduction Potential for FPEC in 2030

The Reduction Potential (RP) is the amount with which one factor is estimated to have reduced fleet-wide passenger car energy consumption (FPEC) in 2030. RP is calculated by multiplying the Relative Contribution (RC) with the weighted average of the improvement potentials (IP) multiplied with the timeframe of 10 years. (Equation 2)

$$RP(RC, IP) = -10 \cdot RC \cdot \frac{IP_{trend} + \frac{IP_{max}}{10}}{2} \qquad \text{(Equation 2)}$$

Factor	**Relative Contribution RC** (-1%)	**Improvement Potential IP** Trend	Max	**Reduction Potential RP** (up to 2030)
Vehicle mass	-0.40% FPEC	+0.0%	-10%	-2.0% FPEC
Aerodynamic drag	-0.30% FPEC	+0.4%	-25%	-3.2% FPEC
Rolling resistance coëfficiënt RRC	-0.15% FPEC	-1.0%	-35%	**-3.4%** FPEC

Table 3: Summary of parameters and calculated Reduction Potentials for FPEC reduction in 2030

In terms of Relative Contribution, the fleet-wide reduction of RRC is inferior to vehicle mass and aerodynamic drag reduction. However, due to lower Improvement Potentials of drag and mass, rolling resistance is the most promising factor in FPEC reduction up to 2030. (Table 3) Additionally, low rolling resistant tires can be deployed instantaneously over the existing vehicle fleet, whereas low mass and drag vehicles take years to be developed and deployed over the European market. Lastly, in contrast to cars, tires are not bought for their appearance, but for their performance. The tire industry is able to contribute to a great extent to future FPEC reductions as well as for other vehicles like vans, trucks and busses. It can be concluded that tire and rubber technology is relevant for the improvement of energy efficiency and subsequently for the reduction of GHG emissions of the road transport sector in the near future.

3.2 Depletion of non-renewable resources

Petroleum and Zinc are identified as main non-renewable resource depletion related to tire technology.[79] In this chapter percentual consumption and reserves to production (R/P) ratios is discussed.

3.2.1 Petroleum

Crude oil is the basis of many hydrocarbon based products, such as fuels in all typical grades, synthetic elastomers (IR, IIR, SBR, BR, …), mineral oil products and thermoplastics. Oil reserves are typically finite, but proved oil reserves grew to 1.73 trillion barrels (+ 2.4%) in 2018 due to newly discovered oil fields and new drilling technologies. The consumption also grew to 3.65 billion barrels (+1.5%) of crude oil. The R/P ratio predicts oil depletion in about 50 years. Future trends in availability, consumption and production are heavily debated since the discovery of new fields and technologies is becoming increasingly tougher but the global R/P ratio is ever growing.[80] (Figure 27)

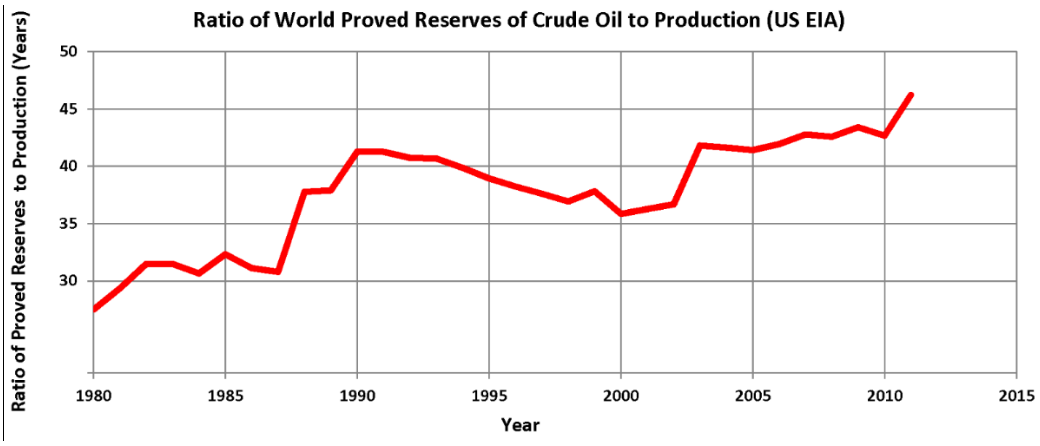


Figure 27: Ratio of global proved reserves to production of crude oil (in years) (1990-2015)[81]

The plastic and tire production account for respectively 4% and 1% of global crude oil consumption.[82,83] Tire rubbers are composed of several compounds from natural and petroleum-based polymers, fillers and processing oils. The production of one tire requires on average 26.6 litre of crude oil for synthetic ingredients and manufacturing energy. [84] Each year 2.5 billion tires are produced, requiring approximately 1 million barrels of crude oil daily and both the plastic and rubber production is growing 3-4% annually. [85] Crude oil depletion is a secondary driver of the increasing urgency to reduce energy consumption in road transport, consuming roughly 50% of the global oil production. The rubber industry impacts oil depletion mostly via fuel consumption in road transportation and to a lesser extent by tire production.

3.2.2 Zinc

Zinc is the 23th most abundant element in the earth's crust and found in cells of organisms and animals for vital functionality like cell division, growth and the immune system.[86] Zinc oxide is also an irreplaceable multifunctional rubber compound ingredient. Vulcanization systems based on sulphur are commonly activated by zinc oxide and provide fast vulcanization times, excellent in-rubber and anti-degradation properties. The depletion of Zinc ore would be disastrous because Zinc is irreplaceable in rubber sulphur vulcanization systems and is a main component in electronics, skin products, metal galvanizing coatings and dietary products. Worldwide roughly 55% of 1.5 million ton zinc oxide consumption was consumed by the rubber industry in 2015.[87] This equals roughly 5% of the 13 million tonnes zinc production (mining and recycling) globally.[88]

The rubber industry mainly consumes “Red Seal” zinc oxide, which is often produced from secondary resources, such as rest products of the galvanization process and recycled zinc from galvanized parts.[79] The average annual mining production of Zinc is 12 million tons, whilst global zinc reserves are estimated to be 225 million tons, which leads to a R/P ratio of approximately 20 years.[88] The ratio could increase based on increasing recycling and zinc ore mining opportunities in the future. Similar to petroleum, the world zinc R/P ratio has not changed significantly from 1990 up to now. This makes the depletion time frame uncertain, but it will eventually affect rubber vulcanization processes and presumably is under the attention of the industry.

3.3 Contamination by wear and disposal of tires

The origin of contamination by tires is two-fold: Firstly, the abrasion of the tire tread and secondly the disposal of end-of-life tires. Truck tires are retreated several times (11% of all tires), which means the casing is re-used and the worn tread is replaced by a new tread. In the EU, retreading is barely applied for passenger car tires and they become practically useless after the tread has abraded. The lifetime of a passenger tire is 60.000-80.000 km, such that for each 15.000-20.000 km driven one tire is disposed. In 2019, 2.5 billion tires are produced globally and 19.25 million metric tons are disposed, of which 3.6 million metric tons are disposed in the EU alone.[25,89]

3.3.1 Tire tread abrasion

On average, passenger car tires are scrapped by 2 kg rubber waste during the use-phase and similarly heavy truck and bus tires are scrapped by 9 kg.[26] Abrasion of tire treads accounts for 30 vol.% of all micro plastic particles in rivers, lakes and oceans.[90] The discovery of large amounts of plastic and rubber micro particles in the Artic snow leads to increasing concerns regarding environment and human health as micro plastic particles (<10 micrometre) are airborne and may penetrate cells, lungs and increasingly affect living organisms.[91] The rubber particles incorporate potentially harmful substances, such as polycyclic aromatic hydrocarbons (PAH’s), metals and accelerator reaction products.[90] Incorporated ZnO can contaminate the environment, but as Zinc is an essential element in nature both, a deficiency and excess, should be avoided in general.[79] Utilization of potentially harmful materials is limited in the EU by the REACH regulations (registration, Evaluation, Authorization and Restriction of Chemicals), which already banned PAH rich oils and nitrosamine forming accelerators.[92]

3.3.2 Disposal of end-of-life tires

In the EU, 94% of ELTs is collected and re-used, of which roughly 40% is burned as tire derived fuel for energy recovery mostly in cement production and 60% are recycled in a variety of material recovery, mostly ground rubber granulation applications.[93,94] (Table 4)

Granulation	Steel mills and foundries	Reuse for other purposes	Pyrolysis	Civil Eng. Backfilling
89%	1%	2%	1%	7%

Table 4: Material recovery purposes for ELT (EU) (2016)[95]

The quality of recycled rubber products does not meet the properties of virgin material and is often used for low duty applications. This is partly due to a high variety of additives and chain scission occurring in the recycling process due to heating and mechanical shearing. Recycling rubber without deterioration of properties compared to virgin rubber material is not yet possible. In contrast to plastic, that can be remolten into another shape, rubber polymer chains are covalently bonded or cross-linked. These bonds should be broken down for re-use of the rubber in a different shape. Rubber is especially difficult to recycle, especially for tire applications, as compounds not only incorporate a variety of additives and chemical crosslink bonds, but the tire is also build-up out of different compounds. (Figure 28) Each compound is produced with different types of polymers, fillers and additives to provide excellent tire functionality.

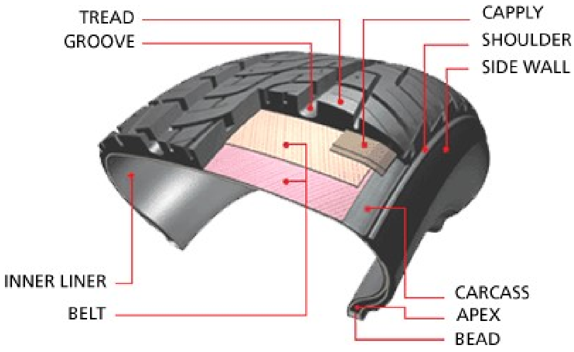


Figure 28: General exploded view of tire components[96]

Figure 29: Lansink's ladder [97]

Lansink's ladder of waste management hierarchy distinguishes between different disposal methods and grades according to their circular economy contribution. (Figure 29) The re-use by retreading of truck tires for example is highly contributing to a circular economy.

Landfill and granulation

In contrast to plastic, landfilling of whole and shredded tires is prohibited in an increasing number of countries and completely prohibited in the EU since 2006.[98] ELTs are granulated for their second application, often incineration or ground rubber applications. (Figure 30) ELTs are grinded in a multiple step process, where steel, textile and fibres are removed, in such a way that only rubber granules remain. Recently, these applications have gained attention for leakage of potentially hazardous substances.[99] Recycling by granulation for ground rubber applications, such as artificial turf sport fields and playgrounds, is causing pollution of groundwater by substances, such as zinc, cobalt and mineral oils. Increasing attention is drawn to investigate alternative compounding ingredients to reduce or replace potentially non eco-friendly substances inside tires.[95]

Figure 30: Recycled rubber granulate on synthetic grass soccer fields[100]

Energy recovery and incineration

Energy recovery and incineration can emit toxic components, such as PAH, azaarenes and oxy-PAH. Potentially harmful metals as Zinc and Lead (Lead is banned in European tires) are present to a small extent as solid waste.[101] Energy recovery by incineration for cement production with ELT derived fuel tends to give similar emission compared to the burning of conventional fuels. In contrast, uncontrolled open tire fires emit large amounts of numerous hazardous air pollutants, dioxins and metals.[102]

Cement production is one of the largest industries worldwide and accounts for 7% of global CO_2 emissions. It is a thermal energy intensive process driven by fossil fuels as oil, coal and natural gas. The potential to decrease the use of fossil fuels is enormous and the cement industry is increasingly using alternative fuels. ELT derived fuel is one of the most promising alternative fuels for the high energy density (30 MJ/kg), in between coal (24 MJ/kg) and petroleum (45 MJ/kg), and low moisture content. Due to high temperatures (~1700 Celsius) the incineration is relatively clean and solid waste (metal, metal oxide) is incorporated in the cement. CO_2 emissions from ELT mixtures tend to be slightly higher compared to traditional fuel emissions, but emission of dioxins, SO_x, NO_x , CO_x and metals are insignificantly different from hydrocarbon feedstock. Tire granules are mixed with 70-80% fossil fuels to avoid incorporation of superfluous Zinc in the cement. This method has proven itself for tire waste disposal, whilst saving fossil fuels. It is an intermediate solution to the energy and waste problems the world is facing today and gives tires a second purpose at level D/E on the Lansink's ladder. (Figure 29) It is nowadays regarded as an ecological and economically justified method of ELT waste disposal.[103,104]

3.4 Summary

This chapter has highlighted the environmental impact related to the tire industry. Chapter 3.1 has highlighted the importance of tire technology in CO_2 reduction of the road transport sector, chapter 3.2 has touched on the depletion of non-renewable resources and chapter 3.3 on contamination by wear and ELT disposal. Figure 31 summarizes the challenges in tire technology and provides general solutions. The improvement of tire tread abrasion resistance contributes to three of the five challenges: the reduction of ELT waste disposal, non-renewable resource depletion and contamination by tread abrasion. Climbing Lansink's ladder by re-using or recycling contributes to two challenges: the reduction of ELT waste disposal and use of non-renewables. Other solutions aim for one specific challenge. It should be noted that implementation of one solution can negatively affect other fields of tire performance and lifecycle.

