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► **To cite this version:**

Michael Saidani, Bernard Yannou, Yann Leroy, François Cluzel. Heavy vehicles on the road towards the circular economy: Analysis and comparison with the automotive industry. Resources, Conservation and Recycling, 2018, <10.1016/j.resconrec.2017.06.017>. <hal-01571577>

HAL Id: hal-01571577

<https://hal.science/hal-01571577v1>

Submitted on 2 Aug 2017

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HAL Authorization

Heavy Vehicles on the Road to the Circular Economy: Analysis and Comparison with the Automotive Industry

Submitted to: Resources, Conservation and Recycling, Special Issue on the Circular Economy, January 2017.

Word count: 14857 words including references and appendix, 11217 without references and appendix.

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Abstract:

With 270 million light vehicles and 20 million heavy-duty and off-road (HDOR) vehicles in use in the European Union, the automotive and HDOR industries form two major sectors of the European economy. Each year, 12 million light vehicles plus 1 million HDOR vehicles reach the end of their lives. In a circular economy perspective, the following two questions are of growing concern: (i) to what extent is the circular economy achieved and implemented in the automotive and HDOR sectors? (ii) what industrial practices and regulations are prevalent and commendable for the circular economy? The end-of-life management of light vehicles (subject to the ELV Directive 2000/53/EC) has been widely studied in the literature, but the end-of-life stage of HDOR vehicles has long been neglected by researchers. To fill this gap, both extensive literature survey and in-depth industrial investigations were conducted. Key factors, i.e. regulations, business models and market evolution, and integration of new emerging technologies affecting the circular economy performance of the automotive and HDOR sectors were analysed. Lessons learned from best industrial practices are highlighted, and remaining challenges for a more circular economy are identified. The two industries are compared in terms of the four building blocks of the circular economy and the four possible feedback loops defined by the Ellen MacArthur Foundation. This research contribution can lead on to practical applications, e.g. help industrial practitioners and policy makers take up the challenges and seize opportunities to close the loops for HDOR vehicles through different approaches.

Key words:

Circular Economy; Automotive; Heavy Vehicles; End-of-Life Management; CE strategies; CE implementation.

Highlights:

- In-depth study reveals huge potential to develop CE solutions in the heavy vehicles sector.
- Impacts of regulations, business models, and emerging technologies are analysed for CE performance.
- Best industrial practices and remaining challenges are examined for a CE of light and heavy vehicles.
- Streamlined, well-controlled dismantling, reuse and recycling are preferred options for the automotive industry.
- Uneven but growing remanufacturing and loosely controlled exports are preferred options for the HDOR industry.

1. INTRODUCTION AND BACKGROUND

Climate change, global warming, and the depletion of natural resources from anthropic root causes can no longer be contested, as highlighted in numerous Intergovernmental Panel on Climate Change reports (IPCC, 2014; IPCC, 2015). Thus optimal designs, uses and management of resources and systems are more than ever essential to protect human societies and ensure biodiversity. Furthermore, as reported by the McKinsey Commodity Price Index (MGI, 2013), resource prices have increased significantly since the turn of the 21st century. The dependence of industries on raw materials, such as precious or rare metals, presents highly strategic challenges for supply management. Besides shortages of metals and their supply challenges in Europe, the rise in global demand for raw materials has created extraordinary price volatility (Hagelüken et al., 2016).

For the automotive and heavy-duty and off-road (HDOR) vehicle industries, these added costs are increasing by several million euros from one year to the next (ACEA, 2015). With 270 million light vehicles (passenger cars and light commercial vehicles) and 20 million HDOR vehicles in use in Europe (ICCT, 2016), the automotive and HDOR sectors are two industrial giants in Europe. Their ever-growing economic and environmental footprints are uncontested: the turnover generated by the automotive sector represents 6.5% of the European Union (EU) gross domestic product, and more than 12 million people are employed in the sector (ACEA, 2016). Being able to forestall shortages and secure supplies of raw materials is of the utmost importance for manufacturers (Sievers and Tercero, 2012). Equally, the geopolitical issues around raw materials and resource efficiency are being

64 integrated at the EU level (EC, 2010; EC, 2011; EC, 2014a; EC, 2015). Some 12 million light vehicles
65 plus 1 million heavy vehicles are taken off the roads every year in the EU, which amounts to millions
66 of tonnes of what actually constitute valuable resources (EMF, 2013a; Weiland, 2014): automotive
67 and HDOR manufacturers thus have a direct interest in more sustainable management of their
68 products, components and materials in order to stay competitive in the face of price rises and volatility.

69 To support both economic growth and sustainable resource management, the circular
70 economy (CE) paradigm offers rich opportunities for industrial practitioners: the promises and benefits
71 expected from circular practices have been comprehensively discussed in the literature (EMF, 2013b;
72 CIRAIG, 2015; MGI, 2015; Lacy, 2015; Ghisellini et al., 2016). CE is viewed as a restorative solution
73 with the potential to eliminate waste (EC, 2015a; EEA, 2015, EEA, 2016); it can also both secure
74 Europe's competitiveness and ensure benefits through the three pillars of sustainable development
75 (Banaité, 2016; Sauvé et al., 2016; Geissdoerfer et al., 2017). In particular, the use of closed-loop
76 approaches mitigates manufacturers' dependency on virgin materials, and attenuates price volatility
77 (Kiser, 2016). Even so, some industrial fields still need help in their transition from a linear to a more
78 circular economy: companies may lack capacity, information, indicators and targets to move toward
79 CE solutions (EASAC, 2016). To date, much more attention has been paid to end-of-life management
80 in the automotive sector than in the HDOR sector.

81
82 End-of-life (EoL) management and recycling issues for cars, i.e. in the automotive sector,
83 have been extensively studied in the literature in the last two decades from different perspectives
84 (Tukker and Cohen, 2004; Wells and Orsato, 2005; Reuter et al., 2006; Froelich et al., 2007;
85 Chemineau, 2011; Millet et al., 2012; Farel et al., 2013; Yi and Park, 2015; El Halabi, 2015; Despeisse
86 et al., 2015; Simic, 2015; Idjis et al., 2017). By contrast, there is a current paucity of studies on waste
87 minimisation and EoL for HDOR vehicles, which seems principally due to the absence of EoL
88 regulations and extended producer responsibilities. Most of the research on HDOR vehicles has
89 focused on the design and use phase of heavy vehicles. This approach is justified, since some 80%
90 of the total environmental impact throughout the entire life cycle of vehicles, light or heavy, is
91 generated during the use phase (Hill et al., 2012; Manitou Group, 2016). Current US and EU
92 improvement road maps related to HDOR vehicles barely address the EoL value chain of HDOR
93 vehicles, and instead emphasise optimising the design and use phases (ERTRAC, 2012; USDoE,
94 2013; Poulikakos et al., 2013): research work focuses mainly on saving fuel during the use phase
95 (Walnum and Simonsen, 2015), mitigating emissions (ERTRAC, 2012), and integrating lightweight
96 materials (USDoE, 2013).

97 The EoL management of HDOR vehicles is nonetheless an important issue for research and
98 industry, whose readiness to identify unexploited or wasted opportunities is a prerequisite for further
99 progress. The preliminary field diagnosis that prompted and steered our research in the HDOR sector,
100 in a CE perspective, identified the following two drivers:

- 101 – Tonnage of EoL HDOR vehicles is of the same order of magnitude as that of EoL ELVs in Europe.
102 This tonnage is around 1 million tons in France (ADEME, 2006). Hence the economic, environmental
103 and social stakes in the HDOR industry are potentially at least as high as in the automotive industry,
104 and so constitute a significant area for job creation and improvement, of importance to both public
105 policy makers and industrial practitioners;
- 106 – Lack of current regulations for the EoL of HDOR vehicles comparable to the ELV Directive
107 2000/53/EC in force, should urge watchful industrial practitioners to plan ahead for likely future or
108 emerging regulations.

109 On this basis, the HDOR sector can be meaningfully positioned in a move towards CE. This
110 paper offers a comprehensive overview of the situation and progress of the HDOR industry in Europe
111 in a CE perspective. It reports on existing initiatives and incentives from the HDOR industry in line
112 with CE principles. In particular, it highlights emerging approaches, such as new integrated
113 technologies or innovative business models in their contributions and impacts in CE. The situation
114 and progress of the automotive industry will also be examined as a benchmark to learn from best
115 practices. Based on both an in-depth literature review through different types of resources,
116 e.g. academic papers, industrial, government and consulting reports, company websites, and
117 investigations in the industrial field, key insights and answers to the following questions will be
118 presented:

- 119 – To what degree is CE achieved and implemented in the automotive and HDOR sectors?
- 120 – What CE-compatible practices already exist for these sectors?
- 121 – How do existing policy frameworks foster the move towards CE?

