Life Cycle Assessment of Resource Effectiveness in a Business Ecosystem of Heavy-Duty Truck Tires

Abstract

Is tire retreading worth it from an environmental perspective? Could sensors be used to increase resource productivity of heavy-duty truck tires? This report explores these questions

Simon Andersson, IVL
Derek L. Diener, RISE Sustainable Business

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This study aims at assessing the environmental impacts related to heavy-duty (truck) tyres. Results shall inform stakeholders on benefits (or impacts) related to four main outcomes (or combinations thereof): (1) retreading and reuse, (2) recycling (of carbon black), (3) maintaining continuous tyre pressure and extending tyre use life, something that may be possible with enhanced monitoring, e.g. with use of sensors, and (4) use of shredded tyres in playing surfaces.

This report includes three main works. First, a literature review is presented. Next, a life cycle assessment conducted focused on the first three outcomes (retread, recycle, tyre pressure) is presented. Then, an assessment of the toxicity related to the fourth outcome, use of shredded tyres, is presented. Finally, results are considered together to garner final thoughts and recommendations.

Contents

Introduction

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Background: Literature review

This report summarizes previous LCA studies of manufacturing, retreading, and recycling of heavy-duty tyres. The purpose of the literature review is:

> 1) to provide an overview of the current knowledge against which the LCA results produced in this project can be compared,
>
> 2) to identify 'hot spots' in the LCA on heavy duty tyres that require attention during the environmental modelling, and
>
> 3) to establish 'correct' ways of modelling retreading and recycling based on the available literature.

Since the literature on retreading of heavy-duty tyres is scant, studies that addresses the environmental impact of retreading car tyres are included in this literature review. Even then, not many LCA studies on retreading versus the production of new tyres are available and data and assumptions taken in these studies varies considerably (Gutowski et al., 2011). Retreading requires new material and energy (Gutowski et al., 2011). On the other hand, retreading extends the lifespan of the tyre, saving embedded energy (Boustani et al., 2010; van Beukering and Janssen, 2001) and reducing the production energy demand for tyres (Boustani et al., 2010). The environmental impacts of retreaded tyres along the various steps (manufacturing, usage, retreading, and recycling) are assessed based on a literature review and the findings summarized in this report.

The manufacturing process

The environmental impact of extraction raw materials and manufacturing tyres depends largely on the tyre specifications (van Beukering and Janssen, 2001). Besides relative large amounts of rubber (natural and synthetic), synthetic elastomers, zinc oxide (a chemical additive), and carbon black are used to produce tyres (van Beukering and Janssen, 2001). One kg of tyre consists of roughly 2/3 rubber and 1/3rd steel (GREET, 2017). Raw materials are mixed to create a rubber compound. Thick slabs of rubbers are fed between a pair of rollers, called milling. The tyre compounds are then extruded to create various components (e.g. tread, sidewall). The rubber is finally coated to increase strength. The manufacturing of tyres requires around 11.7 MJ per produced kg of tyre (Amari et al., 1999 cited in Boustani et al., 2010).

▲ CO2 Total	**2.92e-4 t**
CO2	2.92e-4 t
CO2_Biogenic	-4.12e-7 t
VOC	3.55e-8 t
CO	1.17e-7 t
NOx	2.25e-7 t
PM10	2.24e-8 t
PM2.5	1.49e-8 t
SOx	5.51e-7 t
CH4	3.13e-7 t
N2O	7.36e-9 t
SO2	0 kg
BC	1.1e-9 t
POC	2.8e-9 t
▲ Groups	...
GHG-100	3.03e-4 t

Table 1: Well-to-use emissions of a tyre (GREET, 2017).

The use phase

Most studies only look at the production process and assume that the tyres in the use phase lead to equal emissions and can therefore be excluded. However, a few studies argue that the retreaded tyres usually have a worse tyre rolling resistance leading to higher fuel consumption (Boustani et al., 2010; Continental, 1999, Gutowski et al., 2011). The quality of the retreaded tyre varies significantly, yet it is estimated that retreaded tyres have 7 to 9% increase in rolling resistance compared to new tyres (Michelin, 2009 cited by Gutowski et al., 2011). Continental (1999) argues that the rolling resistance of a retreaded car tyre is at least 3% higher than new car tyres (using the best technologies) and is on average 10% higher. This higher rolling resistance and consequential higher fuel consumption can (partly) offset the environmental benefits of retreading. Gutowski et al. (2011) argue therefore that the results are inconclusive.

When including the impacts of the use phase, a significant share (95%) of the environmental impact of tyres occur can be attributed to this phase, mainly due to fuel consumption to overcome tyre rolling resistance (van Beukering and Janssen, 2001). According to the authors, monitoring tyre pressure would therefore lead to the largest saving. Proper maintenance, in particular having the right inflation pressure, positively impact the retreading success rate and will therefore have an impact on the overall environmental impact (Boustani et al., 2010).

The retreading process

An environmental assessment of retreaded tyres should include the original manufacturing process of the new tyre since changes in the design / manufacturing will have an effect on the scrap tyre that will be used for retreading (Pehlken and Roy, 2006). Not all tyres can be retreaded and a selection process is the first step of the retreading process. This also means that more tyres are transported to the retreading facility than that are actually successfully retreaded. This transport of non-successfully retreaded tyres should be included in the life cycle assessment (Pehlken and Roy, 2006).

Each tyre is first labelled and visually inspected. Tyres which does not show any defects are transferred to rigorous testing using equipment to assess defects and damages that are not visible to the eye, for example fluoroscopic x-rays, ultrasounds, or shearography (Boustani et al., 2010). Buffing entails the removal of the old tread. The old tread is shaved off until the desired tyre radius, profile, and crown width are reached. Another inspection of the saved casing is performed (Boustani et al.,

2010). In the new tread application step, new tread is aligned and centered to the casing. The applied tread and casing are then wrapped around a rubber envelope and a vacuum is created (Boustani et al., 2010). In hot retreading, a layer of unvulcanised rubber is combined with the buffed tyre and vulcanized in a heating press, usually around 150 °C (Rafique, 2012). In cold retreading, a precured tread is combined with the tyre and adhesive to paste the tread on the tyre. A temperature of around 95 to 110 °C is normally used in the cold retreading process (Rafique, 2012). Final inspection and preparation for shipping is the last step in the retreading process (Boustani et al., 2010).

Recycling

On a larger scale, retreading tyres will result in less tyres available for other applications such as construction. Depending on the purpose of the LCA, these effects might have to be included in the assessment. Tyres that are not retreaded are used in different applications. The process starts with shredding to reduce the volume of the tyres with 75% (Rafique, 2012). Shredding requires 19.2 KWh energy per 1000 Kg of waste tyres shredded (Ogilvie et al., 2004 cited in Rafique, 2012). Depending on the size required (which differs for different applications), further shredding in smaller sizes might be needed. Smaller sizes have a higher environmental benefit due to a larger possibility to substitute virgin materials (Genan Business, 2009 cited by Pehlken et al., 2014).

Production of ground rubber from used tyres entails the following process steps (Li et al., 2014):

- Rubber powder preparation: pulverizing the tyres to a fine powder and removing steel from the tyres.
- Devulcanization: to improve the plasticity of the rubber powder, pine tar and rosin are added during the devulcanization process. Coal-fired oil furnace can be applied for keeping a high temperature and pressure in the desulfurization tank (Li et al., 2014). During this process, waste gases are produced.
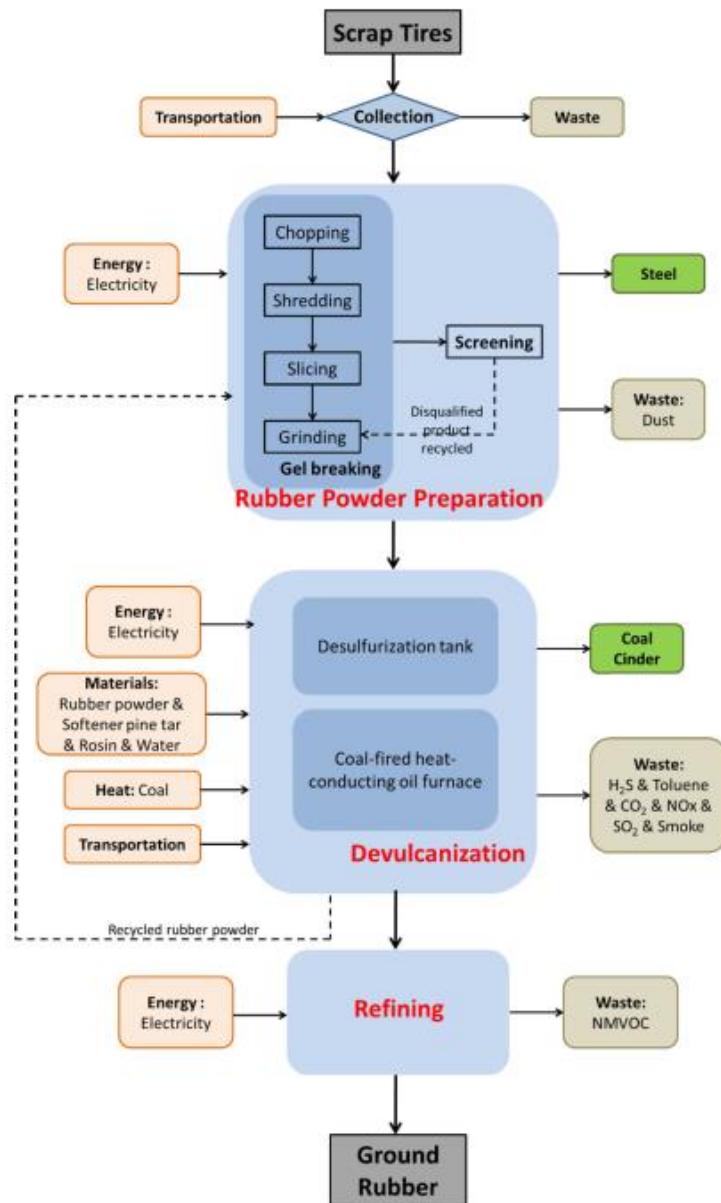- Refining

Figure 1: Producing ground rubber from scrap tyres (Li et al., 2014).