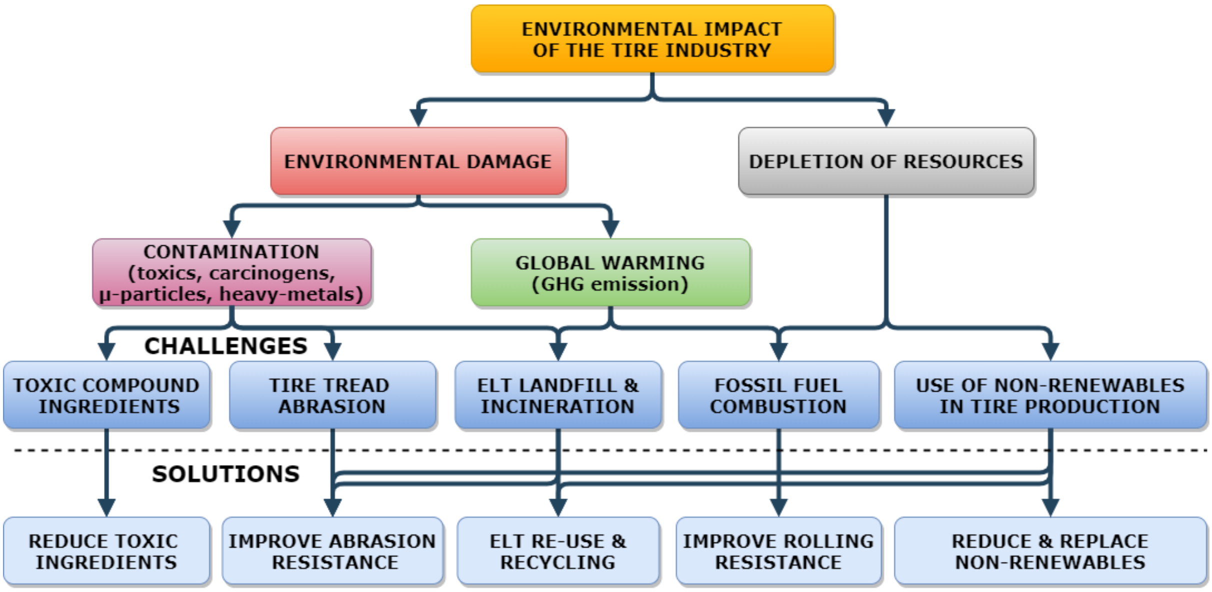


Figure 31: Summary of challenges & solutions for the environmental impact of the tire industry

The rubber industry is expected to aim for similar goals set for the tire industry. Tire specific challenges are abrasion resistance and rolling resistance reduction. Mechanical rubber goods aim for improvement of other, product specific, in-rubber properties. This essentially means that the rubber industry aims to improve product specific performance and hereby contributes to the sustainable character of the product. Project DRIVES aims to support innovation by research and development departments in the rubber industry. The RT job roles in DRIVES aim for awareness about challenges and solutions by providing dedicated information on sustainable rubber technology. In Chapter 4 the development of the RT job roles with sustainable rubber technology solutions is discussed.

4. Rubber technologist skill sets

The primarily RT skillsets were based on 17 general topics of the ESE course and the solutions for environmental impact of the rubber industry, summarized in Chapter 3.4. All were fitted in the DRIVES job role structure, top-down respectively comprised of units, 2-6 elements per unit and 3-6 skills per element. (Figure 32) The skills or competences or learning outcomes are verified by online exams. Online education requires self-explanatory content without theoretical gaps for the student who cannot directly turn to the lecturer for questions. Therefore, the ESE course content is additionally examined for completeness in order to eliminate educational gaps.

This chapter elaborates on the development of the job role skill cards, drafted in three sequential steps:

- Establish the vision for the Rubber Technologist job roles
- Evaluation and extension of Elastomer Science and Engineering content
- Evaluation of Rubber Technologist job roles by the rubber industry interview

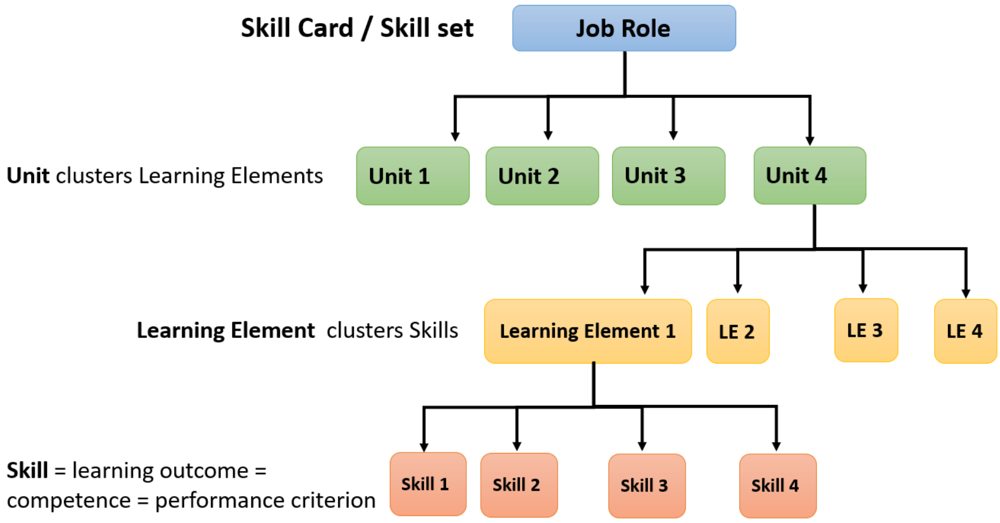


Figure 32: Skill Card model for project DRIVES in accordance with the ECQA

4.1 RT job role vision

The vision for the Rubber Technologist job role was to provide knowledge in all main areas of rubber technology with emphasis on compounding methods, in-rubber properties, behavioral phenomena and the connection between those three. The performance criteria should include knowledge about the use of ingredients and their relation to in-rubber properties and behavioral concepts in order to optimize performance on application level. Rubber technology is complex and the courses cannot teach all the details in the given timeframe. Nevertheless, the students should be able to understand other concepts based on the learned basics in the job roles.

The ESE course was the foundation of both the Basic RT, containing simplified content, and the Advanced RT, containing its full content. Content-wise, the Advanced Rubber technologist aims to offer a greater variety of topics compared to ESE on new and advanced ingredients, modelling and advanced engineering of products and compounds. The ESE and Advanced RT course both aim for 5 ECTS workload and a possible content-wise extension is limited. Therefore, the Advanced RT educational content is intended to be customizable and tailor-made for the position of the trainee by the company. The Basic RT is a reduced version of the Advanced RT and aims to provide a basic understanding of rubber technology, commonly used ingredients and general sustainable compounding technology.

4.2 ESE content evaluation

The ESE course starts with a general introduction regarding the origin, viscoelastic properties and stress-strain modeling of rubber material. Then, common polymer and filler systems are treated, followed by mixing and vulcanization methodology. Finally, more advanced topics such as viscoelasticity, glass transition, special polymers and reinforcement models, are covered. (Table 5) The timeline and structure of the course is divided into segments based on the lecturer's preference of follow-up content. In contrast, the DRIVES skill card demands more clustered content in the learning units. Therefore, the timeline is reorganized and similar topics are merged in one learning unit, where each color representing one unit. (Table 5) This reorganizes the course structure, for example mechanical rubber goods are now treated at the start of the course instead in the end including compounding and vulcanization related content. Theoretical background for thorough understanding of the mechanical rubber goods elements is now taught at a later stage. Additionally, the content of several, mostly polymer and filler related, lectures reveals that the appropriate background to fully understand the theory is not introduced.

ESE course content (Learning Elements)	Clustering
Introduction into rubber material	Introduction into rubber material
Polymer natural rubber	Polymer natural rubber
Carbon black production and characterization	Polymer SBR and BR
Polymer SBR and BR	Mechanical rubber goods - EPDM
Silica Production and characterization	Mechanical rubber goods - Special polymers
Mixing and vulcanization of Silica compounds	Carbon black production and characterization
Dispersion	Silica Production and characterization
Vulcanization and Crosslink density modelling	Reinforcement models
Mixing and plasticizing	Mixing and plasticizing
Creep & Relaxation	Dispersion
Viscoelastic properties	Mixing and vulcanization of Silica compounds
Glass transition temperature	Vulcanization and Crosslink density modelling
Mechanical rubber goods - EPDM	Adhesion
Mechanical rubber goods - Special polymers	Creep & Relaxation
Adhesion	Viscoelastic properties
Recycling	Glass transition temperature
Reinforcement models	Recycling

Table 5: ESE course content (left) and topic wise clustered content (right)

4.3 ESE content extension

The ESE course was examined and that content which was incomplete or unsatisfying was identified and adjusted in dialogue with the ESE lecturers. Examination of ESE revealed that the content is lacking specific elements on introductory and more advanced topics.

4.3.1 Extension of the introduction unit

The current introduction element does not cover a full introduction into in-rubber properties and compounding methodology. The introduction unit is extended in such a way that the student gets a first overview of all relevant fields in rubber technology, before he/she goes into field specific theoretical depth. Three elements are added in the following order: In-rubber properties, Compounding, Elastomer types & applications. "In-rubber properties" gives a full introduction into properties that are considered for elastomer performance. Elements of successive units refer to performance of rubber in terms of in-rubber properties. "Compounding" gives an introduction into general compounding methodologies and typical ingredients included inside the compound formulation. The concept of compound formulations is exclusively used by the rubber industry (the formulation quantifies ingredients by PHR "Parts per Hundred Rubber") and should be thoroughly known. Lastly, "Elastomer types & applications" provides an overview of the broad range of elastomer types, characteristics and applications.

4.3.2 New sustainable technology unit

The sustainability solutions presented in Chapter 3 are hardly present and scattered inside ESE, except for the already present "Recycling" lecture. A new unit was created to gain awareness on sustainable and safe rubber technology for human and environment: Sustainable Rubber Technology. The depletion of non-renewable resources and safe compounding is overlapping for e.g. excessive zinc oxide causes depletion of resources and possible contamination. The replacement of petroleum-based products by alternative from a biological source was regarded a prime topic. The element "Bio-based compounding" was created that teaches compounding by polymers, fillers and oils from a biological source. ZnO reduction was included in the new element "Safe compounding" that aims to replace and reduce potentially toxic compound ingredients. Improving mechanical properties of tires, abrasion and rolling resistance, is treated in a new "Sustainable tire technology" element. Finally, the preliminary "Sustainable Rubber Technology" unit includes four Learning Elements: Bio-based compounding, Safe compounding, Sustainable tire technology and Recycling.

4.3.3 Extension of the polymer and filler units

New polymer and filler technologies were added in such a way that the student knows ongoing developments in the field of rubber technology. The student hereby extents the knowledge from current practice to more futuristic compounding methods. Often new technologies have their pro's and con's and general knowledge about their character improves decision-making for application. New technologies can indirectly promote sustainable compounding but are added to the polymer or filler units instead of adding to the dedicated "Sustainable Rubber Technology" unit. For example, the "Thermoplastic elastomer (TPE)" element treats the mixture of a thermoplastic matrix and cross-linked elastomers, which promotes recyclability by being moldable into another shape without severe loss of properties.[105] (Figure 34) However, TPEs generally do not equal high performance properties of traditional rubber compounds. Therefore it is treated as a different class of polymers instead of new sustainable solution. The "New filler technology" element treats highly reinforcing and conductive material, such as carbon nanotubes and structures. (Figure 33) These materials are added in smaller amounts compared to traditional fillers to reach similar in-rubber properties, hereby e.g. counteracting the depletion of petroleum for carbon black production.[106]

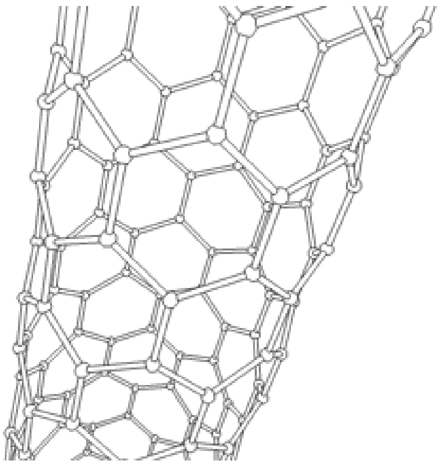


Figure 33: Highly reinforcing carbon nanotubes[107]

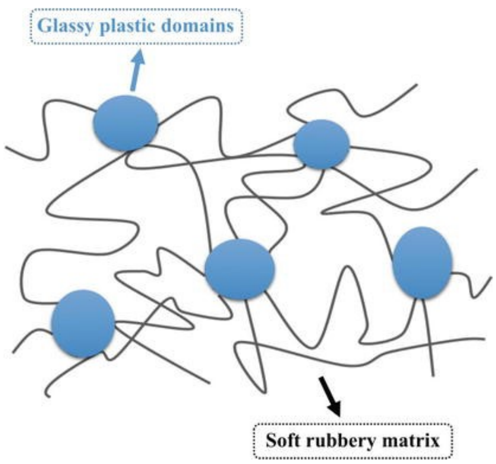


Figure 34: Recyclable TPE structure[105]

4.3.4 Extension of the vulcanization unit

Polymeric materials are vulnerable to degradation due to environmental conditions, e.g. water, sunlight, ozone, oxygen and temperature conditions. ESE does not extensively touch up-on the attack and defense mechanisms and adequate techniques for prevention. Degradation is related to mutation of the polymer backbone and inter-polymer crosslinks. Therefore, the "Anti-degradation" learning element is added to the "Vulcanization" unit. Apart from the awareness of degradation, the element touches up-on solutions for rubber materials to maintain high performance for a longer time period. Hereby the products lifetime is extended, which counteracts the depletion of resources.