122 In what follows, these questions are studied with reference to the four building block CE model
 123 defined by the Ellen MacArthur Foundation (EMF, 2013b).

124
 125 This paper is organised as follows. Section 2.1 defines the terms and boundaries of the study.
 126 Section 2.2 describes the research methodology and investigations undertaken to obtain a
 127 comprehensive view of the automotive and HDOR sectors in a CE perspective. Section 2.3 details
 128 comparison criteria to evaluate the automotive and HDOR industries with regard to CE. In Section 3,
 129 several key factors affecting the CE performance of both the automotive and the HDOR sectors are
 130 analysed. Relevant insights from industrial companies are also presented. In particular, the end of
 131 Section 3 reviews best practices and remaining challenges in these two sectors in their movement
 132 towards an efficient and effective CE. Finally, Section 4 points to relevant research perspectives for
 133 further work to support a shift from a linear to a more circular economy in the automotive and HDOR
 134 industries.

135
 136 **2. MATERIAL AND METHODS**




137 **2.1. DEFINITIONS, SCOPE AND BOUNDARIES OF THE STUDY**

138 **2.1.1. Distinction between light (automotive sector) and heavy (HDOR sector) vehicles**

139 The automotive sector encompasses motor road vehicles weighing less than 3.5 tons and is
 140 covered by the ELV Directive 2000/53/EC in Europe. Less simply, heavy-duty and off-road (HDOR)
 141 vehicles are composed of two categories, namely heavy-duty vehicles (HDVs), mainly trucks, and
 142 non-road mobile machinery (NRMM), mainly agricultural and construction machinery (EC and ERN,
 143 2015). HDV classifications are typically based on the maximum loaded weight of the truck, typically
 144 using the gross vehicle weight rating (GVWR), and they vary by geographical location; for instance
 145 US and EU classifications are different. GVWR is defined as the maximum allowable total weight of a
 146 road vehicle or trailer that is loaded, including the weight of the vehicle. The UK Vehicle Type Approval
 147 Agency calls NRMM any mobile machine, or item of transportable industrial equipment not intended
 148 for carrying passengers or goods on the road, and powered by a combustion engine (DfT, 2016). In
 149 the grey literature HDVs and NRMM are usually brought together under the term HDOR, because of
 150 their similar regulations, emissions, materials, mass, and components: HDOR = HDV + NRMM.

151
 152 The HDOR industry includes firms that manufacture and remanufacture components or parts
 153 of off-highway equipment generally used in the construction, farming, mining, and oil and gas drilling
 154 industries. HDOR equipment is therefore much more diverse than vehicles in the automotive sector:
 155 in contrast to light vehicles, the HDV sector covers all types of trucks weighing more than 3.5 tons,
 156 while the NRMM sector covers a very broad range of machinery, including construction machinery
 157 (e.g. excavators, compactors, loaders, dumpers, bulldozers and mobile cranes), and agricultural and
 158 farming machinery (e.g. harvesters and cultivators). Common and specific features of automotive and
 159 HDOR sectors are summarised in Table 1.

160
 161 Table 1 – Definitions and features of automotive and HDOR sectors

	Automotive sector	Heavy-Duty and Off-Road (HDOR) sector	
Sub-category	Light Vehicles 	Heavy-Duty Vehicles (HDVs) 	Non-Road Mobile Machinery (NRMM) 
Definition	Road vehicles weighing less than 3.5 tons (Directive 2000/53/EC).	Nominally defined as vehicles weighing more than 3.5 metric tons (UNECE, 2016).	Mobile machines not intended for carrying passengers or goods on the road, and powered by a combustion engine (DfT, 2016).

Examples	Passenger cars & commercial-light vehicles.	Trucks, buses.	Tractors, excavators.
Applications, markets, usage.	Mainly private individuals for daily use. Mainly BtoC (business to consumer).	Mainly used for commercial purposes, notably for freight (ICCT, 2015). Mainly BtoB (business to business).	Agriculture, construction, mining and forestry. Mainly BtoB (business to business).
Final owners	Private individuals, garages, insurers.	Transport and freight companies.	Civil engineering, mining and rental companies.
Major constructors	Toyota, Volkswagen, Renault.	Volvo Truck, MAN, Daimler, Scania, DAF.	Caterpillar, Komatsu, Volvo CE, John Deere, Liebherr, JCB.
Main figures	270 million light vehicles in use in Europe (ICCT 2016).	7 million trucks and trailers (from 3.6 to 40 tons) in use in Europe (ICCT, 2016).	10 million agriculture tractors, 2 million off-road, construction and mining vehicles in use in Europe (Weiland, 2014).
	12 million ELV in Europe each year (EMF, 2013a)	Around 1 million EoL HDOR units in Europe each year (Weiland, 2014).	

162 2.1.2. Geographical scope

163 The geographical scope of the study is limited to the EU (28 Member States) for the following
 164 reasons: (i) automotive and HDOR markets are large in the EU, (ii) EU environmental regulations are
 165 among the most stringent in the world, offering a gold standard for other countries, which are usually
 166 moving towards what is current in the EU in terms of regulations, (iii) the authors of the present paper
 167 are located in France, and the stakeholders interviewed were mostly based in Europe. Thus the
 168 European situation could be expected to provide a sound basis for gaining an understanding of the
 169 position and issues of the automotive and HDOR sectors in a CE perspective.

170 2.2. RESEARCH METHODOLOGY


171 To cover the automotive and HDOR industries broadly and conduct an extensive research
 172 study throughout the whole value chain, from a multi-actor viewpoint in a CE perspective, a multi-
 173 method research approach (Creswell, 2003) was implemented. Creswell and Plano Clark (2007)
 174 define multi-method research as combined-method study in which a researcher uses multiple methods
 175 of data collection and analysis. Mixed-method research offers several advantages: (i) triangulation,
 176 i.e. seeking convergence of findings, (ii) complementarity, i.e. overlapping different facets of an issue,
 177 and (iii) development potential, i.e. the first method is used sequentially as input to the second method
 178 (Clarke, 2005). Here, two main types of research were used: desk-based and field-based.










179 Our desk-based research comprised a literature review, library research, database research
 180 and online research using key words. Diversifying the sources was essential here, because the main
 181 information and data concerning the EoL of HDOR vehicles cannot be obtained via the scant
 182 academic literature published on the subject: much relevant information was thus gathered through
 183 industrial, government and consulting agency reports, and from the internet websites of HDOR actors.

184 Our field-based research was through direct contact with the industrial reality through a 5-
 185 month internship at a major NRMM manufacturer, surveys, face-to-face meetings, telephone
 186 interviews, and attendance at workshops and conferences related to the subject. Field-based
 187 research was essential in this study because state-of-the-art information is owned by industrial
 188 companies: meetings or teleconference interviews with diverse stakeholders linked to HDOR vehicles
 189 were useful not only to confirm, validate or challenge the information found in the literature, but also
 190 to collect new complementary information, data, and expert impressions or opinions, and find out
 191 more about existing collaborations between actors that could not have been gleaned from reports.

192 A detailed description of the multi-method research approach, including the variety of
 193 resources used for data collection, is given in Table 2.