Devulcanization contributes the most to the environmental impact of tyre recycling (66% on the eco-indicator 99 due to the high amount of heat needed in the process) while the recycling of coal cinder has a negative environmental impact (credit) which offset the impacts on the ozone layer (Li et al., 2014). The positive effects of coal cinder are however not large enough to offset the other environmental impact categories (Li et al., 2014). The results are based on the situation in China. In environments with less dependence on coal as energy source, the environmental benefits might be larger.

When calculating the environmental impacts of tyre recycling, the avoided impacts of the replaced product and material should be included (Clauzade et al., 2010). For example, recycling of tyres for cement works avoids the extraction, preparation, transportation, and shredding of fuels. It further avoids emissions associated with the combustion of these fuels. Clauzade et al. (2010) assigns the environmental benefits of this to the recycling of used tyres and not to the downstream products

that uses the recovered used tyres. They conclude that all recovery applications assessed (synthetic turf, moulded objects, cement works, steelworks, urban heating, equestrian floors, retention basins, and foundries) lead to a positive significant impact on the environment (except for infiltration basins which has both positive and negative impacts depending on the impact category). Most beneficial is "the productions of synthetic, ELT-based turf, the manufacturing of moulded objects from ELT and energy recovery in cement works" (Clauzade et al., 2010). The avoided impacts outweigh the environmental impacts of collecting, sorting, and shredding the tyres. Genan (2009) reports similar findings arguing that recycling for artificial turf and asphalt is better for the environment than using old tyres for drainage layers. The general LCA guidelines on the allocation of credits due to recycling of materials need to be followed.

One other issue in recycling is the achieved (compared to guaranteed) quality of the crushed tyres (Pehlken et al., 2014). "A complete separation of water material components is not possible" and different quality grades are reached (Pehlken et al., 2014). Depending on the quality grade, certain applications might not be possible. The authors argue that this should be included in the environmental impact assessment, although LCA might not be the most suitable method to include this type of uncertainty and dynamic modeling. The authors propose a combined LCA with material flow analysis (MFA) to assess decisions in waste flows.

Output emissions

Emissions / impact	Manufacturing New car tyre	Production process of Retreated car tyre (excluding higher rolling resistance)
Energy	332 MJ per car tyre	147 MJ per car tyre
Air	66 kg per car tyre	36 kg per car tyre
water	579 kg per car tyre	23 kg per car tyre
Atmospheric emissions	25 kg per car tyre	11 kg per car tyre
Emissions into water	2 kg per car tyre	0.01 kg per car tyre
Global warming potential	20 kg per car tyre	11 kg per car tyre
Acidification potential	0.007 kg per car tyre	0.006 kg per car tyre
Nitrification potential	0.09 kg per car tyre	0.06 kg per car tyre

Table 2: Emissions of new and retreaded car tyres (Continental, 1999).

Including the higher rolling resistance, the energy consumption of a retreaded car tyre over its lifetime increases to 7838 – 8429 MJ. Comparing this to the total energy consumption of a new tyre (7852 MJ), the results are less conclusive (Continental, 1999). Continental concludes that "the resource savings attained in retreading is virtually canceled out by the higher petroleum (fuel) consumption" and that it leads to an increase in global warming potential and nutrification potential (Continental, 1999). The effect on acidification potential depends on the increase in rolling resistance (Continental, 1999). However, technological advance of retreaded tyres since 1999 might diminish this negative effect of higher rolling resistance. A new LCA study on retreading tyres in the current environment is beneficial.

Retreaded versus new tyres

Boustani et al. (2010) argue that retreaded tyres should be compared against new tyres available at that moment for purchase. Since tyres and their rolling resistance are improved constantly, the retreaded tyre will have to be compared against the improved new tyre. The rolling resistance is continuously improving and many tyre manufacturers offer special eco-tyres nowadays. When retreading tyres, the older tyres need to be compared to the new (more efficient) tyres available on the market and which the customers would have bought if not bought a retreaded one (van Beukering and Janssen, 2001).

During usage, tyres lose about 15% of their total weight (Pehlken and Roy, 2006). It is therefore only possible to retreat a car tyre once in its entire life (Rafique, 2012). On the other hand, Michelin argues that the lifetime of the tyre can be doubled or even tripled by retreading although their tests show a 97% lifespan compared to a new tyre (Michelin, 2017). Most LCA studies assume equal lifetimes for the new and retreaded tyre (for example Boustani et al., 2010; van Beukering and Janssen, 2001). However, according to TRIB (cited in Boustani et al., 2010), retreaded tyres last between 75 to 100% of the lifetime of a new truck tyre. On the other hand, a report by EY (2016) argues that a retreaded truck tyre lasts for about 220 000 km while a new truck tyre in Europe lasts usually for 600 000 km. The lifespan depends on the inflation practice and associated tyre pressure. The lifespan of tyres is increasing over the years and can be further increased by improved driving behaviour and monitoring tyre pressure (van Beukering and Janssen, 2001). For example, properly inflated car tyres might even have a lifetime of 95000 to 1280000 km (van Beukering and Janssen, 2001), compared to the average lifespan of passenger car tyres of 30000 to 80000 km depending on mechanical load (Pehlken et al., 2014). There is still uncertainty regarding the actual lifespan of new versus retreaded tyres.

Conclusions

- Rolling resistance of tyres should be included in the LCA as well as the lifespan of new versus new tyres. Access to industry data is needed to make realistic assumptions.
- The moment of purchase is important, i.e. the tyre that is replaced by using retreaded tyres. This means that potential future changes in rolling resistance should be included in the assessment.
- Transport and activities performed to tyres that cannot be retreaded should be included in the LCA. Industry data on the retreading yield rate is needed.

Life cycle assessment

The life cycle assessment described here was tailored to the tyre system at hand and with consideration to the conclusions from the literature review. It was facilitated by actors in the Swedish tyre "business ecosystem", represented by Volvo Group (trucks manufacturer and service provider), Galdax (retreader) and SDAB (recycling company administrating the producer responsibility for tyres in Sweden).

Goal

The goal of this study is to quantify the environmental benefit (impact reduction) of retreading. In addition, there is an interest to assess the possible benefits related to the use of sensors to detect e.g. low tyre pressure (a key determinant in vehicle fuel efficiency and in tyre life length) and hence reduce the use of tyres when they are underinflated.

The study will identify, develop and evaluate methodology and principles which will be incorporated in the final LCA model. This model could then be used for different types of analyses related to the tyre product system including the following questions:

1. What is the difference, in terms of environmental impact, between tyre cores retreaded and tyre cores not retreaded?
2. To what extent can the environmental impact decrease by using sensors ensuring optimal tyre pressure and timing of tyre exchange?

The results can inform actors in the tyre product chain, from producers to users, and help identify opportunities to reduce environmental impact. The results will be communicated internally within the project which includes a tyre retreader, tyre material recycler and tyre customers. Results will allow more generic lessons learned and will be part of the final project deliverables.

Scope

The tyre product system

A schematic flowchart of the heavy duty tyre product system is shown in **Fel! Hittar inte referenskälla.**. After a tyre is used it can either be recycled or retreaded. A tyre core can be retreaded up to three times (Galdax, 2018).
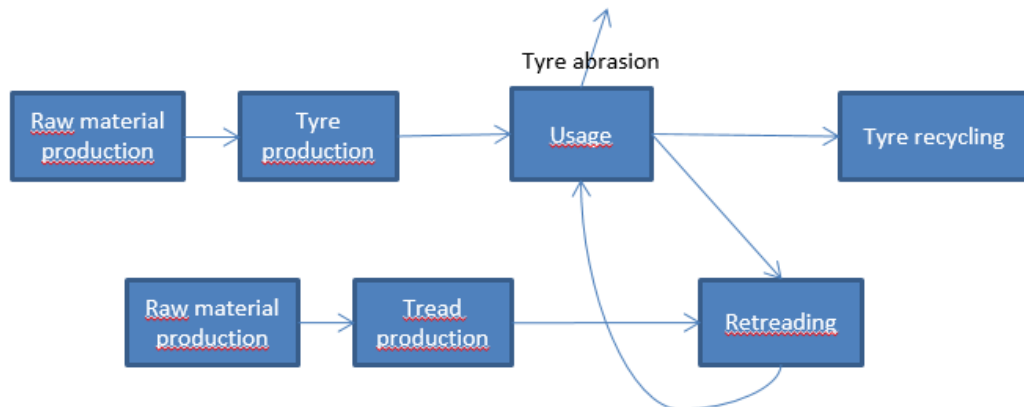

Figure 2: Flowchart (material flows and main activities) of the heavy duty tyre product system. Material losses exist in production and retreading processes, e.g. chips from turning used tyres, but these flows are not indicated in this figure.

The functional unit is defined as one km of usage of a tyre in a heavy-duty truck with a diesel powertrain. The truck is assumed to operate in Sweden (long haul transport).

System boundaries

The study covers the life cycle of the tyre from extraction of raw materials from nature to a delivered product, used at a customer and finally disposed. The boundary between nature and the product life cycle is crossed when materials, such as crude oil and iron ore, are extracted from the ground or when emissions occur to soil, air or water.