4.4 Preliminary skill sets

The Advanced RT structure was drafted based on the ESE course and extensions in Chapter 4.3. The structure is visualized up to element level in Figure 36. The Basic RT structure was derived from the Advanced RT structure and includes the introduction and foundation of rubber technology. Elements for new and special technology are regarded as Advanced RT specific, such as "Special polymers", "Thermoplastic Elastomers", "New polymer technology" and "New filler technology". "Adhesion" and "Recycling" treat the compatibility and lifecycle of rubber material instead of material compounding itself and therefore are regarded Advanced RT specific as well. Tire technology combines mathematical, chemical and engineering expertise for characterization and the development of new tire materials, which is among EQF level 7/8 and the highest bloom levels. Therefore, the "Visco-elasticity & tire technology" unit and "Sustainable tire technology" element were also considered Advanced RT specific. Similarly, "Reinforcement models" and "Crosslink determination & modelling" elements were regarded Advanced RT specific. The element "Reinforcement models" includes in-depth modeling content on reinforcement for the Advanced RT. This content is superfluous for the Basic RT and reduced to introductory concepts of filler reinforcement. Figure 35 visualizes the preliminary Basic RT up to element level.

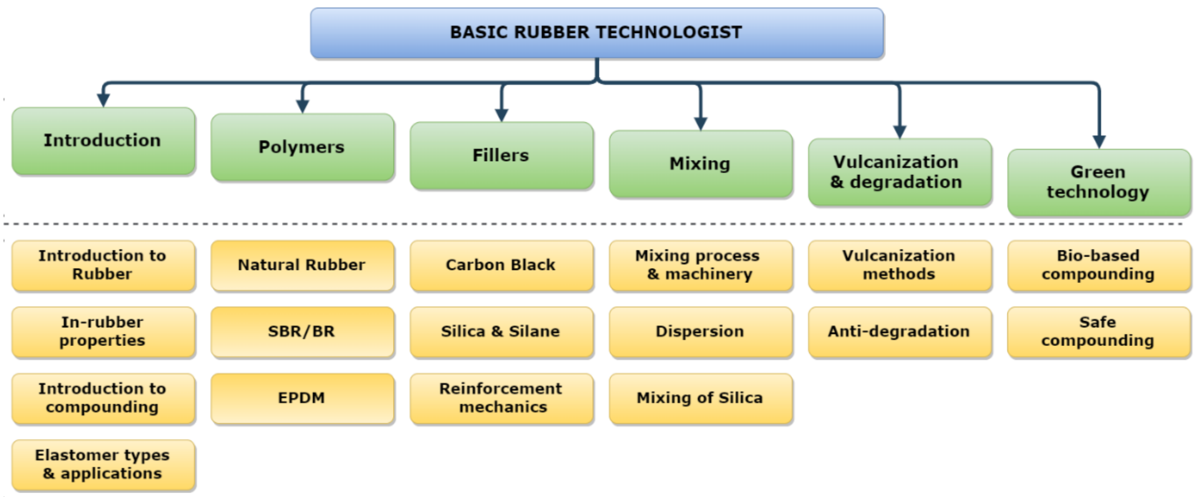


Figure 35: Preliminary skill set of the Basic rubber technologist job role

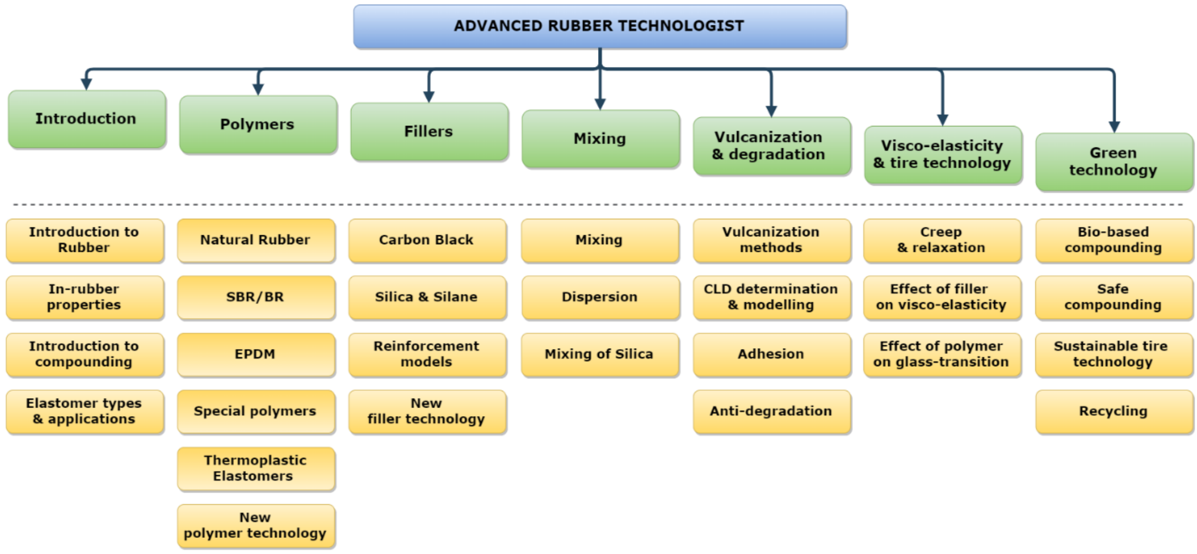


Figure 36: Preliminary skill set of the Advanced rubber technologist job role

4.5 Rubber industry interviews

Project DRIVES and the Rubber Technologist educations were discussed with several partners from the rubber industry with a diverse background: researchers, producers of polymers, filler and other compounding chemicals, manufacturers of mechanical rubber goods and tires. Twenty partners with various company and institute backgrounds were interviewed. (Table 6) This chapter summarizes the conversations and statements made by the respondents. The chapter includes opinions of interviewed partners and the content should be interpreted as such. The identities of the respondents and their companies were not included in the report for confidentiality reasons.

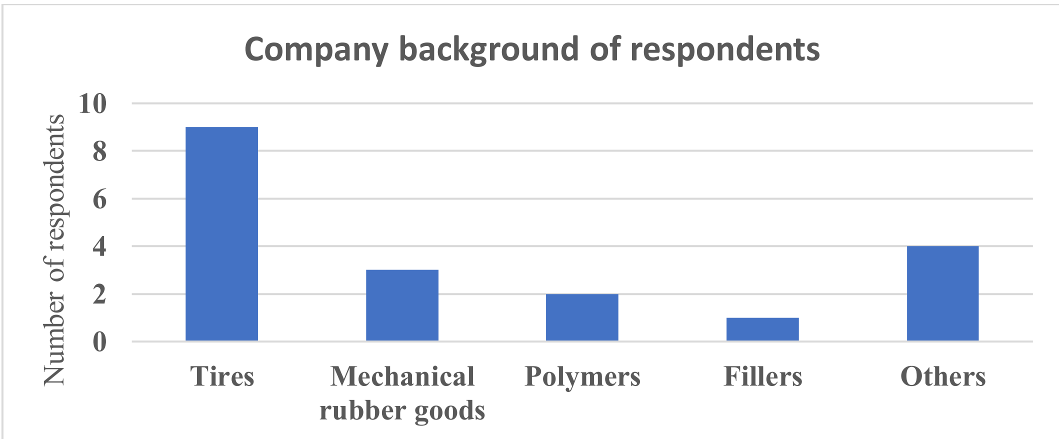


Table 6: Quantitative visualization of respondent backgrounds

The high response rate of roughly three out of every four partners has demonstrated the interest in new educational programs and compounding solutions, although questions were raised on the added value of the program compared to already existing educations. The respondents indicated that the amount of staff in rubber technology and research ranged from either 5 to more than 500 people per company. The respondents did not elaborate on the frequency of rubber related trainings given within the company. The respondents have emphasized that the success of DRIVES will depend on the quality of the online learning environment, including the structure, acquired skills and learning methodology. The concept of online education was regarded to be challenging, also with respect to copyright issues and protection of the content. Nevertheless, it filled in the gap of the online rubber educational niche. It was expected that small to medium size companies benefit mostly from DRIVES provided education because they often lack resources to provide trainings or do not have access to large R&D facilities. However, also large tire manufacturers with running educational systems were interested in basic and advanced rubber training opportunities.

4.5.1 Education and status of knowledge in the industry

Most commonly addressed was the absence of fundamental rubber knowledge within companies due to the fact that staff receives job-specific and "learning-by-doing" education. Hereby employees lack a holistic overview of rubber technology and potentially interfering with robust product development. Rubber technology is multi-disciplinary and rubber properties are in a complex way related to rubber compounding, mixing, processing, vulcanization and product design. In general, the gap between mechanical and chemical engineers is most apparent, but more specifically researchers, compounders, process technicians and product designers regard different aspects in the product development cycle. (Figure 37) In case these groups don't understand nor share their considerations and knowledge, an efficient and robust engineering process is obstructed. Communication and robust engineering can be promoted by wholesome and interdisciplinary education in rubber technology.

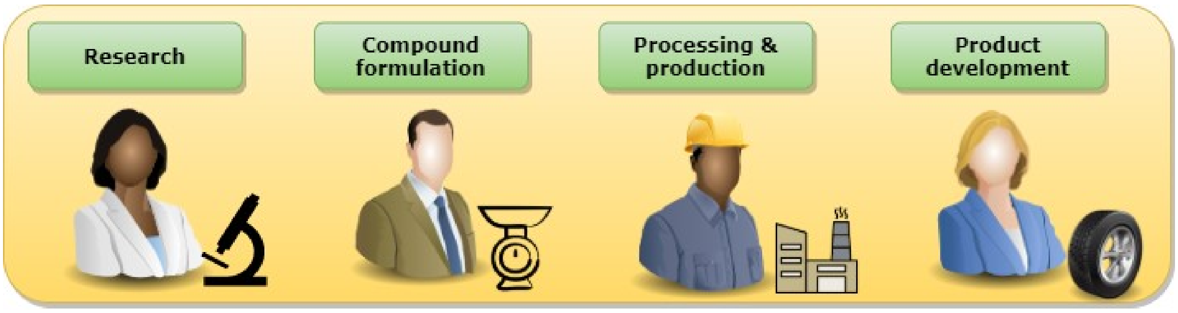


Figure 37: Areas of expertise involved in the production of rubber goods

The degree of internal and external education in companies differs. Several respondents indicated that basic knowledge is taught internally, whilst detailed knowledge is taught externally, and vice versa. Job specific knowledge is often transferred via learning-by-doing from employee to employee. This education has a company and job specific character, therefore could be regarded as detailed education. Respondents indicated that product developers are scarcely educated on rubber technology in order to gain awareness of rubber inside their products or machines. Several respondents question this method, because rubber material provides key functionality in high performance rubber goods. The general consensus was that a broader course at the start of a career, whether it is basic or advanced level knowledge, is effective. The level of education required is depended on the prior knowledge and educational level of the employee. One can often distinguish between employees who studied polymer sciences and others that have no polymer background at all.