194
 195 Table 2 – Description of the resources used in the multi-method research

Resources used		Description, details & contributions
Desk-based research	Field-based research	
Research papers		The following databases were used, some academic some not: Science Direct, Web of Science, Scopus, Springer, Taylor & Francis, Google Scholar and Google. Keywords included combinations and variations of terms such as: vehicle, heavy-duty, off-road, end-of-life, recycling, reuse, remanufacturing, dismantling, disassembly, circular economy, circular

		business model, circular product design, telematics, regulation, etc. While the end-of-life management and impacts of cars have been widely investigated and reviewed by scholars, e.g. around 100 peer-reviewed journal articles on ELV recycling published between 2003 and 2013 (Simic, 2013), the end-of-life of heavy vehicles has seldom been addressed.
Reports		Grey literature, such as reports and technical watches from government and specialised agencies, private companies and consultants were also reviewed, notably to make up for the paucity of information about HDOR vehicles end-of-life and circular economy practices and implementation in the academic literature. For instance, annual reports from major HDOR equipment manufacturers (e.g. Volvo Group Sustainability Report 2015) contain much relevant information on actual progress towards the circular economy.
Regulations		European regulations concerning automotive and HDOR sectors and related, directly or indirectly, to the circular economy were reviewed. EU regulations were available at: http://eur-lex.europa.eu . Reports from the European Commission assessing the impact of certain regulations were also reviewed.
Websites		Major constructors' and manufacturers' websites were systematically reviewed for remanufacturing, telematics, sustainability and the circular economy. Online interviews with managers and videos about end-of-life processing were also analysed to capture additional information.
Databases		Information and statistics available on the Eurostat database website were scanned to obtain an overview of the numbers of HDOR vehicles in Europe, and their relative weighting compared with cars: http://ec.europa.eu/eurostat/fr/data/database .
	Internship	A research internship was carried out at one of the major industrial manufacturers of NRMM and spare parts in Europe. During the 5-month internship, managers from different departments were met to discuss the situation and action of the company on the road to the circular economy.
 	Interviews: – in person during planned meetings; – by audio.	Interviews with field experts were conducted at different stages of the study to confront desk-based research with industrial reality. The interviews were conducted through a semi-structured questionnaire. A generic questionnaire adaptable to the interviewee was designed: it is given in Appendix A, along with the list of HDOR experts encountered. Each consulted expert was systematically asked about their circular practices. These interviews thus yielded indications of enablers and barriers for improved end-of-life management and circular practices in the HDOR sector.
	Site visits	A visit to an NRMM rental company was made. The director manager was met, and gave his strategic view in a circular economy perspective. The NRMM storage warehouse was also visited.
	Thematic day: conference and workshop	Attendance at an annual academic-industrial meeting on the responsibilities of actors for end-of-life vehicles. Discussions were also extended to heavy vehicle end-of-life at a round table.

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197 2.3. CRITERIA TO COMPARE AUTOMOTIVE AND HDOR SECTORS THROUGH THE LENS 198 OF THE CIRCULAR ECONOMY

199 To analyse the situation of both the automotive and the HDOR sectors in a CE perspective, two
200 complementary approaches were used. First, as there are several ways to close the loop (cf. Lansink's
201 waste hierarchy ladder developed in 1979) (Parto et al., 2007; Recycling, 2016), the different
202 pathways that help close the loops are used as criteria for comparison. The four possible feedback
203 loops in the circular economy butterfly diagram proposed by the Ellen MacArthur Foundation (EMF,
204 2013b), were scrutinised, namely: (i) maintain or prolong, (ii) reuse, (iii) remanufacture or refurbish,
205 and (iv) recycle.

206 Additionally, to complete this focus on EoL loops and encompass the CE paradigm more
207 broadly, current situations and practices in the automotive and HDOR sectors were also analysed in
208 terms of the CE building blocks defined by the EMF (2013b). The shift toward a more circular economy
209 involves four fundamental building blocks, namely: (i) circular product design, (ii) new business
210 models, (iii) reverse networks, and (iv) enablers and favourable system conditions. These comparison
211 criteria were selected not only to ensure a systemic analysis of the CE concept applied to these two
212 industrial sectors, but also because the CE model proposed by the EMF is one of the best known and
213 most widely shared and acknowledged visions of CE among academics and industrial practitioners.

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In the following section, current EoL practices (sub-section 3.1), regulations (sub-section 3.2), business model evolution (sub-section 3.3), and promises and challenges of emerging technologies (sub-section 3.4) are used as comparison factors to set in parallel the situations and progress of the automotive and HDOR sectors on the road to CE. Insights from industrial practitioners (e.g. manufacturers) are also given to illustrate business strategies contributing to CE, and practical difficulties that still have to be overcome in a CE perspective. Finally, best practices and remaining challenges from both the automotive and the HDOR industries are summarised at the end of Section 3 for the four CE feedback loops and the four CE building blocks as described above (EMF, 2013b).

3. RESULTS

3.1. CURRENT END-OF-LIFE SITUATIONS

The contributions of reuse, remanufacturing, recycling and export were studied in both industries. As explained in detail below, whereas the EoL processing of the automotive sector is increasingly well-organised and fully formalised in the EU, the EoL management of HDOR vehicles is more disparate, less well-developed and poorly controlled.

3.1.1. Preferred end-of-life options and circular practices for the automotive industry

Social, economic, and environmental aspects in the development of an industrial ecology of the automotive sector have been widely discussed in the literature (Tukker and Cohen, 2004; Wells and Orsato, 2005). Likewise, the EoL management of the automotive sector has benefited from much academic research and industrial breakthroughs over the entire EoL value chain: collection and allocation (Chemineau, 2011; Simic, 2015), reuse, remanufacture of components, or recycling of materials (Reuter et al., 2006; Froelich et al., 2007; Millet et al. 2012; Indra, 2016), and dismantling (El Halabi et al., 2015; IDIS, 2016).

Diener and Tillman (2016) give a concise overview of current vehicle EoL management, showing that (i) component reuse (with or without remanufacturing) and materials recycling are prevalent in the automotive sector, (ii) such EoL management of vehicles leads to economic savings and environmental benefits, and (iii) integration of both new technologies, e.g. connected devices with numerous electrical components, and new materials to reduce vehicle weight are creating new challenges to EoL recycling; as a consequence, not only the integration of new technologies in recycling centres such as the Internet of Things (IoT) and connected devices (Yi and Park, 2015), but also recycling issues for new hybrid vehicles including lithium-ion batteries (Idjis et al., 2017) are now being studied.

In the case of Sweden, studied by Diener and Tillman (2016), an estimated 7% of total cars out of use are exported or left to rust; 2% of cars out of use go directly to material handling facilities, where in line with Directive 2000/53/EC they are prepared for shredding, hazardous materials removal and depollution. The remaining cars (91% of cars out of use) go to dismantlers to recover components and materials for reuse and recycling.

Overall, EoL in the automotive sector, driven by EoL vehicle (ELV) regulations, described in sub-section 3.2., is increasingly controlled, organised and streamlined. Spare parts reuse and recycling of materials are the preferred EoL options and circular practices for the automotive industry. The ELV dismantling procedure is properly established and mastered by automotive recycling centres, as shown in Figure 1. Out of the 12 million vehicles taken off the roads in Europe each year (EMF, 2013a), 7–8 million tons of EoL vehicles are properly handled in Europe at authorised treatment facilities (ATFs) (EC, 2016b). According to experts from ADEME (French environmental agency) and INDRA (precursor and leading player in vehicle recycling in France), around 10% of vehicle mass is removed in a depollution phase (oils, fluids, chemicals, batteries, airbags), and another 10% of vehicle mass is removed on dismantling spare parts (outer and inner parts of high value or with a reuse potential, plus transmission system parts). This step is crucial, since the resale of spare parts is the main source of income for recycling companies (INDRA, 2016a). However, as automotive spare parts are less costly than HDOR ones, remanufacturing is often unprofitable and is therefore less well-developed for light vehicle components. The remaining 80% of vehicle mass is finally sent to shredder and smelting facilities to recycle materials so as to meet mandatory standards.