The following activities are not included in the study:

- Production, use and end-of-life of packaging materials
- Production and maintenance of capital goods and infrastructure (buildings, machines, vehicles etc.) used within the different activities in the life cycle
- Personnel-related environmental impact (travel to work, business travels, food etc.)
- Maintenance of tyres (inflating tyres, repairing flat tyre etc.)

End-of-life methodology

The study applies system expansion in the tyre recycling phase, meaning that the tyre product system is given credits representing avoided impacts related to products which are replaced by products made from recycled tyres.

Impact categories

The impact categories selected for analysis in this study are described in Table 3.

Impact category	Category indicator	Method
Climate change	kg CO2 eq.	Global warming potential (GWP100), excluding biogenic carbon
Acidification	kg SO_2 eq.	Acidification potential (AP)
Eutrophication	kg PO_4^{3-} eq.	Eutrophication potential (AP)
Photochemical oxidation	kg C_2H^4 eq.	Photochemical oxidant creation potential (POCP)
Abiotic resource depletion	MJ	Abiotic Depletion Potential (ADP), fossil resources

Table 3: Selected impact categories.

Climate change, acidification, eutrophication and photochemical oxidation are categories often addressed in LCAs, e.g. LCAs made for marketing purposes in accordance with The International EPD® System (2019). Impact assessments methods used for these categories are considered mature and of high quality (JRC, 2011). Abiotic resource depletion of fossil resources has been added as a large part of a tyre is made from fossil resources and as fossil fuel is used in the usage phase of the tyre. The methods applied are from "CML 2001" (version Jan. 2016), developed by the Institute of Environmental Sciences at Leiden University.

There exist several impacts methods for toxicity, but due to uncertainties and lack of detailed data toxicity will be addressed qualitatively as a separate review activity (Toxicity assessment).

Data quality requirements and sources of data

The results of the study shall be valid for Swedish conditions, i.e. tyres used and disposed within Sweden. Usage and retreading/recycling data should therefore represent Swedish conditions. Data for production of tyres and treads should represent tyres and treads typically used in Sweden.

The study is focusing on the tyre product system as it is today, for this reason the data shall represent the current situation and be up-to-date.

For the activities represented by a partner in the project (e.g. usage and retreading), primary data are collected. For tyre and tread production, including production of the raw material, and tyre recycling data from literature and/or commercial databases are used.

Limitations of the study

The tyre recycling model, aiming to represent the Swedish heavy-duty tyre recycling, is simplified. The recycling system is complex, literature data only exist for some selected recycling options (and might be old) and it is typically hard to define what materials are replaced by the recycled tyres. Recycling results are therefore associated with high uncertainties and should not be seen on as the final truth.

Life cycle inventory analysis

Data collection was performed during 2018 and 2019. Generally, the LCA is using primary data for the processes which are represented by a partner in the project (e.g. retreading), and secondary data for remaining processes (e.g. tyre production), see summary of data sources in Table 4 below.

Process	Source
Raw material production (tyres and treads)	LCA databases + primary data collected from Volvo Group/Galdax
Tyre production	LCA databases/literature
Usage	LCA databases/literature + primary data collected from Volvo Group
Tread production	LCA databases/literature
Retreading	LCA databases + primary data collected from Galdax
Tyre recycling	LCA databases/literature + primary data collected from SDAB
Transportation	LCA databases/literature

Table 4: Summary of data sources.

Modelling of the product system was made in the LCA software GaBi. Results from GaBi were later extracted into an Excel calculation sheet used to calculate and illustrate results depending on a set of parameters that could be changed. Data collection and modelling for each process are briefly described in sub-sections below.

Raw material production

A specification of the tyre material composition from Volvo Group were selected as the basis for modelling the tyre product system. This material composition represents the average of heavy-duty tyres that are used by Volvo Group for long haul trucks. The tyre weight used here is 63 kg, weights of tyres used for long haul typically varies between 54 and 67 kg.

Detailed material composition of the treads could not be obtained from Galdax, the share of raw materials in the treads were instead assumed to be the same as the share of raw materials for the rubber compound in a whole tyre.

Raw material	Tyre		Tread	
	Weight [kg]	Share	Weight [kg]	Share
Natural rubber	23,3	37%	5,0	47%
Synthetic rubber	5,7	9%	1,3	12%
Carbon black	15,1	24%	3,3	31%
Organic chemicals	5,0	8%	1,1	10%
Steel cord	13,9	22%	-	-
Total	63,0		10,7	

Table 5: Material composition of a whole tyre and a tread.

The production of the raw materials in tyres and treads was modelled using data sets from commercial LCA databases. Table 6 describes the data sets used to represent raw material production.

Raw material	Data set	Data source

Natural rubber	DE: Natural rubber (NR)	thinkstep
Synthetic rubber	DE: Styrene-Butadiene Rubber (SBR) Mix	thinkstep
Carbon black	DE: Carbon black (furnace black; general purpose)	thinkstep
Organic chemicals	GLO: chemical production, organic	ecoinvent 3.4
Steel cord	EU: Steel wire rod	worldsteel

Table 6: Data sets used to represent raw material production.

Tyre production

As no LCA data was obtained representing production of heavy-duty tyres, data in an LCA of a passenger car tyre (Sun et al., 2016) was used as an approximation. This study identified four main processes in tyre production: compound blending, rolling and extrusion, cutting and forming, and vulcanizing and testing. Amounts of resources consumed (electricity, steam, water) and emissions released during these processes were taken from Sun et al. (2016), production of the resources were modelled by using thinkstep datasets.

Usage

Impacts from using a tyre could be divided into impacts due to production and combustion of fuel to overcome the rolling resistance and other, tyre specific, impacts. As seen in the literature review, several other studies excluded the fuel related impacts. As suggested after the literature review, and as this study will consider differences in fuel consumption, they have been included. However, results will be presented both with excluded and included usage phase.

Lifespan of tyre

The maximum lifespan of a long-haul truck tyre is around 250 000 km. Typically tyres are changed before it is necessary, on average when there is an additional 22% of mileage left in the tyre (Volvo, 2018). Thus, the average lifespan of a tyre made from virgin materials is set to 200 000 km.

According to Volvo tyre suppliers retreaded tyres have a lower maximum lifespan, around 80% of the maximum lifespan of a tyre made from virgin materials (Volvo, 2018). It is then assumed that retreaded tires are also changed earlier, in relation to this difference, after 160 000 km.

Fuel consumption

The fuel consumption of a long-haul truck can differ significantly, depending on e.g. load and vehicle combination. In this study, average figures were used (Volvo Truck Corporation, 2018), 32 l/100km for a tractor and semi-trailer (common in Europe) and 48 l/100km for a truck with trailer (common in Sweden). The figures represent fully loaded vehicles.

Figure 3: Tractor and semi-trailer (left) and truck with trailer (right).

According to Volvo the retreading of a tyre should not affect its rolling resistance, and by that the fuel consumption, comparing the unused tyres. As was found in the literature review, some tyre manufacturers have indicated an increase though: Michelin have for example stated an increase in rolling resistance of 7-9% (Gutowski et al., 2011), and Continental an increase for passenger car tires of 3% (best technologies) to 10% (average) (Continental, 1999).

As tyre pressure is one major factor affecting the fuel consumption, it is important to regularly check it. If tyres are not checked for 48 weeks the pressure is lowered significantly, leading to a fuel consumption increase of 14% (Bridgestone). As an average scenario it assumed that tyre pressure is checked (and corrected) every 8 weeks leading to a fuel consumption increase of on average 1% compared to tires checked every journey. Low tyre pressure is also influencing the lifespan of the tyre, a tyre pressure of 80% of optimal pressure is decreasing the lifespan with 75%.

Driving with fully worn tires is reducing the rolling resistance and by that decreasing the fuel consumption with a few percent (Volvo, 2018). This factor is not considered in the LCA though.

Allocation of fuel consumption to tyres

As the study focuses on tyres, only the fraction of fuel used to overcome the rolling resistance in the tyres is considered. Gutowski at el. (2011) found figures for this fraction in literature that varies between 13% and 47% and used an average value of 24% as a baseline in their study. Fuel consumed per km allocated to one tyre is calculated as:

$$FC_{one\ tire} = \frac{FC_{total} * Rolling\ res.\ fraction}{Number\ of\ tires}$$

The number of tyres also varies depending on combination, based on input from Volvo 10 tyres is assumed for a tractor and semi-trailer and 24 for a truck with trailer.

Impacts due to combustion and production of fuel

If tyres are used on a diesel truck operating in Sweden, MK1 diesel will likely be used. See Table 7 for share of components in MK1 diesel (Energimyndigheten, 2019) and the data sets used to represent their production.

MK1 diesel component	Share	Data set	Data source
Fossil diesel	79% (volume)	EU-28: Diesel mix at filling station (100% fossil)	thinkstep
HVO	17% (volume)	FI: Hydrotreated Vegetable oil (HVO) from beef tallow	thinkstep
FAME	4% (volume)	EU-28: Biodiesel based on rape seed methyl ester (RME)	thinkstep

Table 7: Shares of components in MK1 diesel and data sets used to represent production.

Data representing fossil carbon dioxide emissions from combustion of MK 1 diesel are calculated based on fossil carbon content in the diesel components. Data representing emissions of regulated emissions as well as nitrous oxide and sulphur oxide are from Hallberg et al. (2013).

Emission	g/l MK1 diesel
CO2 (fossil)	2080
N2O	0,216
CO	17,3
NOx	1,98
NMVOC	0,621
SO2	0,00489

Table 8: Emissions from combustion of MK1 diesel.

Other impacts

The obvious tyre specific impact from usage is release of particles due to tyre abrasion. As the LCA is

only considering impact categories where particulate matter has no influence, this emission is not modelled. Impacts from tyre particles are instead discussed in the toxicity evaluation.