4.5.2 Challenges for the rubber industry

Electric mobility will change the automotive industry for the construction of EVs is less complicated compared to combustion engine cars. The use of high performance rubbers, to transfer forces, fluids and damp out vibrations under high temperatures is reduced due to the absence of a combustion engine. Nevertheless, the majority of rubber goods remains relevant and is facing increasing performance and sustainability demands. The respondents have agreed on the relevance of challenges posed in Chapter 3. Specifically, tire manufacturing companies confirm the relevance of all topics, but cannot elaborate on company specific data for confidentiality related to research activities or compounding formulations. The general aim of the tire industry is to reduce the environmental footprint and make the industry more sustainable by:

- The improvement of magic triangle performance of tires
- The replacement of petroleum-based products by renewable alternatives
- The reduction of potentially harmful ingredients
- Opportunities to promote processing and recycling of waste and ELT

Not all respondents agreed on a high degree of involvement of the tire industry in sustainability goals and find that societal awareness and willingness to invest in a sustainable future is lacking, which is demonstrated by low sales in low fuel economy segments. The respondents stretch that the magic triangle performance is an important driver of sustainability and alternative compounding methods should not set back tire performance. Sustainable technology should at least keep tire performance on an equal level, which is challenging as current engineering is optimized for this purpose. Nevertheless, the respondents expected that effective regulation and tire labelling campaigns will stimulate innovation, because both industry and society don't like to disregard a method or product that has proven itself in the past. Societal awareness and regulations shift the cause of research and development in sustainability from a "thankless task" to a "major project" with high rewards. (Figure 38)

Respondents outside the tire industry are similarly interested in four main objectives for improvement, named in decreasing order of importance: rubber performance, REACH conscious compounding solutions, circular economy solutions and renewable ingredients. As rubber technology is interdisciplinary, the majority of companies benefits from the general knowledge. This is supported by the general trend of assisting in the development of compounding formulations and processing methods by suppliers for small to medium sized mechanical rubber goods companies.

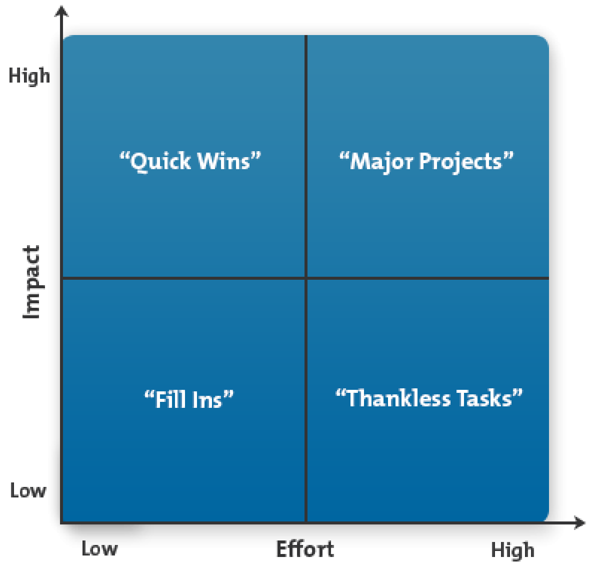


Figure 38: Action priority matrix[108]

One additional challenge was mentioned: the reduction of the quantity of different ingredients can benefit production costs, ecological footprint and recycling purposes. The synthesis of a lower variety of ingredients makes production and transport logistics less complex, hereby reducing costs and the carbon footprint. Moreover, the de-vulcanization reaction in recycling is more effective in less complex compounds due to the reduced interaction of de-vulcanization agents with ingredients other than polymer crosslinks. The final de-vulcanizates also contain less contaminations within the polymer matrix, hereby more closely resembling original rubber polymers. This amplifies opportunities for repurposing.

Renewable compounding

The renewable reinforcing filler silica is increasingly replacing petroleum-based carbon black in tires and is often applied in a combination of the two. This gives the best properties for both ingredients have their own beneficial character. The same goes for renewable bio-based oils that are combined with synthetic oils. The filler lignin is regarded to be a perfect example of circular economy, for it is a waste product. Unfortunately, lignin itself does not have high interacting and reinforcing effects, which makes the application difficult. Bio-based fillers and polymers are under investigation but are not extensively applied by the industry and future feasibility and the availability on industrial scale is unsure. One should also be aware that most biological ingredients have a large water footprint on the environment in contrast to petroleum-based products. Sugar (sugarcane) is an alternative source for plastic and synthetic rubber proportion but it is a niche product for rubber and only some companies are expected to participate in research and application of synthetic bio-based rubbers (IR, SBR, BR), such as Michelin.

The depletion (and potential toxicity) of Zinc is under attention, but it is pointed out that ZnO provides a unique function in tire compounds. Nevertheless, tire industry respondents regard the reduction of Zinc oxide plausible, although research on ZnO reduction is regarded less relevant than research on alternative natural rubber sources, other potentially harmful components and magic triangle performance. The tire industry respondents regard the reduction of ZnO possible with additional research on alternative methods.

REACH conscious compounding

The rubber industry generally distinguishes three classes of REACH regulated materials: Class C includes substances restricted under REACH, such as high PAH aromatic oils. Class B are substances of very high concern placed in a candidate list for evaluation on restriction in the future. REACH places these materials in the candidate list of further evaluation. Class A is not under investigation for banning of restriction in the future. Respondents indicate the industry aims to eliminate REACH class C materials, hereby meeting the REACH regulations, and to minimize class B materials. The elimination of class C highly aromatic oils was successfully executed and class B ingredients are expected to be replaced in the future as well, such as accelerator DPG. Rubber to textile cord adhesion is achieved by applying Resorcinol Formaldehyde Latex (RFL) coatings. Formaldehyde is on the candidate list of very high concern substances, but it is proposed for authorisation approval for use by the EU market. Rubber to steel cord adhesion is achieved by brass coating the cords and compounding the rubber around the cords with Cobalt. The tire industry respondents indicate that the reduction in use of RFL, Cobalt and ZnO is possible, but only by extensive research on alternatives.

Sustainable tire technology

Rolling resistance, abrasion resistance and wet grip are a zero-sum game that is only broken by the introduction of silica silane technology. Silica silane tire technology was regarded to be the future for the production of A/A-label tires, which is more complex and costly compared to only CB filled tires. The silica silane and carbon black filler systems are often combined for both incorporating beneficial properties. The production of silica silane filled tires is challenging due to the difficult dispersion of silica and control of the chemical reaction between silica and silane during the mixing process. The quality and reproducibility of high performance compounds is becoming increasingly relevant. This shifts the focus in the tire industry from compounding to mixing and processing technology.

Recycling

Recycling vulcanized rubber has gained attention in the industry, not only within recycling companies or tire producers, but also among product manufacturers and machinery producers. Manufacturers and machinery producers desire knowledge for effective disposal of vulcanization waste, recycling material and processing of recycled material for repurposing.

4.5.3 Basic RT skill card evaluation

Respondents desired a broadening of the general content but going in theoretical depth in fields related to their company. For example, a recycling company would like the "Recycling" element to be in the Basic RT content or a polymer company requests extensive knowledge on synthesis of polymers in the "Polymer" unit. Secondly, several topics in the Advanced RT were regarded essential for the Basic RT but should be offered in a reduced form. By differing between content in a similar element of the Basic and Advanced RT, more specialist topics were added to the Basic RT, such as the "Adhesion" element.

Polymers

The desire of mechanical rubber goods companies was to make the polymer unit broader and at least include (H)NBR (or ACM) next to NR, SBR/BR and EPDM. NBR is considered to be the working horse in the mechanical rubber goods sector.

Filler technology

The "Filler Technology" unit was regarded to fulfil the demands of the industry and some respondents mention that new filler technology should briefly be mentioned in the Basic RT.

Mixing technology

The "Mixing technology" unit would benefit from more extensive explanation of the mixing plan and fingerprint. The trainee should be able to read the fingerprint and recognize faulty phenomena that ultimately reduce the filler dispersion.

Extensive knowledge on the mixing of silica is regarded superfluous for a general rubber technologist, but some knowledge on the process and reactions taking place is valuable. The theory behind the dispersion of silica clusters with its strong filler-filler interaction is relevant and the silane coupling mechanism is relevant for other renewable fillers, such as lignin.

Vulcanization and degradation

Respondents mentioned that the "Vulcanization & degradation" unit was lacking content related to test methods for rubber vulcanizates. Therefore an element "Test methods for rubber vulcanizates" was added.

Most rubber products consist of rubber adhered to a reinforcing material. The connection between the two is important for functionality and durability of the product. Therefore the "Adhesion" element is included in both job roles. The Basic RT should include a basic understanding of adhesion concepts.

Sustainable rubber technology

The "Sustainable rubber technology" unit was regarded to fulfil the demands of the industry. Although general awareness on recycling is beneficial, detailed information is not regarded to be Basic RT specific content. Recycling can be touched up-on in the introduction.

Processing and characterization of green compounds (new)

Respondents mentioned that the Rubber Technologist job roles were lacking explicit content on processing methods, rheology (flow phenomena), testing methods for green compounds and especially the relation between the three.

Application-based compounding (new)

Respondents desired more explicit content on practicing the complete formulation of compounds as ingredients are a complexly interacting and forming the final rubber properties. Holistic compound formulations were regarded highly relevant for high performance rubber goods and can improve the overall quality of rubber goods in the market. The final "Application-based compounding" element summarizes and applies previously acquired knowledge in the job role.

4.5.4 Advanced RT skill card evaluation

Industry respondents were interested in the Advanced RT job role and liked the concept of tailor-made job roles. The remarks for the Basic RT are applicable for the Advanced RT as well. The general remark for the Advanced RT was that new and special technology should be taught, especially for fillers. New filler technology should include at least content related to carbon nano-fillers (tubes & graphene), fibres (Aramid & Cellulose), lignin and organoclay.

The tire industry respondents desired the development of a more advanced tire technology job role. This can be realised by addition of a "Tire technology" unit inside the advanced RT job role or by addition of an extra tire technologist job role.

4.6 Final skill sets

The discussions with industry partners have led to new insights, the inclusion of multiple new topics and adjustment of existing topics. The main feedback was that the Basic RT should give an even broader overview of rubber technology and both Basic and Advanced job roles should include content related to the testing and processing of rubber. Moreover, the respondents stated that the titles of units and elements are incomplete or could lead to wrong interpretation. A good example was the "Safe compounding" element that raised the question whether all non-included ingredients were typically unsafe. The solution was to adjust and make some titles more informative and less ambiguous.

The final skill set of the Basic RT was adjusted and visualized up to element level in Figure 39. The performance criteria were drafted based on the vision of the job role content and general feedback of rubber industry partners. The skill card up to performance criterion level can be found in Appendix B.

The final skill set of the Advanced RT was adjusted and visualized up to element level in Figure 40. An additional "Sustainable tire tread technology" unit was added to facilitate the demand for the Advanced Tire Technologist education. Both the introduction and sustainable tire tread technology are optional, because the trainee might be familiar in the field of rubber and/or might not work in the tire industry.