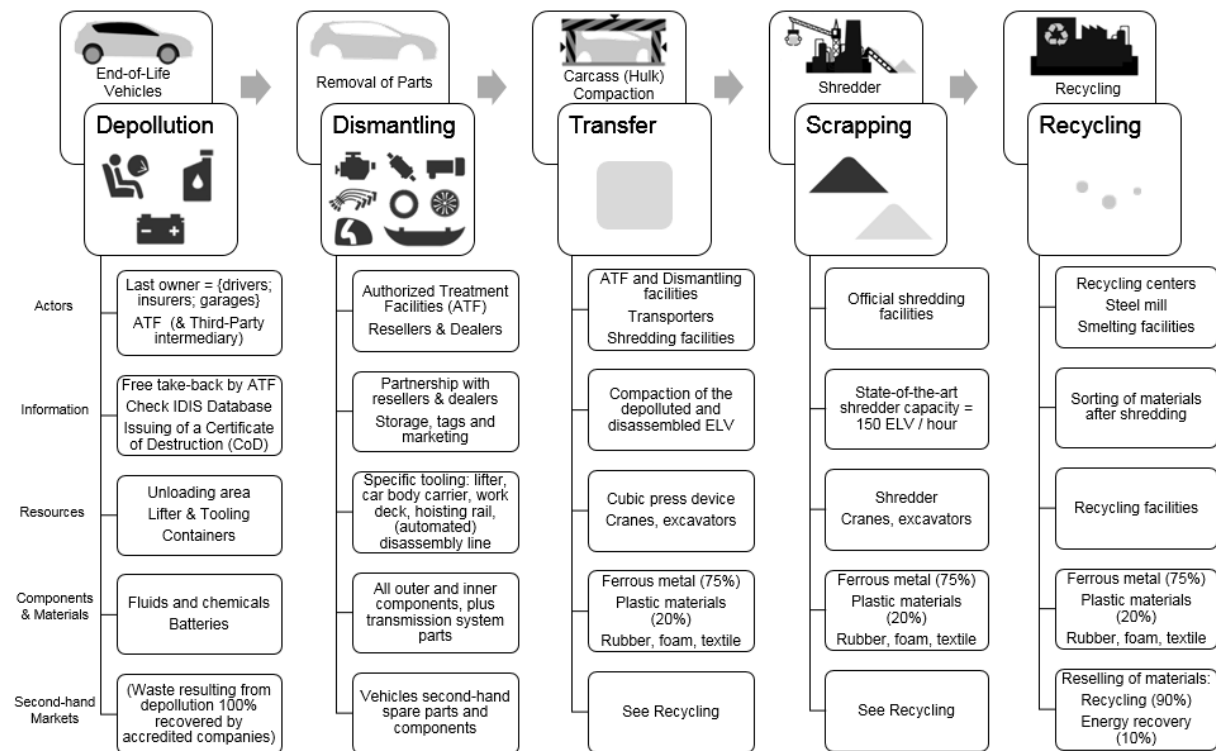


Figure 1 – End-of-life vehicle processing for the automotive sector, based on Toyota (2016) plus additional sources of information (INDRA, 2016a; Directive 2000/EC/53) and consulted experts

3.1.2. Preferred end-of-life options and circular practices for the HDOR industry

Dismantling and recycling of EoL HDOR vehicles is still a minority market outlet compared with resale and export. The export and resale of HDOR vehicles is currently commercially viable. However, this channel does not deal satisfactorily with the ultimate EoL of these heavy vehicles. According to the interviews carried out and knowledge gained in the 5-month internship, the environmental awareness of actors in this sector seems low. Furthermore, there are no specific EoL treatment facilities dedicated to heavy vehicles, unlike light vehicles (ADEME, 2006). Cetim (2014) performed a technological watch on the EoL and dismantling channels for heavy vehicles in France and in Europe (Western and Central Europe): some CE loops for HDOR vehicles, such as remanufacturing, refurbishing and reuse, are operating well, HDOR components being mainly refurbished by remanufacturing processes to give HDOR vehicles a second life. However, these overhauled HDOR vehicles are then exported to developing countries that do not have the means to dismantle and recycle heavy vehicles properly at the end of their lifespans.

The EoL management of HDOR vehicles is still a marginal and poorly structured activity in Europe. Recycling HDOR vehicles is often voluntary and not fostered by recycling targets or extended producer responsibility. To illustrate this point, according to the Center for Remanufacturing and Reuse (Walsh, 2013) in the UK, out of all heavy vehicles reaching their EoL, 50% are reused or resold in other countries after major refurbishment, 43% are remanufactured to extend their lifespan in the UK, and 7% are dismantled and recycled in the UK. In Sweden, approximately 50% of trucks were estimated to be exported after 5 years of domestic use (Diener and Tillman, 2016). Likewise, according to a director of an NRMM rental company, brand new NRMM is usually resold after five years of use to an intermediary actor who exports it to Eastern Europe and North Africa. This is because clients prefer to rent HDOR vehicles in mint condition, and after five years in use the original manufacturer warranty has often expired.

Additionally, as reported by an expert at CIDER Engineering, the number of non-authorized infrastructures handling EoL HDOR vehicles is still too high. Moreover, even in the most developed European countries, current EoL treatment of HDOR is not satisfactory as regards safety, economic, environmental, and technical aspects. In this light, according to CIDER Engineering, true CE needs the optimisation of dismantling processes and the reintroduction on the market of not only components and spare parts, but also materials derived from a well-established recovery procedure.

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To explain the marked difference observed between the two sectors, we review key factors impacting their EoL management: regulations, market and business model evolution, and new and emerging technologies.

306 **3.2. IMPACTS OF EXISTING REGULATIONS**

307 End-of-life in the automotive sector is subject to a set of regulations. By contrast, to date there
308 are no overall EoL regulations for the HDOR industries. HDOR vehicles are presently concerned only
309 by cross-sector regulations, such as those for EoL tyres and oil depollution. A concise overview of the
310 regulations related, directly or indirectly, to CE and applied to the automotive and HDOR sectors is
311 given in Table 3.

312
313 Table 3 – Regulations applied to automotive and HDOR sectors and relevant to the circular economy

Regulation type	Automotive sector	HDOR sector
End-of-life regulations (mandatory recycling and/or recovery targets)	Yes: Directive on ELV 2000/53/EC; Directive 2008/33/EC (amendment).	None
Extended Producer Responsibility	Yes, included in the ELV Directive	None for the whole HDOR vehicle
Emissions regulations	Euro 6b for light vehicles	Euro 6 for HDVs; Stage IV for NRMM.
Cross-sector regulatory frameworks for both automotive and HDOR vehicles and components	Extended Producer Responsibility (EPR) for, tyres, oils, batteries and electrical and electronic equipment (EEE); Directive 2002/96/EC WEEE (Waste Electrical & Electronic Equipment); Regulation (EC) No 1907/2006 REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals); Directive 2008/35/EC RoHS (Restriction of Hazardous Substances).	
Additional, complementary or other policy frameworks linked, directly or indirectly, to the circular economy	Directive 2005/64/EC (on the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability); Directive 2002/151/EC (certification of destruction for ELV handling); Directive 2003/138/EC (components and materials coding standard for vehicles); Directive 2005/293/EC (detailed rules for monitoring compliance with the ELV Directive targets).	None

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In the automotive sector, European Directive 2000/53/EC aims to reduce waste from EoL vehicles. The scope of this directive is limited to passenger cars and light commercial vehicles up to nine seats and up to a total weight of 3.5 tons. The directive sets targets for reuse, recycling, and recovery. Since January 2015, these have been a minimum 85% reuse and recycling rate and a minimum 95% reuse and recovery rate for each vehicle. The directive includes Extended Producer Responsibility (EPR), which involves different actors and involves the following mechanisms:

- 321 – Free take-back of EoL vehicles (ELVs) and used tyres since January 2007;
- 322 – Producer obligation for providing not only take-back of ELVs through accessible networks of
323 authorised treatment facilities (ATFs) and collection points, but also dismantling information for new
324 vehicles within six months of their being placed on the market;
- 325 – Database for the automotive sector: International Dismantling Information System (IDIS);
- 326 – Public Responsibility: the registered owner of a vehicle who wants to discard it as waste is required
327 to bring it to an ATF for appropriate treatment and recovery;
- 328 – Certificates of Destruction: since January 2007, when an EoL vehicle is deposited at an ATF, the
329 operator of that facility shall issue a certificate of destruction to the registered owner.

330
331 Idjis et al. (2013, 2017) see this legislation as pushing for more cooperation between the
332 actors of the automotive sector, such as original equipment manufacturers (OEMs), authorised
333 treatment facilities, end users, and other EoL third parties. The effectiveness, relevance, strengths
334 and weaknesses of the ELV Directive (2000/53/EC) have been discussed by the European

335 Commission (EC, 2014b), and one conclusion drawn is that the various environmental and economic
336 benefits of the ELV Directive outweigh the costs of its implementation: the costs of complying with the
337 Directive are estimated by the industry to be significant, e.g. for car manufacturers to remove
338 hazardous substances, or for recyclers to develop the technologies necessary to meet the targets,
339 but they are outweighed by the profits gained from the sales of recycled parts. However, two major
340 challenges remain. First, the collection and treatment of ELVs by illegal operators and the illegal
341 shipment of ELVs are still flourishing businesses: increasing co-operation among European Union
342 member states is therefore needed to ensure tracking and follow-up of de-registered and exported
343 vehicles. Second, a new issue has appeared: the introduction of complex electronic systems and
344 composite materials in modern vehicles poses significant technological challenges for maintaining the
345 overall reuse, recycling, and recovery rates of ELVs. The ACEA (2015) likewise acknowledges that
346 the ELV Directive has proven highly effective in reducing discard of waste from vehicles, increasing
347 reuse, recycling and recovery, and ensuring that ELVs are treated in an environmentally sound way.