There are also impacts related to maintenance of the tyres, such as the electricity used for the compressor when inflating the tyres. These impacts are considered negligible in this study.

Tread production

Due to lack of data for tread production, tyre production data was used to represent this, but with the processes unique to tyre production excluded (cutting and forming, and vulcanizing and testing). The tyre production data was also downscaled, by mass, due to the lower mass of a tread compared to a whole tyre.

Retreading

Data representing retreading has been collected from Galdax, see Appendix 1 – Collected data for retreading. The process starts with an inspection, and if the tyre is approved for retreading the old tread is removed in a machining process. The tyre is then sprayed with cement, working as adhesive, and if there are holes in the tyre these are filled. The tyre is then built in a machine where the new tread is attached. After that the tyre is put in vacuum for an hour to release stress, before going to vulcanization. The tyres are painted before final inspection.

Production of ingoing products, as well as water and electricity, has been modelled using thinkstep or ecoinvent datasets. The actual material content of the products was not possible to obtain for some of them (e.g. the rubber), due to confidentiality, but safety data sheets and other sources were used to estimate the content. Fumes from the solvent based cement were not measured, these were estimated based on that the solvent (heptane) is completely evaporated and released to air. Probably this flow is lower in reality.

Tyre recycling

In accordance with Pehlken and Roy (2006), it is assumed that 15% of the tyre materials are lost as particles due to tyre abrasion, 85% of the tyre material are modelled going to final tyre recycling. This corresponds to 53,55 kg.

The model aims to represent the average Swedish truck tyre recycling situation. Data from SDAB (2019) were collected representing recycling of truck tyres in 2018, see Table 9.

Type of recycling	Tonnes	Share of recycled tyres*
Material recycling, blasting mats	8894	49%
Material recycling, granulates	1384	8%
Material recycling, other	850	5%
Energy recovery	3100	17%
Energy recovery, cement industry	3100	17%
Material replacement (filling/drainage etc.)	800	4%

Table 9: Recycling of truck tyres in Sweden 2018.
*90857 tonnes of tyres were recycled in Sweden 2018, 20% of these were by SDAB assumed to be truck tyres.

Primary data were not collected for the different types of tyre recycling, instead data from literature were used together with assumptions, leading to a simplified model of the truck tyre recycling

system in Sweden. All the recycling streams, excluding "Material recycling, other", were considered in the model and mapped to available inventory data from existing LCAs, see Table 10.

Type of recycling	Modelled as	Share in model	Based on LCA
Material recycling, granulates	Material recycling (granulates in artificial turfs)	8%	Johansson (2018)
Energy recovery, cement industry	Energy recovery (cement kiln incineration)	18%	Hallberg et al. (2006)
Energy recovery	Energy recovery (district heating incineration)	18%	Hallberg et al. (2006)
Material reuse, blasting mats	Material recycling (blasting mats)	51%	Approximated with tyre cutting
Material replacement (filling/drainage etc.)	Material recycling (drainage material)	5%	Hallberg et al. (2006)

Table 10: Modelling of the different types of recycling and share of a used tyre assumed going to the different types.

Material recycling (granulates in artificial turfs)

The tyres are assumed to be shredded and granulated at Ragn-Sells granulate factory in Vänersborg. The granulation is a purely mechanical process which separates the steel from the tyre rubber. The electricity consumed for shredding and granulation is 212 kWh/tonnes of incoming tyres (Johansson, 2018).

The resulting granulates are used in artificial turfs where they are assumed to replace EPDM infill. 52 tonnes of tyre rubber granulate (representing a football field) are replacing 77 tons of EPDM infill. Table 10 lists raw materials used to produce the EPDM infill. In addition to the raw materials 214 kWh of electricity is used in production (Johansson, 2018).

Raw material	Amount [kg]	Data set	Data source
EPDM	220	DE: Ethylene Propylene Diene Elastomer (EPDM)	thinkstep
Limestone	680	Combination of DE: Limestone flour processes with different grain sizes	thinkstep
Mineral oil	80	EU-28: Lubricants at refinery	thinkstep
Phthalates	20	DE: Polyester Resin unsaturated (UP)	thinkstep

Table 11: Raw materials used to produce 1000 kg of EPDM infill and data sets used to represent production of the raw materials.

The steel separated in the granulation process is credited using the data set *GLO: Value of* scrap from worldsteel.

Energy recovery (cement kiln incineration)

Before the tyres are incinerated they are cut/shredded. Electric cutting machines are assumed to be used which uses 20 kWh of electricity per tonnes of tyres (Alongi Skenhall et al. 2012). Swedish average grid mix electricity is assumed to be used, modelled with the thinkstep data set *SE: Electricity grid mix 1kV-60kV*.

The data used for incineration is representing incineration of tyres in Cementas factory in Slite (Hallberg et al., 2006). 1,35 kg fossil and 1,19 kg biogenic CO_2 emissions are released per kg

incinerated tyre shreds, based on a natural rubber content of 47% in the rubber compound. In line with the previous IVL study no other emissions are accounted for in the model.

1 MJ of tyre shreds are assumed to replace 0,75 MJ hard coal and 0,25 MJ petrol coke. Hard coal and petrol coke production are modelled with the data sets *SE: Hard coal mix* and *EU-28: Petrol coke at refinery* from thinkstep. Carbon dioxide emissions from combustion of these fuels are calculated based on CO_2 emission factors and heat values.

Energy recovery (district heating incineration)
The tyres are first cut, this is modelled as in the case with cement kiln incineration.

In 2004 two district heating plants in Sweden incinerated tyres, the data used is based on the plant of Sydkraft ÖstVärme in Norrköping (Händelöverket). 57% of the tyres going to district heating plants in 2004 were incinerated in renewable fuel boilers and 43% in coal boilers (Hallberg et al., 2006). These numbers were considered old due to recent investments in renewable fuel boilers. Instead 75% were assumed going to renewable fuel boilers and 25% to coal boilers. Emissions from incineration of tyre shreds are from the study by Hallberg et al. (2006).

In the coal boiler 1 MJ tyre shreds are assumed to replace 1 MJ hard coal, in the renewable fuel boiler 1 MJ tyre shreds replace 1 MJ solid biomass. Hard coal and solid biomass production and combustion are modelled with the data sets *SE: Thermal energy from hard coal* and *SE: Thermal energy from biomass (solid)* from thinkstep.

Material recycling (blasting mats)
Blasting mats are made from tyres which are sliced up and bound together with ropes, cables or chains. As no data were found representing production of blasting mats, this was approximated with the tyre cutting/shredding process used in the other modelled recycling scenarios.

The blasting mats are assumed to be worn out when the tyre material is worn down to 75% of the original weight. The mats are then assumed to be incinerated in district heating plants, modelled with the bio boiler model explained in the previous section.

How to apply system expansion in this scenario is not obvious, i.e. what would be used instead if there were no blasting mats made of truck tyres. Here it has been assumed that blasting mats would have been produced from virgin materials (same material mix as in the tyres today, see Table 5). This assumption makes recycling truck tyres to blasting mats very beneficial and is rather hypothetical, no example of producing blasting mats from virgin materials has been found. An alternative assumption could be that blasting is done without blasting mats, or that some other waste material, accounted with low environmental impact, is used.

Material recycling (drainage material)
In this type of recycling tyre cuts are used in the drainage layers when a landfill is finished and final covered. The cutting process is the same as for the other recycling scenarios, 20 kWh of electricity is used per tonnes of tyres.

1 tonnes of tyre shreds replaces 2,5 tonnes of crushed stone, which is another material common to use in drainage layers (Hallberg et al., 2006). Production of crushed stone is modelled with the data set *DE: Crushed stone 16/32* from thinkstep.

Transports

Transports of raw materials to production plants, e.g. tyre production, are assumed to be 500 km. More upstream transports than that, e.g. transport of crude oil to refinery which ultimately will become synthetic rubber, are generally included in the raw material production data sets used.

Transport of tyres and ingoing materials to retreading are longer, 1500 km, assuming they are produced in Europe with truck production and retreading located in Sweden. Transports between tyre workshops and the retreading facility are assumed to 150 km as an average, based on the fact that Galdax collects tyres in Sweden from Skåne up to Stockholm.

Transports in the recycling phase are mainly taken from the literature sources used to model the recycling. For details about the transports modelled, see Appendix 2 – Transport distances. As no information was found for recycling as blasting mats, it is assumed that the transports are equal for blasting mats produced from truck tyres and blasting mats produced from virgin materials, thus balancing out each other in the calculations.