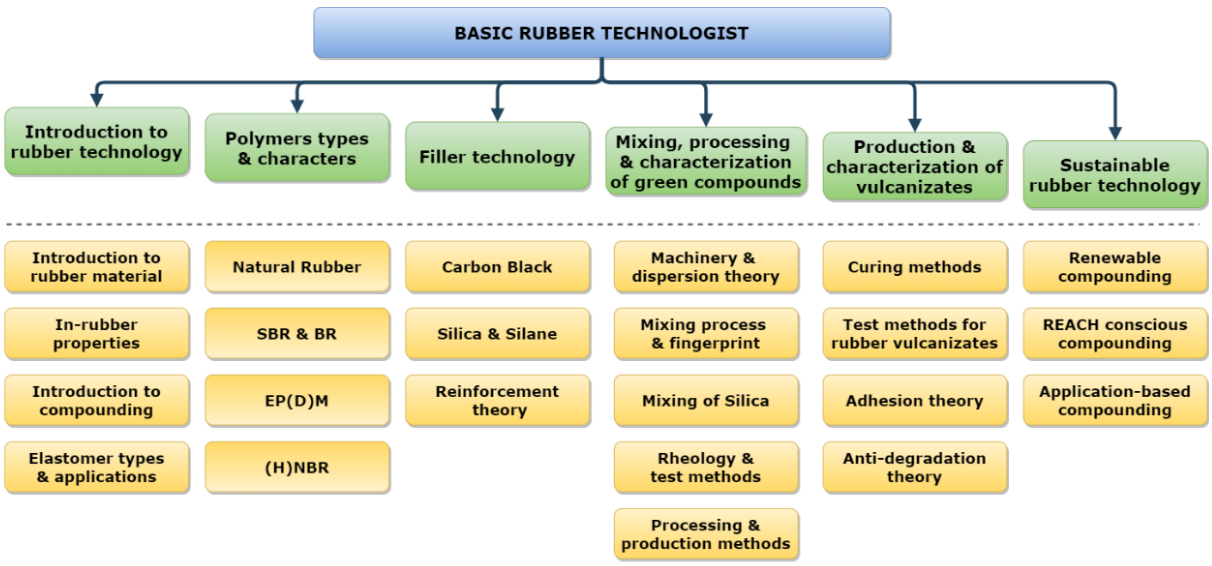


Figure 39: Final skill card Basic Rubber Technologist job role

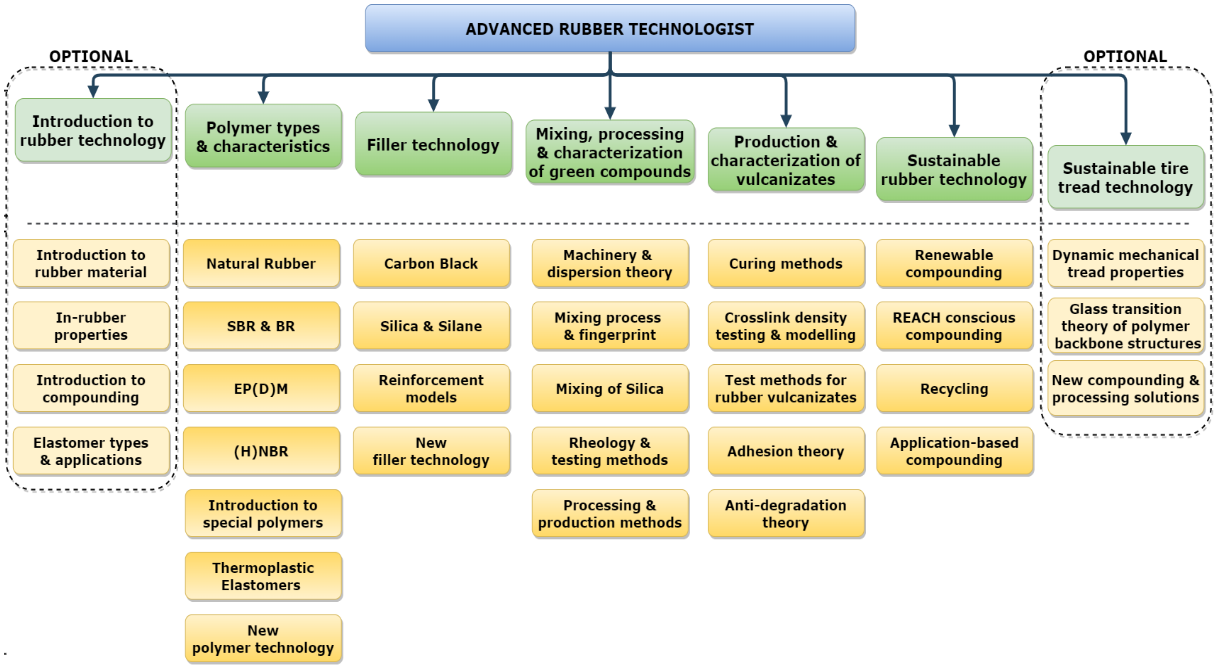


Figure 40: Final skill card Advanced Rubber Technologist job role

The content for most elements in the Basic RT job role can be extracted from ESE and other educational programs. The "Application-based compounding" element is extractable from the ESE course content. The new "Sustainable Rubber Technology" unit has two elements needed to be drafted content-wise. In Chapter 5 the development of new "Renewable" and "REACH conscious compounding" is discussed.

5. Sustainable rubber technology

Ongoing research is performed to contribute to sustainable innovation by the rubber industry, universities and governmental rubber institutes. The proposed solutions in Chapter 3 and 4 are in scope of R&D departments worldwide and their efforts to create better and more sustainable compounding solutions should not be underestimated.[57,109] Rubber technology is a complex science and potentially toxic or "unsustainable" compounding methods sometimes provide the most reliable performance. These contradicting interests increase decision-making problems in the rubber industry. The new sustainable rubber technology unit aims to facilitate the transition to more sustainable methods. The goal is to teach safe and renewable compounding solutions providing the best performance, whilst closing the loop for rubber lifecycles by effectively disposing or recycling rubber material.

This chapter elaborates on renewable and REACH conscious compounding solutions and is exemplary for the content in the new Sustainable Rubber Technology unit.

5.1 Renewable compounding

The rubber industry aims to produce renewable source rubber and a big contribution is made by substituting petroleum-based ingredients for bio-based alternatives. In general, renewable bio-based ingredients possess a different (polar) character than common petroleum-based ingredients, such that mixing and compound properties differ.[110] The focus is on finding alternatives for the three main ingredients: polymer, filler and plasticizer. These account for 90 wt% (indication) of the final rubber product. One should be aware that bio-based ingredients made from vegetable crops are competing with the food industry. This does not go for Natural Rubber, which can be regarded renewable for the primary source "Latex" originates from the Hevea Brasiliensis or "Rubber tree" and alternative natural sources are investigated for Latex production. Organic fillers from plants and sand raw material are investigated and applied in the endeavor to improve or replace the highly reinforcing petroleum-based carbon black.[111–113] Additionally, vegetable plasticizers are investigated for compatibility with the rubber matrix; and already vegetable oils are incorporated into tire treads for improving magic triangle properties, rolling and abrasion resistance.[84]

This chapter elaborates on recent developments in the field of renewable and bio-based compounding.

5.1.1 Renewable fillers

Precipitated silica, organoclay and lignin are regarded renewable alternatives for petroleum-based carbon black. The compatibility of the polar surface of silica with the non-polar rubber matrix of NR, SBR and BR is a challenge and coupling agents are developed to couple the filler and polymer matrix. Polar and functionalized polymers tend to give better filler-polymer interaction for polar fillers.[114]

Precipitated silica

Silica has gained attention due to Michelin's Green tire invention in 1992.[115] Silica silane technology is known for improved rolling resistance and wet grip performance, whilst maintaining acceptable abrasion resistance.[76] Abrasion resistance of carbon black is superior e.g. due to better dispersibility compared to the silica silane filler system.[116] (Figure 41)

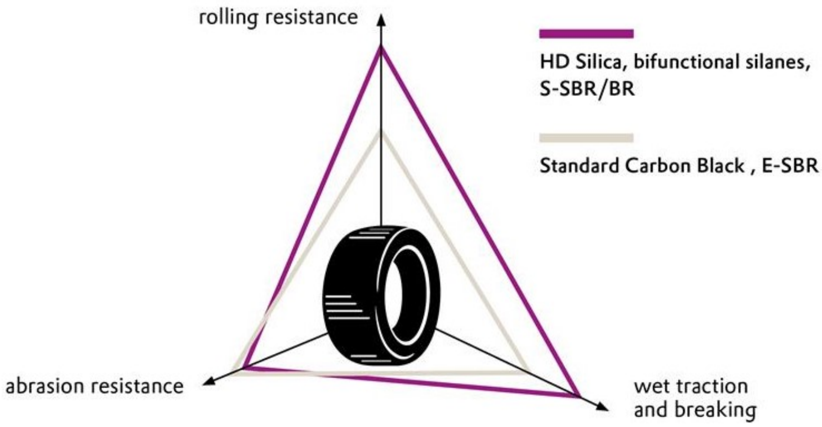


Figure 41: Magic triangle of tire performance[117]

Precipitated silica is produced by a chemical process that converts sand (SiO_2) into silica with polar silanol surface groups. These groups cause strong hydrogen bonds between filler clusters, subsequently increasing difficulty of mixing silica with non-polar rubbers. The challenge in processing and application of silica is to overcome the high in-rubber filler-filler interaction related to micro dispersion. Silica is highly reinforcing but cannot match carbon black reinforcement due to the incompatibility with non-polar rubber matrices. Silane coupling technology couples the polymer with the silica, providing a chemical interface. (Figure 42) The silane coupling during mixing hydrophobizes the silica surface and reduces silica surface interactions and improves dispersion. During vulcanization the silanized silica is coupled to the polymer matrix hereby forming a covalent bonded network of polymers and fillers. Silica silane technology tends to give high hysteresis at high frequencies in tread and road interaction (grip), but low hysteresis at lower frequency of rolling over the road. The technology has proven beneficial for fuel economy and wet grip in tires, and is applied on industrial scale in the western tire market. Carbon black has superior abrasion resistance compared to silica silane tire technology. New highly dispersible silica and advances in silane technology have improved dispersion quality and subsequently abrasion resistance approaches the level of carbon black compounds.[76,112]

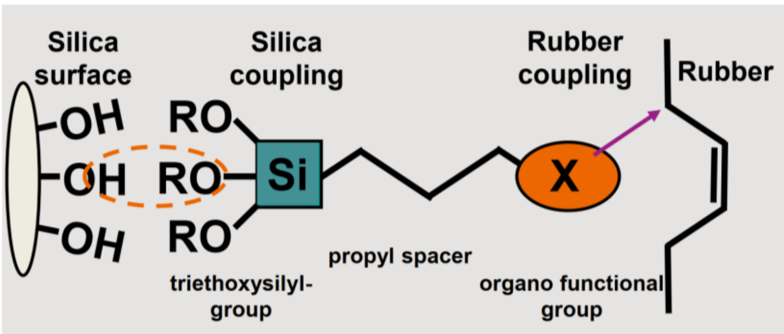


Figure 42: Schematic Silica-silane coupling mechanism[118]

Technical lignin

Lignin originates from the cell wall of plants, which is made up of cellulose, hemi-cellulose and lignin. It makes up for 20-35 wt% of biomass on earth. [119] (Figure 43) The chemical structure and character of lignin is highly dependent on the type of plant and gen. Technical lignin is generated as byproduct from pulping for paper production and is considered to be potent as renewable filler material. By pre-treatment, lignin becomes a modified, more active, polymeric material with, among other functional groups, contain phenol groups attached to the backbone giving it an aromatic and polar character. Modified technical lignin has a similar hydrophilic character as silica, thus generally it is incompatible with the rubber matrix, but can potentially be coupled to the rubber matrix by silane. [120] Reinforcement by uncoupled modified lignin is found to be, like silica, inferior to carbon black reinforcement. [121] Lignin is investigated for its reinforcing character but is not yet mature for application.

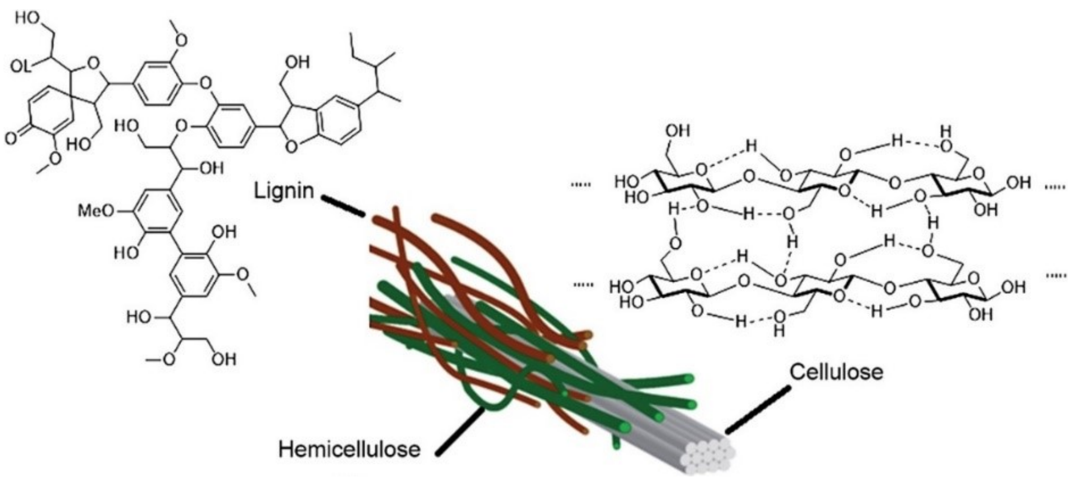


Figure 43: Source and chemical structure of lignin[119]

Silane modified hydrothermally carbonized (HTC) lignin is reported to have significantly lower hysteresis loss at 60 °C than conventional silica silane and carbon black filler systems but shows disadvantages with regard to reinforcing and wear properties. (Figure 44) The specific surface area of HTC lignin is 2-4 times lower than that of high performance carbon black or silica. When the specific surface area is amplified and in-rubber properties are enhanced, the filler may be suited for real-world application.[122]

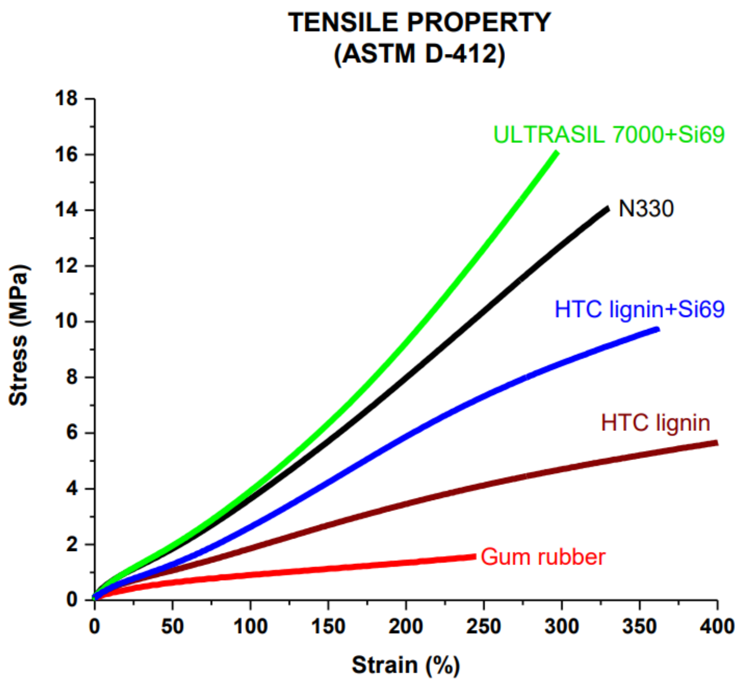


Figure 44: Comparison of reinforcement by HTC, Silica and Carbon Black[122]