348 Meanwhile, in the HDOR sector, except for legal necessities such as REACH and RoHS,
349 emissions regulations (Euro 6 in Europe for HDVs and Stage IV for NRMM) and cross-sector
350 regulatory frameworks (EPR on tyres, oils and batteries), as detailed in Table 3, there are no
351 regulations or directives that compel the HDOR industry to apply more sustainable management of
352 vehicle EoL. In Europe, there are some 20 million HDOR vehicles in use that are not subject to overall
353 EoL regulations (Weiland, 2014). According to an expert from ADEME (French environmental
354 agency), although a possible extension of the ELV Directive (2000/53/EC) to EoL HDOR vehicles was
355 mooted by Spanish representatives at the European Commission in Brussels in 2014, no new
356 European legislation concerning HDOR vehicles is expected in the short term. In the absence of any
357 regulation in the HDOR industry, the HDOR manufacturers are not asked to deal with the retired fleet.
358 Motivation of manufacturers to participate in EoL HDOR projects, and in circular practices, has to be
359 sought elsewhere, for example in the residual value of EoL HDOR vehicles, or in the reuse or recovery
360 of key components and materials for second-hand products that require less primary raw materials
361 extraction, energy, and labour.

362 Wilts et al. (2016) stress the importance of policy mixes, such as waste targets for resource
363 efficiency and extended producer responsibility, in driving progress towards a more circular economy.
364 The impact of recent CE policy initiatives in Europe, such as the “European Commission Circular
365 Economy Package” (EC, 2015) has not yet been evaluated. Nevertheless, the policies and targets in
366 place do not directly concern the HDOR vehicle industry. Furthermore, the question of materials
367 ownership and responsibility in CE also remains unanswered for many industrial sectors including the
368 HDOR sector, and is therefore a key challenge in seeking insights on “how the loop will close and by
369 whom?” (Velis and Vrancken, 2015).

370 **3.3. BUSINESS MODEL EVOLUTION: IMPACTS OF REMANUFACTURING AND PSS**

371 In the automotive and HDOR industries, new business models are emerging and will continue
372 to flourish, favouring usage-based income opportunities, both for ownership and servicing of vehicles
373 (IBM, 2009): evolution towards more circular businesses and processes could offer economic,
374 environmental and social benefits through remanufacturing (Japke, 2009; Kwak and Kim, 2016) or
375 product-service-system (PSS) practices (Bocken et al., 2015; Tukker, 2015). These business
376 practices that seek to close the loops in the automotive and HDOR sectors are examined in this sub-
377 section.

378 Automotive vehicles in use far outnumber HDOR vehicles, at around 270 million against 20
379 million in the EU (ICCT, 2016). However, HDOR vehicles use more remanufactured components, and
380 HDOR components are 4–5 times more expensive (Weiland, 2014). For light vehicles, standard
381 components that are remanufactured are mainly starters and alternators, fuel injection parts,
382 electronic control modules, transmissions, engines, gearboxes and turbochargers. For HDOR
383 vehicles, further components are remanufactured, such as hydraulic pumps and cylinders, water and
384 oil pumps, oil coolers, air compressors and actuators, radiators, retarders and particle filters,
385 differentials and hydraulics, and tyres. HDOR component values and dimensions are also much
386 higher: for instance, an average car transmission weighs 40 kg, whereas an average HDOR
387 transmission weighs 200 kg. Overall, in Europe, the HDOR remanufacturing market is performing well,
388 with 3.5 million remanufactured spare parts sold in 2013, corresponding to 3.7 billion euros in annual
389 sales and 279,000 tons of annual CO₂ savings. In comparison, the European automotive
390 remanufacturing business is estimated to be worth 5.7 billion euros. As a relevant illustration,

391 retreading HDOR tyres is one of the most successful HDOR remanufacturing practices. Unlike car
392 tyres, which have a low value and are not worth retreading, the value of HDOR tyres for mining or
393 construction applications is high and so such practices are attractive. The European market for HDOR
394 tyres is vast, with a market share of retreaded and remanufactured HDOR tyres of 3.8 million units,
395 corresponding to 1.1 billion euros in annual sales and a source of non-negligible environmental
396 savings (285,000 tons of annual CO₂ saved) (Weiland, 2014). The remanufacturing market for HDOR
397 vehicles was also recently analysed by the European Commission and the European
398 Remanufacturing Network (EC and ERN, 2015). Globally, the HDOR sector is currently worth 122
399 billion euros to the European economy, which includes new manufacturing and repair of HDOR
400 equipment. More specifically, the European remanufacturing market was estimated to be worth 4.1
401 billion euros in 2014, consistent with the figure of 3.7 billion euros in 2013, as stated above. Germany
402 is estimated to account for 27% of the market, France, Italy and UK representing 15%, 13% and 12%
403 respectively. The sector is estimated to employ 20,000 people in more than 500 firms in Europe (EC
404 and ERN, 2015).

405 However, some issues still have to be tackled to reach the full potential of the HDOR
406 remanufacturing market. HDOR spare parts handling and processing are very heterogeneous. Some
407 components are well-suited to profitable remanufacturing (e.g. tyres, alternators and starters account
408 for 70% of the remanufactured market), but others are directly replaced by brand-new parts (e.g.
409 catalytic converters and pneumatic brakes account for 75% of the brand-new market) (Weiland, 2014).
410 Additionally, the requirement to keep large inventories of remanufactured components to cover all the
411 potential parts that may need replacing is a prohibitive obstacle, and only attempted by the largest
412 OEMs (e.g. Caterpillar and JCB). A few smaller businesses indicated that they felt they were too small
413 to get involved in remanufacturing activities, and it would not be cost-effective for them to embark on
414 such activities. On the other hand, the aftersales market, previously managed and handled by third-
415 party companies and intermediaries, is now becoming a key challenge for OEMs, competing with
416 independent firms.

417 Compared with the automotive sector, the remanufacturing market for HDOR stands out by
418 some specific features: not only is it already a sizeable business area, but it can also claim a greater
419 growth potential than any other industrial sector, according to the CRR Institute in the UK (Walsh,
420 2013) (Chapman et al., 2010). NRMM rental, for instance, is still a growing market that has not yet
421 reached its full potential (Cetim, 2014). As a result of the acceleration of technological innovation and
422 the increasing complexity of equipment, the construction sector is also characterised by a rising
423 demand related to continuous maintenance services for equipment leased on a 24/7 basis. Teams,
424 infrastructures and organisations capable of repairing or replacing failing equipment using
425 remanufactured products are increasingly active (Cetim, 2014). Major manufacturer companies such
426 as Caterpillar are well aware of the current trend in business model evolution: “before, core business
427 was manufacturing, soon it could be remanufacturing” (Snodgrass, 2012).

428 In Europe, the remanufacturing market for HDOR parts is therefore large, competitive and
429 very dynamic, with great promise of growth. Manufacturers have identified this growing market,
430 creating special services and channels of remanufactured products for their clients. Rental companies
431 are also increasingly entering this market, while also starting to compete with original equipment
432 manufacturers to extend the operational lifespan of their heavy vehicles (Cetim, 2014). While
433 remanufacturing activities are still alive throughout the EU, the increased availability of inexpensive
434 new aftermarket parts from Asia has reportedly made it difficult for remanufacturers in Western Europe
435 to remain competitive (USITC, 2012).

436 Lastly, Diener et al. (2015) set out to determine whether product-service-system (PSS) was
437 really a relevant solution for materials efficiency in the HDOR sector. In their study, the following
438 questions were addressed: “what would the company do differently if they were to sell truck function
439 and retain truck function throughout the truck’s lifecycle?” and “how would changes made by the
440 companies affect the materials use required to deliver truck function?”. To assess the potential effects
441 and benefits of PSS on materials efficiency, three HDOR components made mainly of steel were
442 considered (engine, gearbox, and wheel-end). Experiments on Business Model Canvas (BMC) and
443 Material Flow Analysis (MFA) comparing current state and modified PSS-state concluded on a benefit
444 of 23% for materials efficiency for the latter. However, while organisational capabilities (networks and
445 resources) were considered in this study, financial aspects (cost structure and revenue streams) and
446 possible exportations to less developed countries lie outside its scope.