Results

Retreading

The following charts presents results per delivered kilometre for the selected input categories. Results are provided for a tyre never retreaded and tyre cores retreaded one, two or three times. The results are valid for a tractor and semi-trailer, assuming no difference in fuel consumption between tyres made from virgin materials and retreaded ones and assuming the fraction of fuel used to overcome the rolling resistance to be 24%.
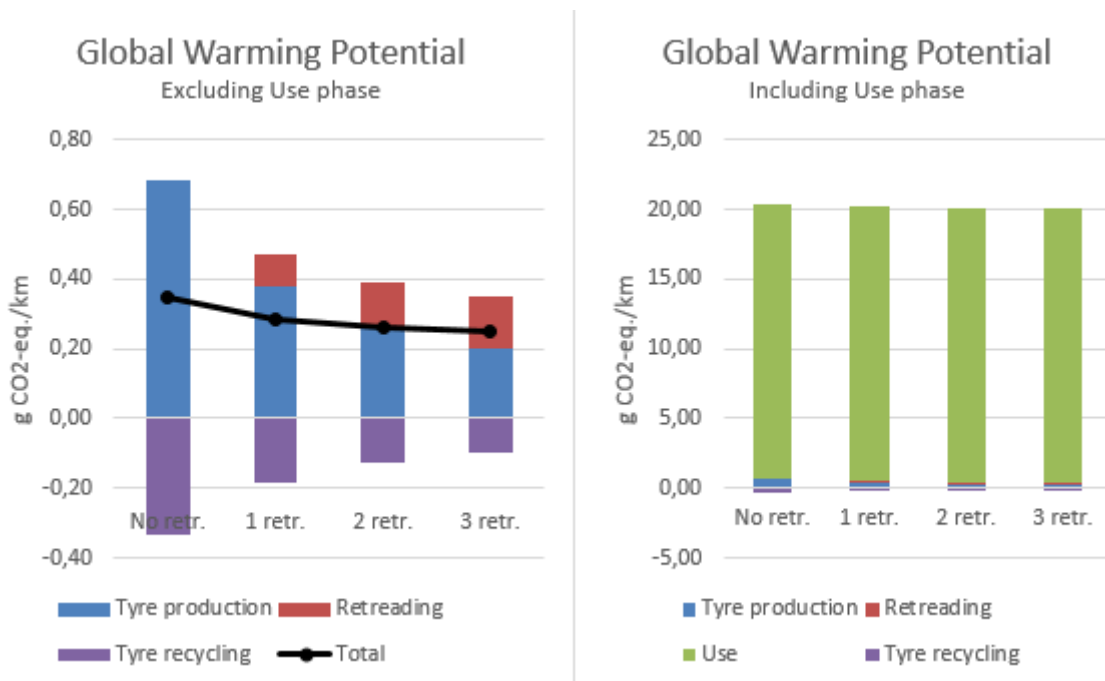

Figure 4: Global Warming Potential per delivered kilometre for a tyre never retreaded and tyre cores retreaded one, two or three times.
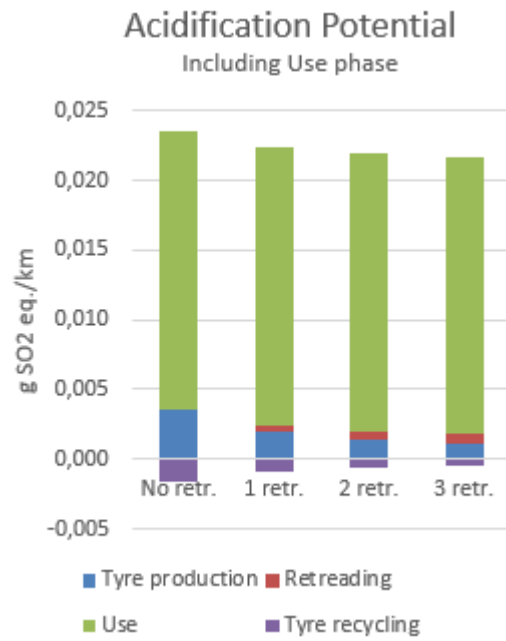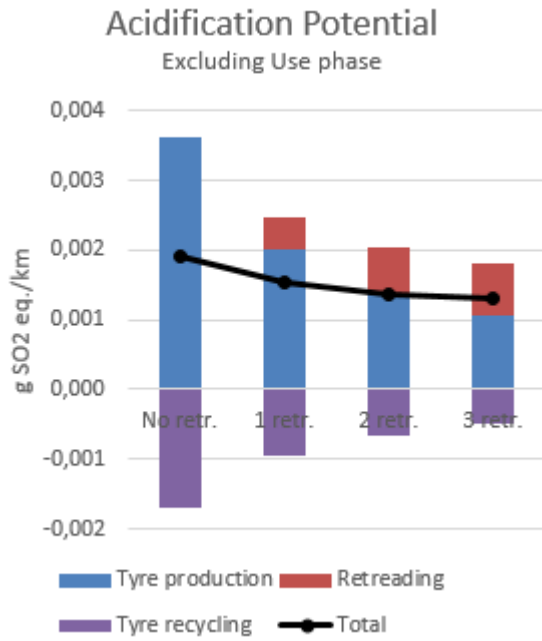
Figure 5: Acidification Potential per delivered kilometre for a tyre never retreaded and tyre cores retreaded one, two or three times.
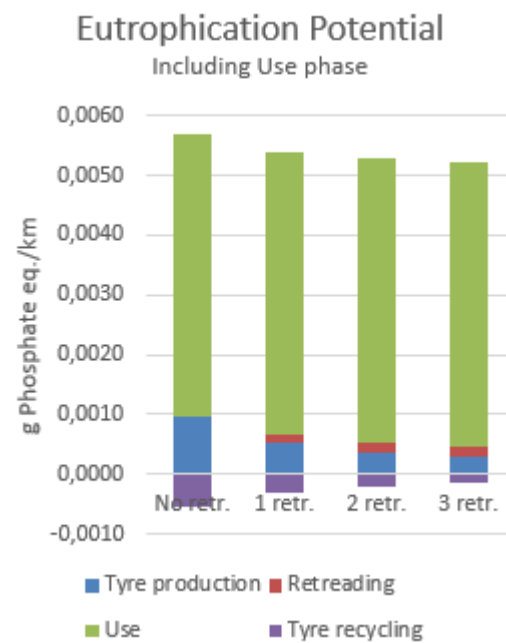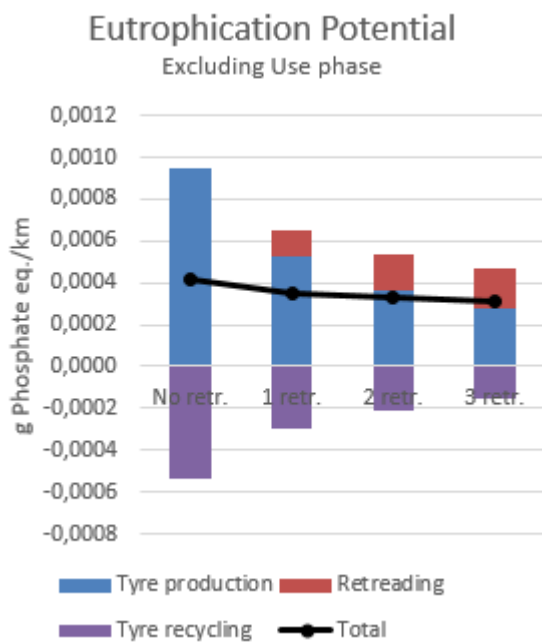

Figure 6: Eutrophication Potential per delivered kilometre for a tyre never retreaded and tyre cores retreaded one, two or three times.
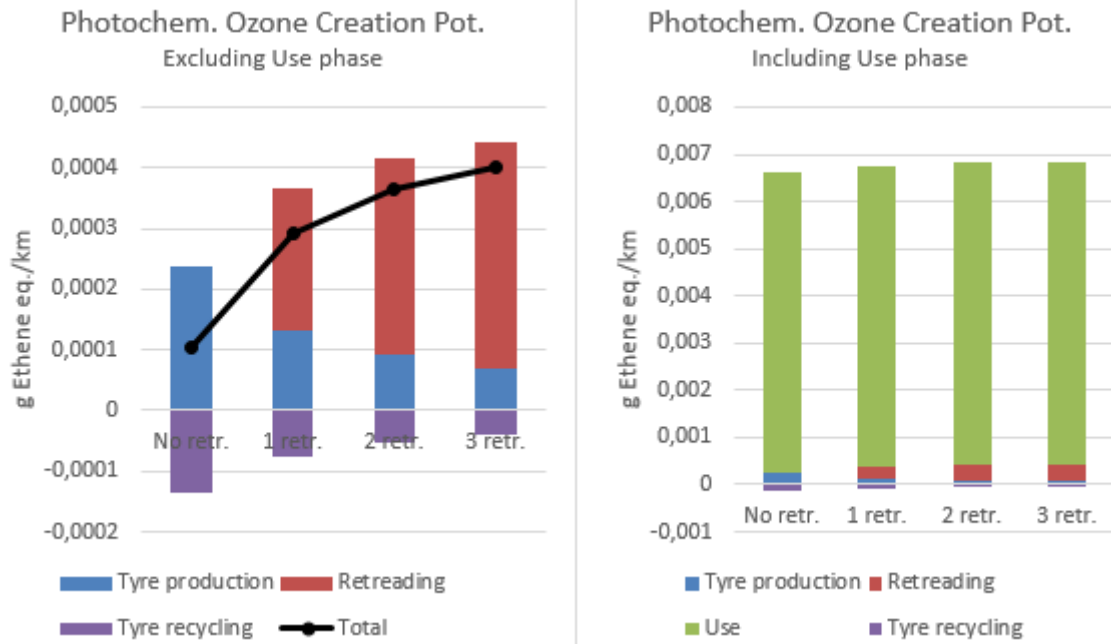
Figure 7: Photochemical Ozone Creation Potential per delivered kilometre for a tyre never retreaded and tyre cores retreaded one, two or three times.
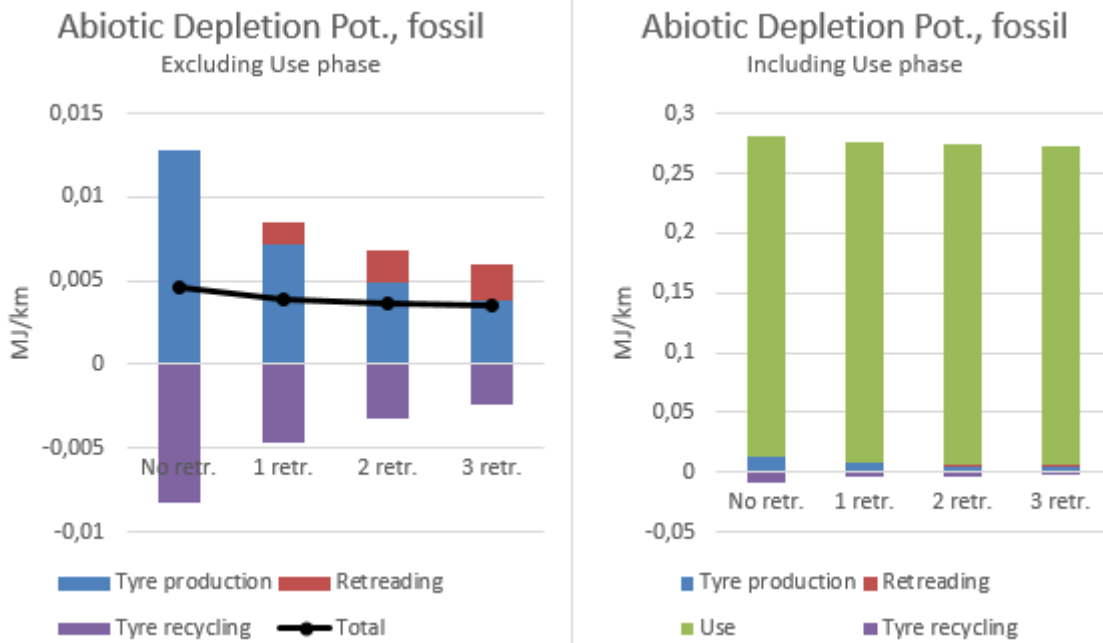