Organically modified nanoclay

Organoclay is synthesized from naturally occurring clay mineral and has a lamellar structure. (Figure 45) This structure can be penetrated by polymer groups and hereby provides a reinforcing effect. Studies showed that the primary filler content can be reduced using organically modified nanoclay. For example, 25 phr N330 carbon black and 6 phr nanoclay filled SBR shows similar reinforcement compared to 40 phr N330 carbon black filled SBR and improved dynamic properties.[113] The secondary filler organoclay, in combination with a modifying agent and primary fillers carbon black and/or silica, has shown improved in-rubber properties by decreased filler-filler interaction and improved dispersion. It is expected that the organoclay system shields the polar silanol groups of the silica surface and hereby reduces the Payne-effect by better dispersion during mixing and shielding the fillers in application.[123]

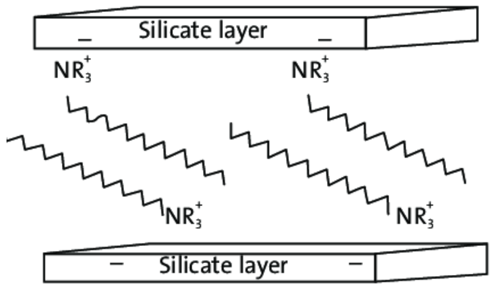


Figure 45: Schematic representation of organoclay[124]

5.1.2 Bio-based plasticizers

Bio-based oils, having a non-toxic and sustainable character, are considered to be an alternative for petroleum-based plasticizers. (Figure 46) Vegetable oils derived from plants or seeds of industrial crops are a near future alternative due to fact that they already are produced and successfully extracted in large amounts. An extensive literature study has been performed by P. Borenius (Tampere University of Technology) on bio-based and renewable plasticizers in rubbers.[84] The following information is partly extracted from his thesis for it provides a valuable summary of research on vegetable oils in the last two decades (2000-2018):

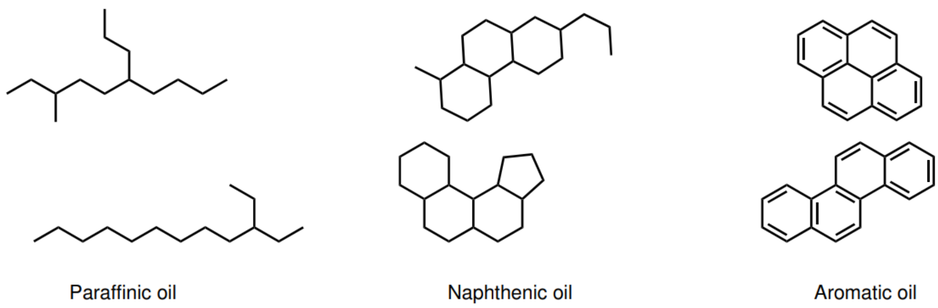


Figure 46: Petroleum-based mineral oils in rubber compounds[84]

80% of the 200 Mt/year of global vegetable oil production consists of sunflower, soybean, rapeseed, palm and palm kernel oils. Other oils which are under investigation are e.g. castor oil, cashew nut shell liquid, coconut, olive, orange and linseed oil. Vegetable oils generally contain triglycerides, derived from fatty acids and glycerol, which have a more polar character compared to (aromatic) mineral oils. This reduces compatibility with non-polar rubber matrices. Polymer chain mobility is increased, but also blooming of oil to the surface occurs more easily. Often a combination of mineral and bio-based oil results in favourable properties. The degree of unsaturation and functional groups on oil backbones are one of many properties that affect the interaction with the rubber matrix. The above mentioned vegetable oils do have a similar chemical structure and viscosity, therefore resulting in-rubber properties which are similarly influencing rubber compounds characteristics.[84] (Table 7)

Rubber property	Compared to reference	Number of comparison
Shore A hardness	decreased	41
Elongation at break	increased	39
Swelling index	increased	26
Thermal stability (TGA)	increased	16
Compression set	increased	16
T_g	slightly decreased	14

Table 7: General character difference between mineral and bio-based oils based on studies from 2000-2018[84]

Bio-based oil improves the thermal stability of rubber, due to the more thermally stable character of the bio-based oil backbone compared to mineral oil backbones. A change in properties, such as hardness, elongation, swelling and compression set, in vegetable oil compounds is possibly caused by lower crosslink densities compared to mineral oil compounds. The unsaturated character and functional groups of bio-based oil backbones influence the rubber vulcanization behaviour. Moreover, bio-based oils can bleed out of the compound when it has a high polarity difference with the polymer matrix. In-rubber properties are highly dependent on the rubber formulation and the character of the vegetable oil. More detailed examples of bio-oils enhancing in-rubber properties are: Coconut oil which can improve filler dispersion compared to naphthenic oil due to polar functional groups that interact with silanol groups of the silica surface in NR compounds. Cardanol and cashew based oil have superior properties over aromatic oil for plasticizing CB based NR compounds.[84,125]

Several companies apply bio-based oils. Michelin for example released the Primacy MXM4 tire with 25-40 phr sunflower and 6 phr MES oil tread compound. In 2014, it is reported that Continental and Goodyear investigated dandelion flower oil and Soybean oil-based compounds. Vegetable oils can improve the ease of dispersion of silica and increase tread life. Silica is known for difficult dispersion characteristics, therefore vegetable oils can improve the magic triangle properties whilst increasing the use of renewable oils.[126]

5.1.3 Bio-based polymers

The market is relying on the rubber tree plantations in South-America and Asia. Therefore, research is aiming to investigate alternative “Latex” sources for natural rubber. One reason is that Natural Rubber trees have similar genetic character and are vulnerable to diseases. Various species are under investigation that produce Latex, such as the Russian Dandelion and Mexican Shrub Guayule. The Russian dandelion and Guayule are already grown in small plantations for research by e.g. Apollo Vredestein and Bridgestone. New research aims to expand growth and use of alternative NR crops and unravel the mystery of natural rubber biosynthesis.[127,128]

Sugar from biological sources as sugarcane is regarded an alternative for plastic and synthetic rubber proportion. Non-the-less, for rubber this is a niche product and only some companies are expected to actively participate in research related to synthetic bio-based rubbers, IR, SBR and IR, such as Michelin.

5.2 REACH conscious compounding

Toxicity of rubber compounding ingredients has gained attention, especially in EU. Governmental subsidies studies are initiated to get more insight in whether potentially dangerous ingredients can be substituted by more safe alternatives. [95] Several potentially harmful substances are formed during the vulcanization on high temperatures, therefore co-workers in the factory are primarily exposed. REACH (registration, Evaluation, Authorization and Restriction of Chemicals) regulation, that entered into force on 1 June 2007, supports the protection of human health and the environment from risks induced by chemicals. The regulation applies to all chemicals applied in European products and partly on imported products from outside the EU. REACH has limited the use of polycyclic aromatic hydrocarbon oils (2010) and has a candidate list for substances for high concern.[92]

This chapter elaborates on exemplary developments in the field of REACH conscious compounding.

5.2.1 Accelerators

Vulcanization accelerators provide irreplaceable functionality for effective and complete vulcanization but some are known to release potentially harmful substances as a result of specific functional reactions during vulcanization of the rubber compounds at high temperatures.

Generally, two types are incorporated: primary and secondary accelerators. Secondary accelerators support the primary accelerator's reaction. Commonly used primary and secondary accelerators types are respectively N-cyclohexyl 2-benzothiazylsulphenamide (CBS) and diphenylguanidine (DPG). CBS is composed of 2-mercapto benzothiazole (MBT) and cyclohexyl-amine (alkaline activator). DPG is applied for additional accelerator of thiazoles, e.g. MBT, and sulphenamides. CBS is regarded to be a safe accelerator, but DPG liberates aniline under high temperatures, which has been classified as a suspected carcinogen.[129–131] (Figure 47)

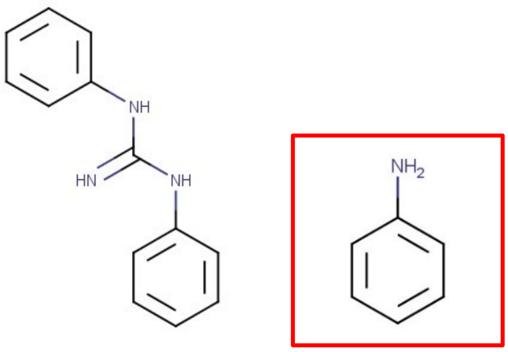


Figure 47: Accelerator DPG (left) forms the reaction product aniline (right)[129,130]

CBS and DPG are used in different tread compounds. DPG, apart from accelerating vulcanization, shields the silica surface (hydrogen bonding of the silanol groups) from interaction with silica and CBS, resulting in improved filler dispersion and lower filler-filler interaction. Alternatives that provide similar functionality as DPG are investigated and replacement is feasible when similar mechanical properties and magic triangle character, e.g. rolling resistance, can be obtained. Linear aliphatic amine accelerators, especially Octadecylamine (OCT), are found to be feasible for replacing DPG in NR truck tire treads.[132]

Nitrosamines are formed during curing by interaction between accelerator and NO_x. They can form rather spontaneously by a reaction between NO_x and secondary amines. Secondary amines are the cleavage products of ultra-accelerators like TMTD, and NO_x is present in any normal environment. (Figure 48) Ultra-accelerators are often used for curing polymers having a low amount of double bonds, such as EPDM. Various ultra-accelerators or sulfur-donor systems, thiuram sulphides, dithiocarbamates and some sulfenamides, contain secondary amine groups that are released during vulcanization and form N-Nitrosamines. (Figure 48) N-Nitrosamines with two R-groups are considered to be carcinogenic for animals and humans. R-groups are either H, aliphatic or aromatic hydrocarbons. These structures will be involved in the metabolism of the human body and form carbonium ions that mutilate DNA. Accelerators that generally do not form nitrosamines are thiazoles (e.g. MBT) and sulfenamides (e.g. CBS and TBBS) because bulky aromatic diamines, tetrabenzyl thiuramdisulfide (TBzTD) and dibenzyl dithiocarbamate are considered to be non-carcinogenic as well. A general rule is: the bulkier the R group in the amine, the lower is the level of carcinogenicity.[131] Nitrosamines forming accelerators are now banned from the EU market.[133]

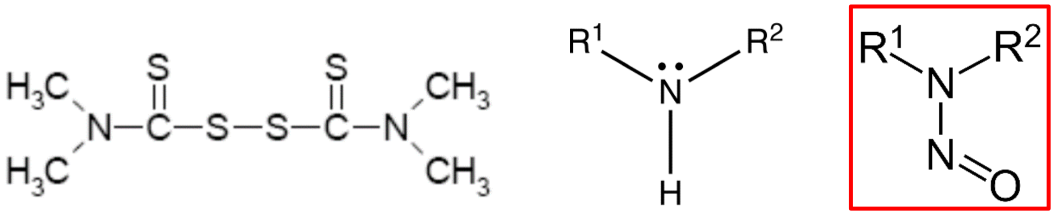


Figure 48: TMTD (left) & reaction product amine (middle) forms nitrosamine (right)[134,135]

5.2.2 Bonding agents and promoters

The interphase between two materials generally requires strong adhesive systems. Several types of adhesives in tire applications are under investigation. Rubber to textile cord adhesion is achieved by applying Resorcinol Formaldehyde Latex (RFL) bonding coatings. Rubber to steel cord adhesion is achieved by brass coating the cords and compounding the rubber around the cords with cobalt. It should be noted that both RFL and cobalt are not present in the tread compound, thus are not released in the environment by abrasion.[95,136]

Unreacted Resorcinol and Formaldehyde are considered to be respectively harmful and carcinogenic by REACH.[92] Alternative bonding methods are acrylic resins, modified fibres and plasma treatment. Acrylic resins should be less toxic and are regarded to be only a short-term alternative. Bonding by fibre surface modification is challenging because a transition interface is lacking between the stiff fibres and flexible rubber. Plasma coating or plasma assisted surface activation are regarded to be a suitable futuristic solution, for example by surface modification with oxygen groups that increase the surface energy of the cords for improved wettability and provide a bonding interface.[136]