447 **3.4. INTEGRATION OF EMERGING AND PROMISING TECHNOLOGIES: CHALLENGES AND**
448 **NEW OPPORTUNITIES**

449 New and emerging technologies integrated in automotive and HDOR vehicles, such as
450 telematics, Internet of things (IoT) and connected devices, should be intelligently used as enablers.
451 They could be deployed as a means to an end, rather than as an end in itself, for industrial operators
452 to manage their automotive or HDOR vehicles and components throughout their life cycles, and
453 thereby run more competitive and greener businesses (Walker and Manson, 2014; Husnjak et al.,
454 2015; Gnimpieba, 2015). Telematics systems are automobile systems that combine wireless
455 communications for automatic roadside assistance and remote diagnostics. A review of available
456 telematics systems offering an analysis of the usefulness of each telematics solution was made by
457 the NSTSCE (2012). The contributions of telematics during the use phase, e.g. fuel savings, have
458 been widely studied and are beyond the scope of the present paper. To give an example, a case study
459 on real benefits of telematics has shown that telematics can be used to monitor and improve safe
460 driving behaviour as well as monitor and improve fuel economy in trucks (USDOT, 2014). Importantly,
461 the question of the potential contributions of new and emerging technologies as a support in the move
462 towards CE in the automotive and HDOR industries, is becoming increasingly significant: telematics
463 and associated connected devices could certainly facilitate and foster new and closer relationships
464 between suppliers, service providers and users, through customised insurance, take-back offers,
465 technical warnings, and preventive maintenance (NSTSCE, 2012). Also, thanks to the tracking and
466 monitoring of transportation systems with the IoT, enhanced control of illegal exports will be possible.
467 According to IBM (2009), telematics will be an indispensable part of tomorrow's heavy vehicles.
468 Whereas today's vehicle diagnostic techniques typically require the technician to physically connect
469 to the vehicle, the future capabilities of telematics will enable remote vehicle diagnostics.

470 Additionally, IoT sensors add intelligence to automotive and HDOR vehicles as hundreds of
471 sensors fitted on vehicles such as commercial trucks generate large volumes of real-time data. The
472 current challenge is to translate the data thus obtained into meaningful information that optimises, for
473 instance, vehicle usage or maintenance (Intel, 2015). Some ongoing research and studies are ready
474 to go further, capturing real-time performance, user activities and feedback from the field, not only for
475 the purpose of real-time usage optimisation, but also to improve the future design of vehicles and
476 machinery considering their entire life cycle (Ma et al., 2014). However, only a small proportion of
477 automotive HDOR vehicles are currently equipped and monitored with such advanced telematics
478 systems: a survey performed in 2014 by the Association of Equipment Manufacturers found that 62%
479 of US construction companies had no plans to implement telematics anytime soon. Also, according
480 to a director manager from an NRMM rental company, such technologies are not seen as really useful
481 for small machinery users, but only for major construction sites with large fleets of heavy machinery
482 working together. Another challenge is to link these telematics and connected devices with business
483 models facilitating the EoL management, (prolong, maintain, reuse, remanufacture, recycle), of
484 automotive and HDOR vehicles. Among innovative business models interlinking leasing services and
485 connected devices, a geo-tracking online platform allowing HDOR equipment, and particularly NRMM,
486 to be localised, that is available in a chosen area at both end of usage and EoL is increasingly used
487 by civil engineering companies (Matexchange, 2016). As advocated by a road construction site
488 supervisor from Colas, who has used NRMM since 1979 and has therefore noted some evolution, it
489 would be useful to have more information about the wear and tear of components through the use of
490 such connected devices in order to prevent component breakdown and forecast more accurate
491 preventive maintenance, and thereby contribute to the circular economy in practice.

492 **3.5. INDUSTRIAL PRACTICES, INITIATIVES AND INCENTIVES TO CLOSE THE LOOPS**

493 To illustrate the previous sub-sections with concrete examples from the industrial field, we
494 now make an in-depth analysis of best industrial practices in the automotive and HDOR sectors to
495 close the loop. The practices of major NRMM constructors in progress towards CE were analysed:
496 Liebherr (DE ownership), Caterpillar (US), John Deere (US), Volvo Construction Equipment (SE), and
497 Manitou (FR). Likewise, remanufacturing programmes and innovative commercial offers of five main
498 HDV constructors were analysed to gain relevant insights and identify best initiatives in a CE
499 perspective (Volvo Truck (SE), Scania (SE), MAN (DE), DAF (NL) and Daimler Trucks North America
500 (US)). For the automotive sector, the example of French major constructor Renault was taken to
501 illustrate best automotive practices on the road to CE. In the NRMM sector, although Caterpillar has

502 the most extended and developed remanufacturing program and offer, several commercial offers
503 related to aftersales services from main NRMM constructors are also discussed. In the HDV sector,
504 the example of Volvo Truck lends significant insights into the EoL stage and new business offers.

505 **3.5.1. Insights from automotive operators**

506 Renault was chosen by the Ellen MacArthur Foundation to illustrate CE in the automotive
507 industry (EMF, 2013a). In 2012, Renault's Choisy-le-Roi plant remanufactured around 200,000
508 components of six types of mechanism, such as gearboxes and injectors. In this remanufacturing
509 centre, the savings from producing a remanufactured part compared with a new part are 80% less
510 energy, 88% less water, and 92% less chemicals. In terms of raw materials, the Choisy-le-Roi factory
511 does not send any waste to landfill: 43% of a carcass is re-usable (72% of the mass of a gearbox and
512 37% of the mass of an engine); 48% is recycled in the company's foundries to produce new parts,
513 and the remaining 9% is valorised in processing centres, meaning the entire recovery process is
514 waste-free. Additionally, Renault has built a network for the efficient, profitable EoL treatment of
515 vehicles, which includes INDRA (a pioneer in automotive recycling) and Suez Environment (a
516 specialist in global waste management and recycling).

517 More specifically, the INDRA network activities help disseminate best practices among EoL
518 treatment facilities regarding management, depollution, dismantling and recycling of ELVs (INDRA,
519 2016a). INDRA also "provides ELV centres with a dedicated software suite, designed to meet their
520 every need and guarantee traceability throughout the chain, from the administrative management of
521 vehicles to evaluating demand, dismantling, and the technical identification of reusable parts intended
522 for resale" (INDRA, 2016b). This recent advance helps fill a gap noted by Despeisse et al. (2015),
523 who examined the circularity of EoL vehicles in the UK and Japan. A clear lack of an information
524 system to support the EoL management in a centralised way was observed. They report that data
525 collected and available were still insufficient to understand and decide on the best fate of components
526 and materials. Since this study was completed, progress has been made in these areas: the complete
527 handling of ELVs is becoming an increasingly efficient industrialised procedure. For instance, the
528 entire dismantling time has been optimised to 3 hours per vehicle, and state-of-the-art ELV centres
529 can ensure the complete disassembly of 25 vehicles per day.

530 Overall, by prolonging and maintaining the lifespan of the vehicles by parts remanufacturing,
531 the factory in Choisy has created a comprehensive circular model. Moreover, this activity complies
532 closely with the principles of the three pillars of sustainability. First, socially, it involves a skilled
533 workforce and creates jobs locally (325 employees are working on the site). To be economically viable
534 (turnover of 100 million euros), remanufacturing has to be performed within the market region in which
535 the vehicles are used. Though 30–50% less expensive, the remanufactured parts have the same
536 guarantee, and are subject to the same quality control tests as new parts. Lastly, environmentally, it
537 retains added value of components and saves energy, while reducing waste, as detailed above.

538 Additionally, in the automotive sector, research projects and investigations also focus on
539 mechanisms to improve recycling and recovery rates during early design and development phases,
540 and thereby the circularity of vehicle components or materials. Garcia et al. (2015) propose a tool for
541 evaluating the impact of innovation on the EoL pathway of a vehicle. The goal of this tool, called
542 OSIRIS (Simulation Tool of the Impact on Recyclability of Innovations), developed in collaboration
543 with the French automotive manufacturer PSA, is to help the engineers of the innovation department
544 evaluate the impact of their innovations on a vehicle's recyclability and recoverability rates.

545 **3.5.2. Insights from HDV sector practitioners**

546 In terms of design and during product development, the Volvo Group (2015) meets major
547 prerequisites to fit CE principles: Volvo's trucks are largely recyclable, almost 85% of their weight
548 consisting of metal, mostly iron, steel and aluminium. The additional materials are mainly plastic,
549 rubber and materials from electronic components. Today, approximately one third of a Volvo Group
550 truck is produced from recycled materials, and 80% of the engine can be reused. The Volvo Group
551 has developed manuals and other tools to assist disassembly workers in extracting the most from
552 used vehicles. For instance, the dismantling manual (Volvo Truck Corporation, 2012) provides
553 practical and illustrated recommendations about the possible handling, reuse or recycling of chemicals
554 and fluids (oil, AdBlue, solvents, coolant, brake fluid, refrigerant, glycol, glue, washer fluid, sulphuric
555 acid) and other components and materials (batteries, air bags, belt tensioners, oil filters, laminated

556 glass, silencer, electrical and electronic waste, lamps and tubes, switches, gas discharge lamps,
557 brake discs, rubber).