Figure 8: Abiotic Depletion Potential (fossil resources) per delivered kilometre for a tyre never retreaded and tyre cores retreaded one, two or three times.

For all impact categories except Photochemical Ozone Creation Potential there is a slight decrease in impact per delivered kilometre as the tyre is retreaded more times. For Photochemical Ozone Creation Potential there is an increase instead, because of the retreading. Almost all of this impact is caused by the modelled release of heptane from the rubber cement.

Sensitivity analysis: Increased fuel consumption for retreaded tyres

Figure 9 illustrates the case where retreading the tyres leads to a 10% increase in fuel consumption. The additional impacts from the extra fuel consumed becomes larger than the savings made by retreading the tyres.
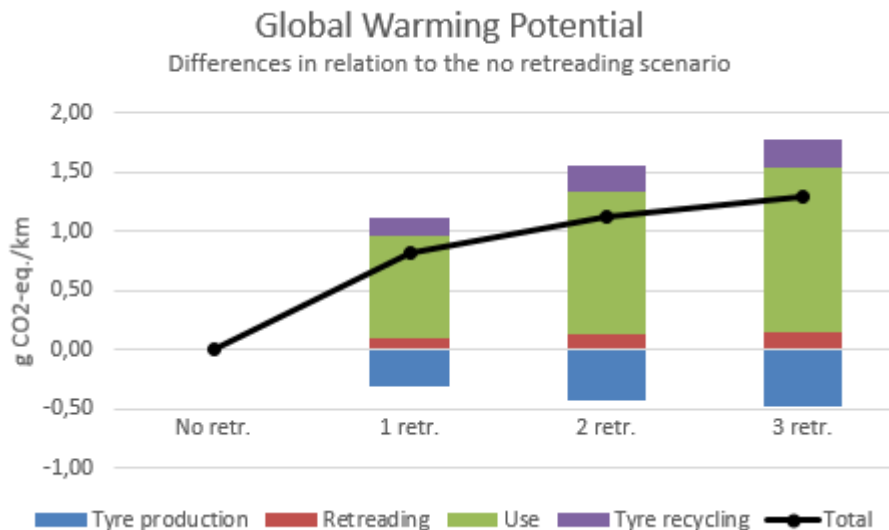

Figure 9: Differences in Global Warming Potential per delivered kilometre for a tyre core retreaded one, two or three times in relation a tyre never retreaded, assuming 10% increase in fuel consumption for retreaded tyres.

Even for only a 1% increase in fuel consumption the retreaded tyre cores would be associated with a higher GWP100 impact, assuming the fraction of fuel used to overcome the rolling resistance is 24%. If this fraction is set low (13%), it would require around 2% increase in fuel consumption for the additional impacts to balance out the savings from retreading the tyres.

Sensitivity analysis: Influence of vehicle combination and rolling resistance fraction on use phase

The type of vehicle combination and assumed fraction of fuel used to overcome the rolling resistance has a large influence on the resulting impact from the use phase, see Figure 10. The use phase impact becomes lower for tyres on a truck with trailer. This is because the fuel consumed (fuel consumption is actually higher) is allocated to 24 tyres instead of 10.
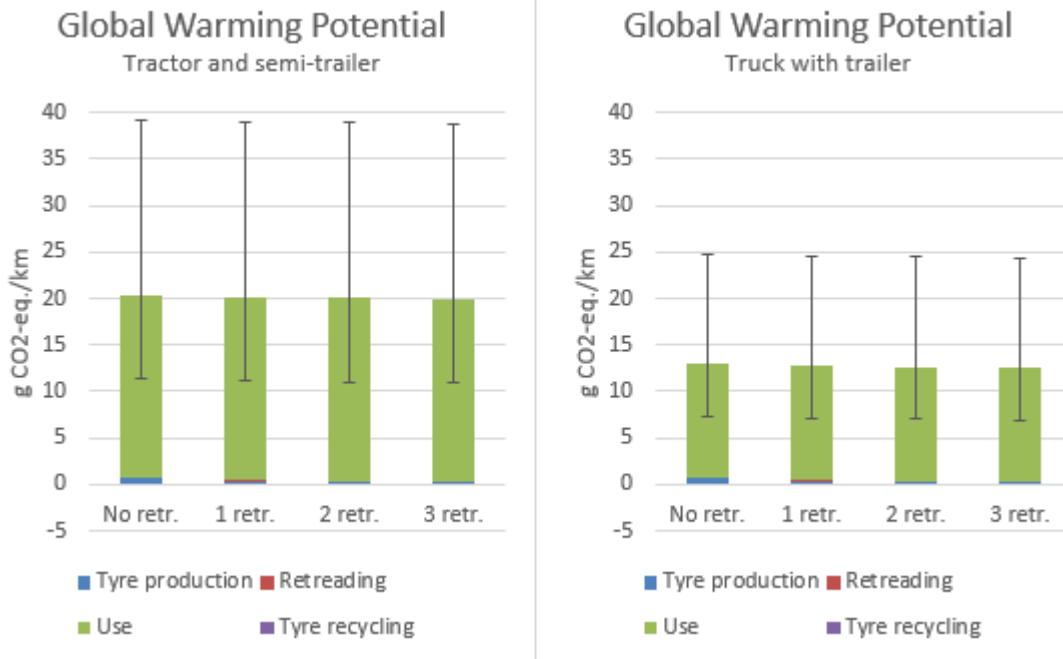
Figure 10: Global Warming Potential per delivered kilometre for a tractor and semi-trailer and a truck with trailer. The error bars represent variation of the fraction of fuel used to overcome the rolling resistance (min: 13%, average: 24%, max: 47%).

Sensitivity analysis: Influence of electrification

The use phase is very dominant when comparing the life cycle phases. An analysis was made to see how this change for a truck with an electric driveline. It is assumed that the electric truck would require the same amount of energy to overcome rolling resistance. The truck is using Swedish average grid mix (44 g CO2-eq./kWh). Figure 11 shows the result, the dominance of the use phase is now not that extreme as for the diesel trucks.

Figure 11: Global Warming Potential per delivered kilometre for an electrified truck.

Sensitivity analysis: Influence of recycling option and blasting mats recycling model

In the previous figures the tyre recycling result represented the average truck tyre recycling. How the tyre actually is recycled has an impact on the result, see Figure 12.
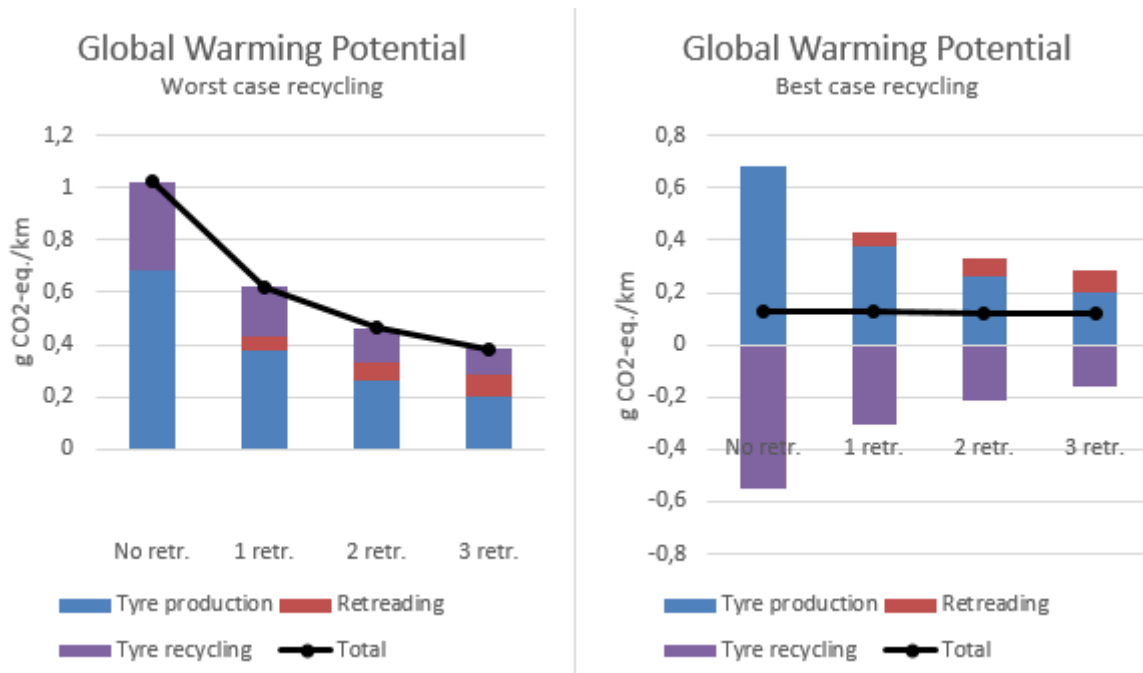

Figure 12: Global Warming Potential per delivered kilometre (use phase excluded). Worst case represents incineration in district heating plants (replacing biomass), best case incineration in cement kilns.