Cobalt is regarded essential for brass to rubber crosslinking by delaying the formation and protection of zinc sulfide bridges in the bonding interface. The amount of cobalt can be reduced by coating the steel cords with cobalt instead of incorporation in the rubber, which as well improves long term stability of in-rubber properties. Alternative methods are available, e.g. solvent based adhesives, but should be optimized for tire industry applications and contain other potentially harmful chemicals.[95]

5.2.3 Plasticizers

Plasticizers are used for lowering viscosity during processing and changing in-rubber properties such as flexibility and low temperature performance. Typically, mineral oils used are, in order of decreasing polarity: Aromatic, Naphthenic and Paraffinic oil. In 2010, REACH has banned carcinogenic PAH rich aromatic oils (DAE) from the market, which have been replaced by Mild Extract Solvates (MES) and Treated Distillate Aromatic Extracts (TDAE). The oil type is selected depending on the compound formulation, especially based on the polarity of the polymer. Aromatic oils are typically known for good compatibility with low polarity polymers NR, BR, SBR, which are typical tire compound polymers, and EPDM. Bio-based oils can partly serve as alternatives for the already banned DAE but have a completely different (polar) character.[84] (Chapter 5.1)

5.2.4 Activator Zinc oxide

Zinc oxide (ZnO) is essential in sulfur curing systems and activates the accelerators. The role of ZnO in the vulcanization process is not yet fully understood, but it is assumed that ZnO reacts during the crosslinking reaction and irreversibly forms Zinc Sulfide. ZnO is a multifunctional ingredient in rubber compounding for efficient vulcanization, excellent in-rubber properties and processability. Tires and tread wear particles normally contain 1-2.5 wt% of Zinc, but it is not excessively used as Zinc is typically expensive.[79]

Several studies have investigated the reduction of ZnO in rubber compounds. The particle size and specific surface area of ZnO can promote the reactivity of Zinc and the application of the more recently developed Nano ZnO can reduce Zinc by a factor of 10. However, the processability of Nano ZnO has proven to be challenging due to blooming of Nano ZnO to the rubber surface.[95]

It is estimated that for S-SBR compounds the level of conventional ZnO can be reduced from 3 - 5 phr to respectively 1 - 2 phr, whilst retaining the in-rubber properties of the vulcanized rubber product. S-SBR contains less impurities compared to more traditionally and commonly used tire tread elastomers E-SBR and NR with contaminations by respectively emulsifiers and, among others, proteins. These contaminations interact with ZnO and consume part of the ZnO that activates the vulcanization reaction. S-SBR is more expensive, but in terms of tire tread properties gives better wear and rolling resistance performance than E-SBR. Concluding, the performance of the tire tread and amount of ZnO in the compound can simultaneously be improved.[79]

6. Recommendations & Outlook

The Rubber Technologist job roles are unique for their intended scaffolding character in online training, but content development based on the skill cards has yet to be started. It is recommended to fully develop the Basic RT training and verify the demand from the industry for this specific job role. The development of additional job roles in rubber technology and engineering, such as the Advanced Rubber Technologist or Tire Technologist, should only be performed in the case that the Basic RT is frequently requested .

6.1 Additional job roles & elements

The majority of rubber goods are tires. New staff for innovative research and development in the tire industry usually has a polymer background and requires advanced knowledge. Therefore, an Advanced Tire Technologist is useful to be developed additional to the RT job roles. The University of Twente is a specialist in tire rubber technology and could develop such a job role in co-operation with tire industry partners.

Research methodology related to the design, analysis and statistical relevance of experiments is not included in the RT job roles. The Advanced RT in particular benefits from additional elements on these topics, which are extractable from other job roles in the DRIVES framework.

6.2 Copyright-protection

The content of RT job roles should be developed, assessed, evaluated and improved continuously. The DRIVES project is for educational purposes and it is recommended that the University of Twente develops and offers the content as a non-profit educational institute. The activities related to maintain and develop the job roles should be paid by the trainees or funded by the EU or other institutes. The digital use of copyright-protected content is partly allowed for the purpose of illustration for teaching in non-profit organizations such as universities, according to the Berne Convention (Art. 10.2) and Directive 2001/29/EC (Art. 5.3).[137] These copyright regulations have been adjusted by the European Commission in 2019 in order to enable cross border access and wider opportunities for copyrighted material in education. [138]

Online content is easily copied by external parties and the educational institute risks copyright claims. It is recommended to give exclusive access for known parties and let them agree not to spread nor copy nor make-use of content other than for educational purposes in the DRIVES framework.

6.3 Evaluation & development of educational content

The University of Twente, or other partners with a holistic overview on rubber technology, should receive feedback from parties or trainees taking the courses. A conceptual idea is to phone trainees on two instances, directly after finishing the training and 1-3 months later, hereby informing on direct feedback and later feedback on the relevance of the training in his/her job. The content should be adjusted based on these feedback rounds. It is difficult to include the latest technological breakthroughs content-wise, but awareness created by the RT job roles on sustainability is expected to stimulate the trainee to discover these fields of expertise by him or herself. Similarly, in the Advanced RT job role in-depth knowledge on new and special ingredients should be investigated. In the case that trainees and partners demand more in-depth knowledge, the content can be extended with additional elements on new and/or special compounding ingredients or processing solutions.

7. Summary

Rubber is known for its unique elastic properties and provides irreplaceable functionality in automotive applications, for example in tires that account for roughly 60% of global rubber consumption. Tires and mechanical rubber goods are facing challenges in fulfilling the performance and sustainability demands. DRIVES, co-funded by the Erasmus+ program of the EU, has identified the field of rubber technology to require new competences. The scope of this thesis was to substantiate the relevance of rubber technology in a sustainable automotive future, assist in the development of the rubber technologist job role structures and acquire complete, future sound, educational competence skill sets. Two Rubber Technologist job role skill cards (Basic & Advanced) were developed based on the already existing training material in the Elastomer Science and Engineering course of the University of Twente together with a study into the future needs of the automotive and rubber industry.

Chapter 2 substantiates that the reduction of environmental impact, especially GHG emission reduction, is a key driver behind future automotive trends. The road transport sector fails to join the EU-wide $C0_2$ reduction trend, emissions have increased with 25% since 1990. The EU aims to reduce road transport emissions to levels below those of 1990 by applying vehicle emission targets and tire performance labelling. Rolling resistant force generated by friction and material hysteresis accounts for roughly a third of the total energy consumption of a car.

Chapter 3 describes the environmental impact related to tire technology and substantiates that rolling resistance reduction is the most promising factor for road transport emission reduction in the near future. Fleet-wide rolling resistance reduction is expected to reduce fleet-wide passenger car energy consumption up to 3.4% in 2030. Other challenges in tire technology regard tire tread wear and tire lifecycle. Each year 2.5 billion tires are produced worldwide whose treads are scrapped by 2-9 kg of rubber during the use-phase. These rubber particles are released and contribute to contamination of the environment, the depletion of resources and end-of-life tire waste. The improvement of tire abrasion resistance and circular economy solutions are most effective in tackling these challenges.

Chapter 4 describes the development of the Rubber Technologist skill cards and interviews with the rubber industry. The skill card of the Advanced RT is developed up to element level and Basic RT up to skill level. The Basic Rubber Technologist aimed for a broad overview on rubber technology and in-depth knowledge on compounding and in-rubber behavioral phenomena. The Advanced Rubber Technologist aimed to offer a variety of in-depth topics with a higher EQF level of understanding than the Basic Rubber Technologist. The Advanced Rubber Technologist can be tailor-made for the position of the trainee in the company. The ESE course material was extended based on the study in future needs of the automotive and rubber industry. Solutions for sustainability objectives were clustered into new "Sustainability" educational elements with new competences to facilitate a further transition to a more sustainable rubber and automotive future. Two new elements were added compared to the existing ESE framework: Renewable compounding and REACH conscious compounding.

Interviews with twenty respondents with a rubber, often tire technology related, background indicated that sustainability is promoted by increasing societal awareness, effective regulations, appropriate education and additional research. Respondents pointed towards a general lack on holistic rubber technology knowledge on different levels of product development. The rubber industry is interested in new online educational programs that provide holistic education and new compounding and processing solutions for facilitating a robust and sustainable product design. The discussions with the rubber industry revealed four main improvement objectives in decreasing order of importance: rubber performance enhancement (tire magic triangle performance), REACH conscious compounding solutions, circular economy solutions and the replacement of non-renewable ingredients.

Chapter 5 describes the development of exemplary content for sustainability elements following from the previously executed investigation about the future needs of the rubber and automotive industry. The elements contain information to stimulate awareness of renewable and REACH conscious compounding solutions. Renewable compounding solutions on fillers and oils can partly replace petroleum-based ingredients and simultaneously improve in-rubber performance. Silica, lignin and organoclay can partly substitute carbon black based filler systems. Vegetable oils can partly substitute mineral oils. The main benefit and challenge in application of polar renewable ingredients is the incompatibility with non-polar rubber matrices. Bio-based oils can bloom from the rubber matrix, but also enhance tire performance. REACH regulations aim to reduce the use of harmful ingredients. The REACH conscious compounding element aimed for awareness on plasticizers, vulcanization systems and bonding systems that incorporate potentially harmful ingredients and provide alternative solutions.

Concluding, rubber and tire technology are highly relevant for the reduction of environmental impact caused by the road transport sector. New rubber technology job roles with holistic education and innovative solutions can facilitate the transition to a more sustainable rubber and automotive sector.

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Appendix A: Structure for industry partner interviews

General questions on rubber technology
How many rubber technologists are working in your company?
How frequently are new rubber technologists educated and/or given additional trainings?
What methods are used to educate rubber technologists in your company?
Do you feel this education is sufficient, or are certain areas of expertise lacking in content?
What are general problems your rubber technologists struggle with?

Challenges and trends in the rubber & tire industry (Chapter 3)
Do you agree with the presented challenges and solutions?
What do you and/or your company see as most promising innovation or challenge?
How do you approach these challenges?
Do you wish to extent knowledge or awareness about these topics?
Renewable / bio-based compounding
Do you see future applications for renewable / bio-based ingredients?
Safe compounding
What does your company regard as (potentially) toxic ingredients?
To what extent is your company willing to compound with less toxic ingredients?
Recycling
Does your company require knowledge on, or is involved in, recycling?
Rolling & Abrasion resistance (Tire industry)
What does your company / the industry require to further improve these properties?
Is abrasion resistance improving even though it is not part of the tire label?
What percentage of tires are currently Carbon black and/or Silica filled?
To what extent is knowledge on the application of Silica lacking in the company?

Rubber Technologist job roles (Chapter 4)
What units and/or elements are most relevant for your rubber technologist(s)?
What elements are least interesting or irrelevant?
What units and/or elements are missing?
Do you feel the broad and depth of the performance criterions is sufficient?

Final questions on project DRIVES
Do you have doubts about DRIVES?
Would you use of DRIVES training in the future?
What is your main consideration (not) to do so?

Appendix B: Basic Rubber Technologist skill card

UNIT 1: INTRODUCTION TO RUBBER TECHNOLOGY	
Element: Introduction to rubber material **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U1.E1.PC1	The student has a basic understanding of history and breakthrough inventions in the rubber and tire industry
RT.U1.E1.PC2	The student understands the difference between thermoplastics and elastomers and is able to explain how vulcanization gives an elastic character to rubber material
RT.U1.E1.PC3	The student is able to explain the concepts of chain length, molecular weight distribution and their general influence on in-rubber properties and processing character
RT.U1.E1.PC4	The student has a basic understanding of the elastic and viscoelasticity character of rubber; and knows associated spring/dashpot model, poisson effect and basic shear stress deformation equations
RT.U1.E1.PC5	The student is able to draw the general stress-strain curve of rubber, separate the three different stages of strain and has a basic understanding of characterization of rubber tensile test properties, e.g. M100, M300, stress-at-break
RT.U1.E1.PC6	The student is able to assign models to sections of the stress-strain curve and recognize their behavioural phenomena and has a basic understanding of the practical meaning of material related parameters of the Mooney Rivlin equation
Element: In-rubber properties **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U1.E2.PC1	The student understands physical rubber properties that are statically and dynamically tested and has a basic understanding of their meaning and relevance for applications
RT.U1.E2.PC2	The student understands the concept of hysteresis in static and dynamic applications and has a basic understanding of phase shift in sinoidal applied stress and strain response graphs and related tangent delta quantification
RT.U1.E2.PC3	The student understands the concept of the glass transition trajectory and knows the relation with tangent delta and tire tread performance
RT.U1.E2.PC4	The student knows the concept of aging resistance under weathering and application conditions, such as ozone resistance, oil resistance and heat resistance
Element: Introduction to compounding **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U1.E3.PC1	The student is familiar with the general steps in production of a rubber product and their purpose: compounding, mixing, processing, vulcanization, adhesion and recycling