558 When a Volvo FH Globetrotter is properly dismantled, i.e. 95% of its weight (approximately
559 7,000 kg), the total resale of spare parts can reach 40,000 euros. According to an environmental
560 manager at Volvo Truck Recycling, the EoL processing of a truck is much more complex, energy and
561 labour-intensive, as well as less well developed than in the automotive sector. In a Volvo dismantling
562 plant, EoL processing comprises cleaning and depollution (i.e. batteries and fluids removal),
563 undressing (i.e. headlights, sheet metal bodywork, and cabin removal), dismantling (all components
564 to access the engine) and butchering (axles, chassis, wheels). It also requires two expert garage
565 mechanics working for three days in a workshop with specific tools.

566 The remanufacturing market share of Volvo is also expanding, a good indicator of the move
567 towards CE. In 2015, the total sales of remanufactured components amounted to 0.83 billion euros,
568 an increase of almost 20% over 2014. Remanufactured components reduce customers' ownership
569 and operating costs (Volvo Group, 2015). Volvo is also one of the most mature companies for
570 telematics integration in their HDOR fleet. In 2015, approximately 470,000 Volvo Group vehicles were
571 connected via different telematics solutions, including services such as Volvo Dynafleet, Renault
572 OptiFleet, UD Telematics and the Volvo CE CareTrack, in a fleet of more than two million trucks.

573 Regarding circular product design practices, many of the Volvo Group's products have a
574 common architecture and shared technology (CAST) based on a modularised concept and standard
575 interfaces. The Volvo Group's heavy-duty and medium-duty engine platforms are at the centre of the
576 CAST strategy, as illustrated in Figure 2. There is also a high degree of commonality in electronics
577 and transmissions. This modular product design (MPD) approach makes remanufacturing and reuse
578 of spare parts easier, and thereby contributes to the shift towards CE. Furthermore, according to Ma
579 and Okudan Kremer (2014), adopting a systematic MPD strategy leads to benefits in terms of the
580 three pillars of sustainability.

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Figure 2 – Volvo Common Architecture and Shared Technology (CAST) to facilitate component reuse, and contribute to the circular economy of spare parts. Excerpt from Volvo Group (2015)

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Another industrial example that illustrates the transition of HDVs towards CE is the DAF Company. DAF has already anticipated a possible extension of the European Directive related to ELV (2000/53/EC). More than 93% of all the materials in a standard DAF truck can now be reused. For example, the plastic parts of a DAF truck can easily be separated during dismantling. Like Volvo, DAF provides special sorting guides for each truck type. Also, DAF is proactive in the remanufacturing and reuse of components. In DAF's overhaul workshop in Eindhoven, an annual total of more than 50,000 parts are overhauled and supplied for reuse. These parts include starter motors, fuel pumps, gearboxes and even complete engines. These exchange parts are of a similar quality to new parts, and the same guarantee is provided for both.

3.5.3. Insights from NRMM sector practitioners

Caterpillar is a renowned model of an off-road equipment company embracing CE through remanufacturing; it ended runner-up among The Circularity 2016 Finalists. Caterpillar has incorporated CE principles across its value chain, including product development, supply chain, dealer network, and customer relationships. Caterpillar's remanufacturing activity began in 1973, and has since grown to encompass 17 facilities worldwide, employing over 4,100 people dedicated to remanufacturing activities in a business model with an emphasis on component recovery. In 2012 Caterpillar's remanufacturing programme took back over 2.2 million EoL units for remanufacturing, representing 73,000 tons of materials, and including 6,000 different remanufactured products. Incentives such as a deposit scheme and voluntary take-back of products ensure that large quantities of parts are returned to Caterpillar, as shown in Figure 3. Caterpillar has a global network of remanufacturing hubs in which the returned products are remediated; in Europe the following sites undertake remanufacturing activities: Chaumont in France; Bazzano, Castelvetro, Frosinone, and San Eusebio in Italy, Radom in Poland; and Shrewsbury and Skinningrove in the UK. Another success factor for Caterpillar's remanufacturing program is that the company considers the entire product life cycle during the design phase, taking into account types of materials used and ease of disassembly for repair, remanufacture, reuse or recycling. The company also implements digital technology to drive circular transformation via its remanufacturing. One example is the telematics platform "Caterpillar Product Link", which provides information about the location, utilisation and condition of any given equipment, which facilitates remanufacturing processing. Lastly, Caterpillar is also finding ways to expand its remanufacturing business model to help address growing environmental concerns, such as the electronics waste increasingly left by HDOR equipment (Snodgrass, 2012). All in all, the company's circular economy portfolio generated almost 10 billion euros in 2014, accounting for 18% of the company's total sales and revenues.

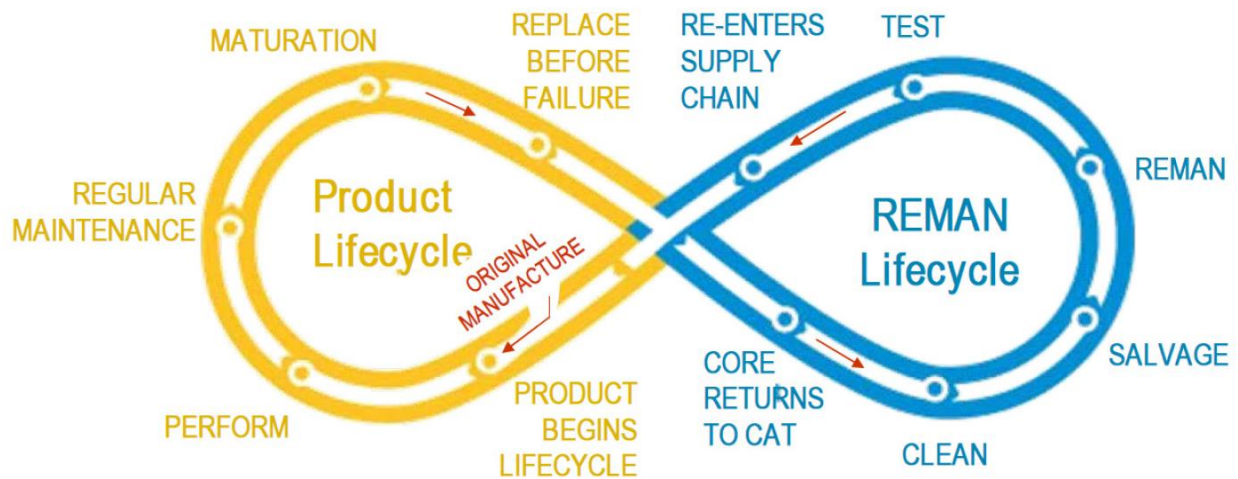


Figure 3 – Caterpillar's REMAN value chain to close the loop, excerpt from Snodgrass (2012)

Recently more and more other companies have been developing their remanufacturing offers in order to stay competitive. For instance, Liebherr has been extending its remanufacturing programme since 2004 at its Ettlingen site in Germany, offering three remanufacturing options for a range of components: exchange, general overhaul or repair. Concerning emerging technologies and connected devices for HDOR equipment, the telematics platform LiDAT, designed and developed by Liebherr, includes maintenance management with services such as an automatic reminder of routine maintenance (e.g. gearbox oil changes or maintenance on brakes) or date planning for acceptance procedures (e.g. expert inspections). Fostering preventive maintenance is thus one good step towards maintaining and prolonging the lifespan of NRMM, and so contributes positively to CE. Similarly, John Deere's JDLink telematic offer allows owners and fleet managers to monitor equipment remotely: the JDLink telematics system includes location tracking, remote diagnosis and repair sessions for a better traceability and usage of the machine throughout its life cycle.





Taking into account the different legislations for automotive and HDOR sectors, it is noteworthy that Renault offers an example of practices commonly applied by other car manufacturers in the EU,

638 such as the German Volkswagen Group, whereas the approaches of Volvo, DAF and Caterpillar are
639 not followed by their competitors in the HDOR sector. Possible transfer of best practices from light
640 vehicles to heavy ones, and *vice versa*, are analysed in the next sub-section through the lens of the
641 circular economy.