The assumption that blasting mats made from truck tyres replaces blasting mats from virgin materials also has an influence. Figure 13 represents the alternative assumption, that blasting is done without blasting mats if truck tyres are not used for this purpose, or that some other waste material is used instead. The benefit from retreading is now more obvious.

Global Warming Potential
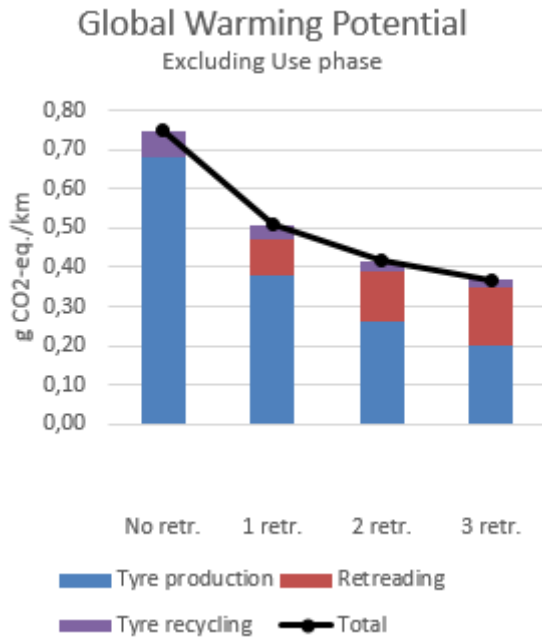### Excluding Use phase

Figure 13: Global Warming Potential per delivered kilometre, without credit for blasting mats replacing blasting mats made from virgin materials. To be compared against Figure 4.

Use of sensors

The charts in this section presents GWP100 results per delivered kilometre, now for an average scenario and a scenario where sensors are used to optimise tyre exchange and tyre pressure, see differences in Table 12. The results are also here valid for a tractor and semi-trailer, assuming no difference in fuel consumption between tyres made from virgin materials and retreaded ones and assuming the fraction of fuel used to overcome the rolling resistance to be 24%.

	Average	Optimal
Fuel consumption [l/100 km]	32	31,68
Driven distance, "virgin" tyre [km]	200 000	244 000
Driven distance, retreaded tyre [km]	160 000	195 200

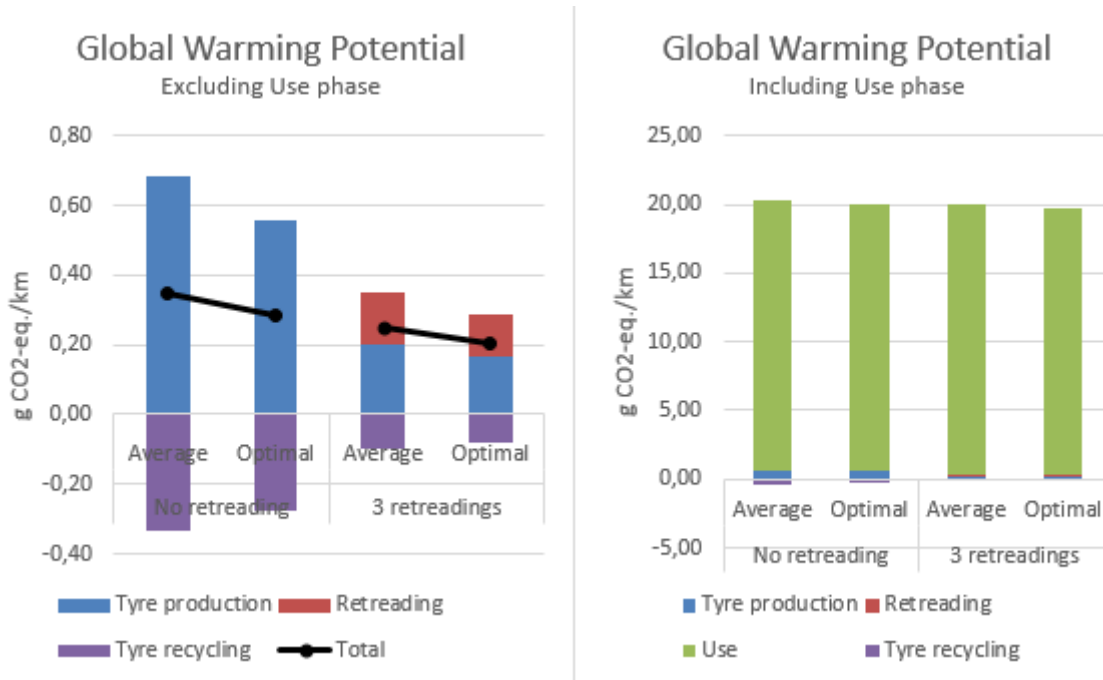**Table 12: Definitions of average and optimal scenario, when analyzing use of sensors.**

Figure 14: Global Warming Potential per delivered kilometre, average scenario vs. optimal scenario. The result is presented both for the case were no retreading takes place and when the tyre is maximally retreaded (3 times).

Breakdown of tyre production and retreading results

The charts in this section brakes down tyre production and retreading results into the different activities modelled. In Figure 15 it could be seen that the largest contribution of impact in tyre production is from production of the raw materials.
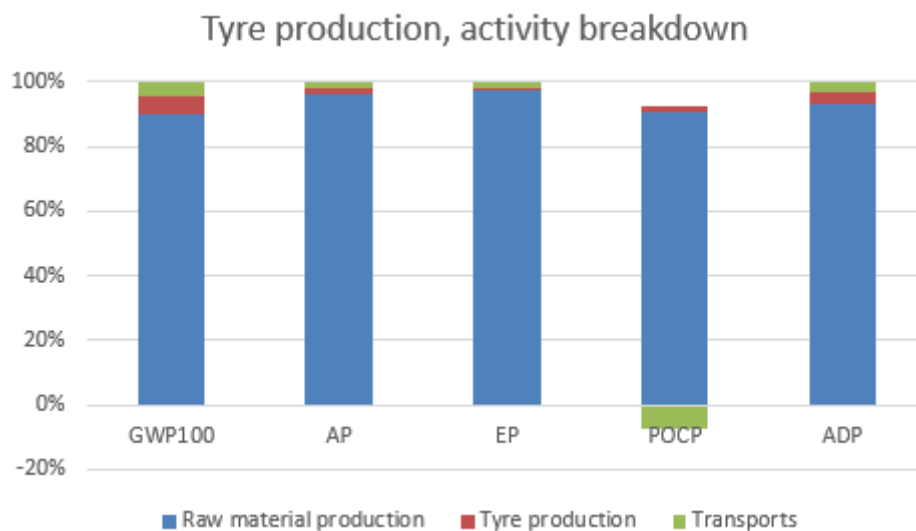

Figure 15: Tyre production results broken down into the different activities modelled.

Also for retreading the production of raw materials (for the tread) is dominant, see Figure 16. The exception here is POCP where the retreading activity itself is dominant due to modelled release of heptane from the rubber cement.

Figure 16: Retreading results broken down into the different activities modelled.

Recycling results

Figure 17 presents results from the tyre recycling model, where the different options are compared against each other. As explained earlier the results varies substantially depending on recycling option and comes with high uncertainties.

Figure 17: Global Warming Potential per tonnes tyres recycled for the recycling options modelled. Transports are not included for the blasting mats option as they are assumed balancing out each other in the calculations.

Discussion: Method considerations

As usual, a number of interesting challenges related to 'properly' representing the system with the LCA arose during the course of the project. One challenge was identified even before the project, how to model casca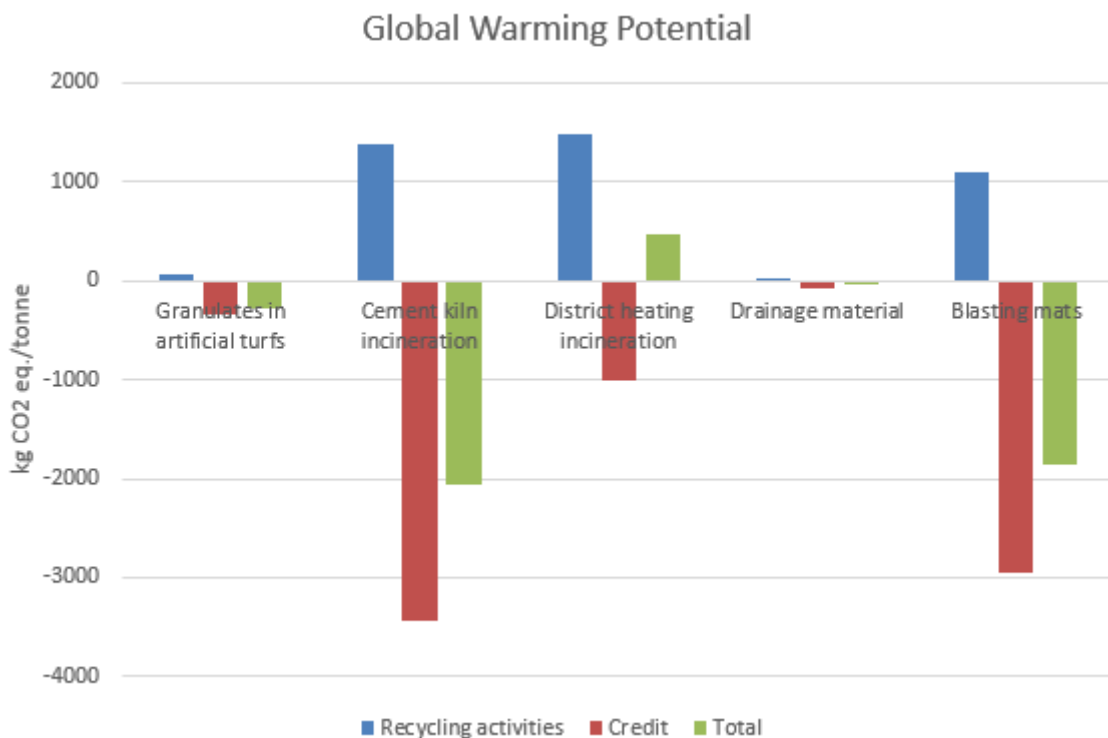ding use of retreaded tyres. Cascading refers to the reuse of a product in another use, and while it implies a downcycle, it can result in a upcycle (Sirken and ten Houten 1994, actually refer to upcycling as relinking).