RT.U1.E3.PC2	The student understands the concept of a compound formulation and is able to apply the conversion of PHR to mass in grams
RT.U1.E3.PC3	The student knows the general type of ingredients and systems that are included in the compound formulation and is able to define the ingredient's functionality
RT.U1.E3.PC4	The student knows commonly applied fillers and understands the general effect of reinforcing fillers on in-rubber properties
RT.U1.E3.PC5	The student knows the main curing systems and understands the general effect of crosslink density on in-rubber properties
Element: Elastomer types & applications	**Evidence check:**
Performance criteria	**The student can demonstrate that**
RT.U1.E4.PC1	The student has a knows general rubber types, characters and market prize; and understands the concept of main chain saturation (R/M type rubber) and its relation to degradation resistance
RT.U1.E4.PC2	The student has a basic understanding of various rubber applications and is able to recognize conditions that are important for the choice of the polymer type
RT.U1.E4.PC3	The student is able to choose, with help of relevant general in-rubber property tables and graphs, the appropriate elastomer type for a situation in which key performance properties are easy to recognize
RT.U1.E4.PC4	The student knows the magic triangle of tire tread performance, typical carbon black and green tire tread compound formulations and understands the changes from the past which led to these formulations

UNIT 2 : POLYMER TYPES & CHARACTERISTICS	
Element: Natural rubber	**Evidence check:**
Performance criteria	**The student can demonstrate that**
RT.U2.E1.PC1	The student has a basic understanding of the origin and production methods of the polymer raw material.
RT.U2.E1.PC2	The student has a basic understanding of the polymer, grades and material components (e.g. proteins) that make for the special character of NR and related in-rubber properties
RT.U2.E1.PC3	The student is able to explain typical NR strain crystallization phenomena and draw general NR and synthetic IR stress-strain curves.
RT.U2.E1.PC4	The student is able to draw the molecular structure (backbone) of NR and is able to define cis, trans and vinyl polymer chain configurations
RT.U2.E1.PC5	The student has a basic understanding of typical NR applications and required in-rubber properties for which NR is superior to other polymer types
Element: SBR & BR	**Evidence check:**
Performance criteria	**The student can demonstrate that**

RT.U2.E2.PC1	The student has a basic understanding of the production methods of the polymer raw materials.
RT.U2.E2.PC2	The student is able to draw the polymer backbone of SBR and BR and has a basic understanding of grade, functionalization, character and acronyms.
RT.U2.E2.PC3	The student knows typical SBR/BR applications and is able to recognize how SBR styrene and BR ratio influences in-rubber character and tire tread properties (wear, grip and rolling resistance)
RT.U2.E2.PC4	The student understands how the SBR styrene and vinyl content influence the in-rubber character (glass transition temperature) of the polymer
RT.U2.E2.PC5	The student has a basic understanding of difference in properties of SBR, BR and NR, also related to tire compounding applications
Element: EP(D)M	
Performance criteria	**Evidence check:** **The student can demonstrate that**
RT.U2.E3.PC1	The student has a basic understanding of the production method of the polymer raw material
RT.U2.E3.PC2	The student is has a basic understanding of the saturated polymer backbone of EPM, possible functionalization and extension e.g. by third monomer for sulfur curing (EPDM) and its implications of low double bond availability on processing, silane coupling and vulcanization
RT.U2.E3.PC3	The student understands how ethylene/propylene ratio and molecular weight are related to the in-rubber properties
RT.U2.E3.PC4	The student knows beneficial properties follow from the (saturated) polymer backbone and typical applications
Element: (H)NBR	
Performance criteria	**Evidence check:** **The student can demonstrate that**
RT.U2.E4.PC1	The student can draw the molecular structure of (H)NBR and knows how properties are effected by the acrylonite and butadiene backbone content
RT.U2.E4.PC2	The student knows about the polar character of NBR in contrast to NR/SBR/BR, and is able to recognize compatibility with typical ingredients, e.g. polar oils and fillers
RT.U2.E4.PC3	The student understands the saturated polymer backbone of HNBR and implication of low double bond availability on processing, silane coupling and vulcanization
RT.U2.E4.PC4	The student knows typical (H-)NBR applications and typically required in-rubber properties for these applications

UNIT 3: FILLER TECHNOLOGY	
Element: Carbon black **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U3.E1.PC1	The student has a basic understanding of the production process of thermal and furnace carbon black
RT.U3.E1.PC2	The student has a basic understanding of the morphology of carbon black and is able to name and explain characterizing morphological factors
RT.U3.E1.PC3	The student has a basic understanding of characterization methods of specific surface area and structure and understands how these influence general in-rubber properties and ease of dispersion
RT.U3.E1.PC4	The student knows of different characterization methods of pore and understands aggregate size distribution and its influence on dispersion
RT.U3.E1.PC5	The student is able to reproduce the functionality of Carbon Black apart from the reinforcing character, such as colouring and conductivity
Element: Silica & silane **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U3.E2.PC1	The student has a basic understanding of the production process of precipitated Silica
RT.U3.E2.PC2	The student has a basic understanding of the specific surface area grades and is able to reproduce the relation between SSA and particle diameter
RT.U3.E2.PC3	The student is able to define the chemical nature of the silica surface
RT.U3.E2.PC4	The student is able to recognize the difference of Silica and Carbon Black w.r.t. filler-filler and filler-polymer interaction based on surface activity of the filler
RT.U3.E2.PC5	The student has a basic understanding of the difference in tan delta character between silica & silane and carbon black filler
RT.U3.E2.PC6	The student is able to reproduce mechanism and purpose of the Silica Silane Polymer reaction
Element: Reinforcement theory **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U3.E3.PC1	The student is able to associate reinforcement with more specific in-rubber properties and to recognize main reinforcement mechanisms in structure models
RT.U3.E3.PC2	The student is aware of the different theoretical approaches for reinforcement with regard to adhesion and filler-filler interaction models
RT.U3.E3.PC3	The student is able to identify the loss in shear modulus G* due to strain as being the Payne effect, is able to name one explanation of why it occurs and the effect on application level
RT.U3.E3.PC4	The student is able to identify the Mullins effect and its effect on application level

RT.U3.E3.PC5	The student knows the effect of silane-polymer coupling on the Payne effect
RT.U3.E3.PC6	The student is able to explain the term paradox of reinforcement and how this affects the application of e.g. hard rubber compounds

UNIT 4: MIXING, PROCESSING & CHARACTERIZATION OF GREEN COMPOUNDS	
Element: Mixing machinery & dispersion theory **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U4.E1.PC1	The student knows different mixers and rotors types and understands the meaning and relevance of mixing process parameters, such as rotor speed, temperature, torque, power and ram movement
RT.U4.E1.PC2	The student has a basic understanding of the dispersive and distributive mixing, dispersion quality and their underlying mechanical processes (rupture, erosion, disintegration)
RT.U4.E1.PC3	The student knows the definitions visual, macro and micro dispersion and has a basic understanding of dispersion measurement methods
RT.U4.E1.PC4	The student understands the influence of process parameters on dispersion mechanics and dispersion quality
RT.U4.E1.PC5	The student understands that the Payne effect is a predictor of micro dispersion quality
RT.U4.E1.PC6	The student understands the influence of dispersion on in-rubber properties, such as reinforcement, fatigue, tire rolling (hysteresis) and abrasion resistance
Element: Mixing process & fingerprint **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U4.E2.PC1	The student has a good understanding of the function of plasticizers in mixing and compound applications, the different grades and has a feeling for the amount that generally is used for typical applications
RT.U4.E2.PC2	The student has a good understanding of the mixing process and understands typical behaviour of process parameters in accordance with the mixing plan
RT.U4.E2.PC3	The student is able to draft the mixing procedure of a simple compound
RT.U4.E2.PC4	The student is able to read the mixing fingerprint and recognize faulty mixing phenomena based on the mixing fingerprint
Element: Mixing of Silica & Silane compounds **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U4..E3.PC1	The student has a basic understanding of the production procedure for Silica and Silane compounds and typically related

	phenomena of Silica to Silane coupling during mixing and Silane to Polymer coupling during vulcanization.
RT.U4.E3.PC2	The student knows of flocculation (degrading dispersion quality) during storage of ready-mixed compounds
RT.U4.E3.PC3	The student has understands Silica-Silane compound mixing and typical approaches to improve incorporation and reactivity of Silica and Silane
RT.U4.E3.PC4	The student understands the optimum dump temperature range by the Mooney viscosity vs. dump temperature graph for mixing
RT.U4.E3.PC5	The student has a basic understanding of polymers extended with functional side groups on the backbone
Element: Rheology & testing	**Evidence check:**
Performance criteria	**The student can demonstrate that**
RT.U4.E4.PC1	The student understands the concept of viscoelasticity and associated viscoelastic behavioural concepts of hysteresis, creep and stress relaxation
RT.U4.E4.PC2	The student understands typical processing and application related polymeric behavioural character and phenoma, such as green strength, die swell, tacticity, the Deborah number, entropy elasticity and shrinkage
RT.U4.E4.PC3	The student understands relaxation test methodologies such as Mooney viscosity, Mooney Stress Relaxation (MSR), Rubber processing analyser (RPA), Dynamic mechanical analysis (DMA) and capillary rheometry; and their relation to the compound's in-rubber and processability character
Element: Processing & production	**Evidence check: The student can demonstrate that**
Performance criteria	
RT.U4.E4.PC1	The student knows common rubber product processing and production methods
RT.U4.E4.PC2	The student understands challenges related to common general rubber processing and production methods
RT.U4.E4.PC3	The student is able to adjust a compound's rheological character for improved processability in a case where processing issues are easily recognizable

UNIT 5: PRODUCTION & CHARACTERIZATION OF VULCANIZATES	
Element: Curing mechanisms	**Evidence check:**
Performance criteria	**The student can demonstrate that**
RT.U5.E1.PC1	The student understands the peroxide and sulfur vulcanization system mechanisms, their difference in crosslink character and in-rubber properties
RT.U5.E1.PC2	The student understands "Moving Die Rheometer" method and the relevant vulcanization curve characteristics such as scorch time (ts2), vulcanization time (t90) recognize curing phenoma such as marching, plateau and reversing modulus

RT.U5.E1.PC3	The student is able to name typical sulfur crosslinking systems, accompanying sulfur crosslink chain length character and resulting character of in-rubber properties, such as temperature resistance and dynamic performance
RT.U5.E1.PC4	The student has a good understanding of various ingredients involved in the vulcanization process and their functions (activator, accelerator, cross linkers, alkalizers, stearic acid, retarder) and is able to estimate a shift in the vulcanization curve from manipulation of the compound formulation
RT.U5.E1.PC5	The student is able to choose a suitable vulcanization system for a given situation in which requirements are easy to recognize
Element: Test methods for rubber vulcanizates **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U5.E2.PC1	The student understands common test methods for mechanical and dynamical physical properties of rubber vulcanizates
RT.U5.E2.PC2	The student can pick the relevant in-rubber properties and test methods for common rubber applications
Element: Adhesion theory **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U5.E3.PC1	The student knows materials that are commonly used to provide reinforcement in rubber applications
RT.U5.E3.PC2	The student has a basic understanding of general in-rubber, rubber to rubber and rubber to substrate bonding mechanisms, such as intermolecular and covalent bonding, diffusion and interlocking
RT.U5.E3.PC3	The student understands adhesive and cohesive bonding failure
RT.U5.E3.PC4	The student is understands the relevance of surface wettability
Element: Anti-degradation theory **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U5.E4.PC1	The student has a basic understanding of degradation mechanisms and the effect of degradation on functional properties
RT.U5.E4.PC2	The student knows commonly applied anti-degradants and their protection mechanisms
RT.U5.E4.PC3	The student is able to estimate degradation mechanisms based on application conditions and select the appropriate anti-degradant type(s)

UNIT 6: SUSTAINABLE RUBBER TECHNOLOGY	
Element: Renewable compounding **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U6.E1.PC1	The student is able to explain the general difference in origin between renewable and synthetic compounding ingredients
RT.U6.E1.PC2	The student is aware of the purpose and drawbacks of bio-based compounding and is able to substantiate a choice for biological source ingredient instead of a synthetic ingredient
RT.U6.E1.PC3	The student knows high potential renewable oils, fillers and polymers and recent advancements in the field of renewable compounding
RT.U6.E1.PC4	The student understands the challenges faced in replacing the (non-polar) character of petroleum based polymers, oils and fillers
Element: REACH conscious compounding **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U6.E2.PC1	The student is aware of the potential toxicity of rubber compound ingredients and the EU REACH regulation
RT.U6.E2.PC2	The student knows what type of ingredients and reaction products are potentially harmful for humans and/or environment
RT.U6.E2.PC3	The student is able to recognize potentially harmful ingredients inside rubber compounds and adhesives and is able to propose alternatives with similar functionality
Element: Application-based compounding **Performance criteria**	**Evidence check:** **The student can demonstrate that**
RT.U6.E3.PC1	The student is able to draft mechanical, dynamical and chemical requirements for typical rubber applications
RT.U6.E3.PC2	The student is able to draft a compound formulation for typical rubber applications based on a set of mechanical, dynamical and chemical requirements