Assessing product life cycles in which materials are shared is not new. It is, in fact, one of the most defining challenges of LCA. Peters 2016 highlights some implications of goal and scope definition and assesses how goal and scope of LCAs of remanufactured products leads to great differences in results. Specifically, system boundaries are perhaps the most defining decision.

Some other insights can be gathered from circular products in general. Guvendik (2014), under supervision of Guinée, applied LCA to assess circular product designs of a smartphone. Assuming that a circular smartphone would be used twice as long as the current smartphone with a refurbishment step half way and where end-of-use phones will be used to harvest still functioning parts to be used in the production of new phones, they apply a replacement chain method to calculate the environmental impact of using the phones over a period of six years. First, an estimation is made on the usage duration of the various components and parts and consequently how many components will be used in six years. Second, an estimation of the reusability of the components at their end-of-use is made. The reuse of components would mean that less components need to be produced as 'new' phones are assembled from a combination of new and reused parts. Third, the environmental impact is calculated of all components linked to the usage of the phone for 6 years.

McLaren et al 2000 emphasize that static, linear analyses usually conducted as part of LCA or MFAs may lead to false conclusions. This may be related to the applicability of LCAs for use at the system level. LCAs assess environmental impacts at the product-level, for a functional unit, and system-level affects, including rebound, can be difficult to include.

How cascading is to be handled in LCA is essentially, an allocation problem, which is, as always, dependent on system boundaries drawn. Difficulties depend on choice of functional unit and how well it fits with each use. For example, utilizing a FU of kilometer for use of a tyre first used on a long-haul truck and then on a fork lift could skew results as the amount of kms logged over time for a forklift is substantially less than that of a long-haul truck. Moreover, a forklift's primary function is not necessarily distance focused. Specifically, a second use in a forklift would not greatly reduce the amount of environmental impact per kilometer for that product system. In cases in which environmental impacts are to be allocated to different uses, such a FU (km) is, for the same reasons, is not 'fair'. The long-haul use would likely be allocated the large majority of the environmental impact (even if it were to be after the forklift use). Thus, for some cascades, basic availability (measured by time) or economic measure (cost as measure of value) may be appropriate functional unit as these measures could better represent the uses relative to each other, like done with economic allocation (Ardente & Cellura 2012).

Conclusions

Tire rolling resistance drives the majority of tire-related emission, that during the use phase. As such, substantial reductions in emissions from long-haul transport (and other types) could be made if the right tire pressure were to be maintained. Tire monitoring systems, such as tire pressure sensors, offer a solution. Nonetheless, retreading represents an opportunity to reduce emissions and tire material use and becomes more fruitful for an electrified fleet.

Repurposing of tire material in public spaces (such as playing fields) does represent less environmental impact than producing new material, and it appears to result in risk to human health that is comparable to other daily exposures (e.g. cosmetics, shampoo) and likely much less than exposures of tire particles that are released during use. However, studies on this question are limited and doubt remains.

Recycling of carbon black results in tangible environmental impact reductions for the input of carbon black, so from the tire producer's perspective, this source holds promise. Even incineration of tires is beneficial when compared with using other virgin petroleum-based inputs instead. In the end, the main challenge related to making the tire more truly sustainable is that its production depends on fossil fuels and it is embedded in today's fossil system.

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Data collection: Retreading

Reference unit:	The data should be collected based on a reference unit e.g. 1 year or per tonne of product output. Please state the re
Reference unit:	1 year (2016)

Enter the use of raw materials, energy etc. per reference unit.
Energy such as e.g. electricity, natural gas etc. Note that we need to know the fuel input and not energy in terms of "heat" or "steam" (internally produced from a fuel). If you use externally produced heat such as district heat this should be entered as well.
Apply the unit you prefer e.g. kWh, MJ, Nm3 etc.
Auxiliary materials are materials which are not part of the final product, but used in the production e.g. chemicals.
Emissions to air could either be from combustion of fuels or process specific.

	Unit	Retreading Amount [Unit/Year]	Data source	Modelled as (by IVL)
Materials/Products				
Slitbanor	T	245	Kontrollprogram för Galdax AB	Natural rubber: 47% Synthetic rubber (SBR): 12% Carbon black: 31% Organic chemicals: 10%
Rågummi/ovulkat gummi	T	25	Kontrollprogram för Galdax AB	Natural rubber: 61,98% Synthetic rubber: 15,07% Carbon black: 17,50% Zinc oxide: 1,25% Organic chemicals: 4,20%
Cement	T	4,24	Kontrollprogram för Galdax AB	Heptan
Gummi sealer	L	15,04	Galdax - Patrik Christensson	Organic chemicals
Vattenbaserad färg	L	2 400	Galdax - Patrik Christensson	Water based paint white
Water use				
Vatten	m3	263	Galdax - Patrik Christensson	
Energy use				
El	kWh	489 619	Galdax - Patrik Christensson	
Emissions				
AIR				
- Process specific emissions				
Ångor från utsug	T	3,56	Estimation based on Kontrollprogram för Galdax AB	
Waste				
Däckspån	T	192	Kontrollprogram för Galdax AB	
Production: Main product				
Regummerade däck	Antal	23 000	Galdax - Patrik Christensson	

Appendix 2 – Transport distances

Transports: Tyre production   **Transport 1**

Cargo	Weight	Origin	Destination	Est. distance [km]	GaBi dat set
Raw materials	63	Raw material production plants	Tyre production plant	500	TruckTrailer 34-40 t, MPL 27 t, Euro
Tyre	63	Tyre production plant	Truck production plant	1500	TruckTrailer 34-40 t, MPL 27 t, Euro
Transports: Retreading					
Raw materials, for tread	10,65	Raw material production plants	Tread production plant	500	TruckTrailer 34-40 t, MPL 27 t, Euro
Tread	10,65	Tread production plant	Retreading	1500	TruckTrailer 34-40 t, MPL 27 t, Euro
Raw materials, for non-vulcanized rubber	1,09	Raw material production plants	Rubber production plant	500	TruckTrailer 34-40 t, MPL 27 t, Euro
Non-vulcanized rubber	1,09	Rubber production plant	Retreading	1500	TruckTrailer 34-40 t, MPL 27 t, Euro
Other raw materials	0,29	Raw material production plants	Retreading	1500	TruckTrailer 34-40 t, MPL 27 t, Euro
Used tyre	53,55	Tyre workshop	Retreading	150	TruckTrailer 34-40 t, MPL 27 t, Euro
Retreaded tyre	63,00	Retreading	Tyre workshop	150	TruckTrailer 34-40 t, MPL 27 t, Euro
Tyre shreds	8,35	Retreading	Recycling facility	Used scaled Transports: Tyre recycling plan	
Transports: Tyre recycling					
Used tyre	53,55	Tyre workshop	Tyre shredding	150	TruckTrailer 34-40 t, MPL 27 t, Euro
Tyre shreds	16,07	Tyre shredding	Cement kiln	26	TruckTrailer 34-40 t, MPL 27 t, Euro
Tyre shreds	14,46	Tyre shredding	Distric heating plant	285	TruckTrailer 34-40 t, MPL 27 t, Euro
Tyre rubber granulate	16,60	Tyre shredding/granulation	Football fields	1000	TruckTrailer 34-40 t, MPL 27 t, Euro
Tyre shreds	2,14	Tyre shredding	Landfill	200	TruckTrailer 34-40 t, MPL 27 t, Euro
Transports, replaced materials					
Hard coal	13,23	Hard coal production plant	Cement kiln	3860	TruckTrailer 34-40 t, MPL 27 t, Euro
Petrol coke	3,84	Petrol coke production plant	Cement kiln	10058	Ship, bulk, ocean
Hard coal	3,97	Hard coal production plant	Distric heating plant	3860	TruckTrailer 34-40 t, MPL 27 t, Euro
Biomass	36,15	Biomass suppliers	Distric heating plant	254	TruckTrailer 34-40 t, MPL 27 t, Euro
Raw materials, for EPDM infill	18,22	Raw material production plants	EPDM infill production plant	500	TruckTrailer 34-40 t, MPL 27 t, Euro
EPDM infill	18,22	EPDM infill production plant	Football fields	1500	TruckTrailer 34-40 t, MPL 27 t, Euro
Crushed stone	5,36	Crushed stone production	Landfill	300	TruckTrailer 34-40 t, MPL 27 t, Euro