642 **3.6. BEST PRACTICES AND REMAINING CHALLENGES IN A CE PERSPECTIVE**

643 The situation of automotive and HDOR sectors on the road towards CE are compared and
644 summarised in Table 4 in terms of the four CE building blocks, and in Table 5 for the four generic
645 loops of the CE model defined by the EMF (2013b). Best practices (BP) and remaining challenges (C)
646 are indicated as relevant.
647





648 Table 4 – Best practices (BP) and challenges (C) in both sectors in terms of the CE building blocks

Building blocks of CE	Description (EMF, 2013b)	Automotive sector	HDOR sector
 <p>Circular Design Product</p>	Product design that facilitates the reuse, remanufacturing, recycling and recovery of components and materials.	<p>BP:</p> <ul style="list-style-type: none"> Eco-design practices, tools and environmental requirements are increasingly integrated within the design and development processes. <p>C:</p> <ul style="list-style-type: none"> Trade-off between the need to improve performance during the use phase (e.g. making vehicles lighter often requires replacing steel with lighter materials, such as aluminium, polymers, composites or carbon fibres) and design for recycling. Integration of electronic systems leads to new challenging issues for reuse in another vehicle, operator-friendly remanufacturing or recycling. 	<p>BP:</p> <ul style="list-style-type: none"> Volvo's trucks are highly recyclable: 85% of their weight consists of iron, steel and aluminium. One third of a Volvo Group's truck is produced from recycled materials. Modular product design: the high degree of commonality of Volvo Group's products facilitates the remanufacturing and reuse of spare parts. <p>C:</p> <ul style="list-style-type: none"> Complex components (multi-material plus small electronic parts) are often impossible to dismantle without damaging them and are less re-usable.
 <p>New Business Model (BM)</p>	Innovative business models (BM) that enable circular value chain, foster exchanges and products loops.	<p>BP:</p> <ul style="list-style-type: none"> Cooperation and shared information between automotive actors - from manufacturers to second-hand dealers through authorised treatment facilities - to meet the ELV Directive and make profits from the EoL management of cars. <p>C:</p> <ul style="list-style-type: none"> Used parts market in the EU is still small compared with used parts markets in Middle East, Asia and North Africa. 	<p>BP:</p> <ul style="list-style-type: none"> OEMs creating special services and remanufactured offers for their clients: continuous maintenance services for leased equipment on a 24/7 basis. Innovative BM interlinking leasing services and connected devices: a geo-tracking online platform allowing localisation of HDOR equipment. Caterpillar's take-back programme including a deposit scheme and voluntary take-back of products. <p>C:</p> <ul style="list-style-type: none"> Initial investments required to launch circular practices are non-negligible. Increased availability of less expensive aftermarket parts from Asia.
 <p>Reverse Cycles</p>	Reverse logistics recovering products back from users into the supply chain.	<p>BP:</p> <ul style="list-style-type: none"> Free take-back of end-of-life vehicles. High accessibility of collection points (at least one every 50 km in France). Renault and its collaborative network all along the end-of-life value chain. <p>C:</p> <ul style="list-style-type: none"> ELV that reached non-authorized treatment facilities. Final owners unaware of the free take-back of their end-of-life vehicles. 	<p>BP:</p> <ul style="list-style-type: none"> Emergence of telematic systems and connected devices to foster the tracking of HDOR fleet. <p>C:</p> <ul style="list-style-type: none"> Lack of transparency of the end-of-life value chain due to the significant number of subcontractors and intermediary third parties. The question of who will own, fund and be responsible for infrastructures for reverse cycles is unclear.
 <p>Enablers & Favourable System Conditions</p>	A number of system conditions that can help businesses make the transition, such as education, policies, collaborations and market mechanisms.	<p>BP:</p> <ul style="list-style-type: none"> Large numbers of HDOR units in circulation: 270 million in the EU. End-of-life vehicles Directive (2000/53/EC) with mandatory levels of reuse, recovery and recycling. Sweden, an example where 91% of cars out of use are taken to dismantlers. <p>C:</p> <ul style="list-style-type: none"> Time period between pre-life and end-of-life: 17.5 years for cars. Meanwhile, technologies and materials used evolve. Around 4 million European ELV are still handled by non-authorized or illegal treatment facilities: in France, 1.1 million ELV are properly handled by ATF out of 1.8 million ELV generated each year: loss of 700.000 ELV in illegal treatment facilities. 	<p>BP:</p> <ul style="list-style-type: none"> Large numbers of HDOR units in circulation: 20 million in the EU. High residual value of components and materials included in EoL HDOR vehicles. Enhanced fleet management location tracking, remote diagnosis and repair sessions aiming at a better traceability throughout the life cycle. 470,000 Volvo Group vehicles are connected via different telematics devices in a fleet of more than two millions trucks. <p>C:</p> <ul style="list-style-type: none"> Time period between pre-life and end-of-life: around 20 years for HDOR vehicles. Meanwhile,

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			<p>technologies and materials used are evolving.</p> <ul style="list-style-type: none"> No end-of-life regulations for HDOR vehicles, nor extended producer responsibilities. Current mind-set of HDOR actors and users.
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Table 5 – Best practices (BP) and challenges (C) in both sectors to close the loops

Feedback loops of CE	Description (EMF, 2013b)	Automotive sector	HDOR sector
<p>Maintain Prolong</p> 	<p>The goal is to keep artefacts in circulation as long as possible, with as high a value as possible. Design for service and maintenance. From (end) user to (new) user (sometimes a third party can also intervene)</p>	<p>BP:</p> <ul style="list-style-type: none"> Extension of the lifetime of the vehicle economically viable thanks to the remanufacturing of spare parts: example of Renault and its remanufacturing plant. <p>C:</p> <ul style="list-style-type: none"> Environmental and economic trade-offs between extending the lifespan of old vehicles and introducing brand new vehicles, which pollute less during the use phase. 	<p>BP:</p> <ul style="list-style-type: none"> Capturing real-time performance and users' activities from the industrial level to improve future design and machinery considering whole life cycle. Maintenance management with services such as automatic reminder of technical warning or preventive maintenance activities. <p>C:</p> <ul style="list-style-type: none"> Poor traceability aftersales from the manufacturer side to intervene properly for repairing components during the life of an HDOR vehicle.
<p>Reuse Redistribute</p> 	<p>Design for reuse and optimisation of second-hand market to avoid value loss. From end-user to service providers.</p>	<p>BP:</p> <ul style="list-style-type: none"> Well-established dismantling system is a viable source of second-hand parts to the automotive aftermarket. Around 60% of car spare parts are reusable at the end of car's lifetime. Feedback information about current stocks and market demand provided to state-of-the-art recycling centre. Computer software specialising in monitoring second-hand spare parts and their dismantling for resale. <p>C:</p> <ul style="list-style-type: none"> - 	<p>BP:</p> <ul style="list-style-type: none"> In the UK, 50% of all heavy vehicles reaching their end-of-life are reused or resold in other countries with major refurbishment; 43% are remanufactured to extend their lifespan in the UK. Redistribution of second-hand components is a profitable business: e.g. when a Volvo FH Globetrotter is dismantled properly (95% of its weight, i.e. 7,000 kg), the overall resale of spare parts can reach 40,000 euros. <p>C:</p> <ul style="list-style-type: none"> Numerous uncertainties about the quantity and location of end-of-life HDOR vehicles, and about the quality and conditions of used spare parts.
<p>Remanufacture</p> 	<p>Returning a product to its original performance with a warranty. Process that makes extensive reuse possible. From end-user to manufacturer factories or remanufacturing centres.</p>	<p>BP:</p> <ul style="list-style-type: none"> Renault's Choisy-le-Roi remanufacturing centre with its associated collaborative and reverse supply chain network. <p>C:</p> <ul style="list-style-type: none"> Limited number of remanufactured spare parts from light vehicles. 	<p>BP:</p> <ul style="list-style-type: none"> More remanufacturing spare parts than in the automotive sector. Retreading of HDOR tyres. In 2012 Caterpillar's remanufacturing programme took back over 2.2 million end-of-life units for remanufacturing, representing 73,000 tons of materials, and including 6,000 different remanufactured products. <p>C:</p> <ul style="list-style-type: none"> Disassembly and remanufacturing of many newly-designed and more advanced components is not possible without damage. Some components are still systematically replaced by brand-new ones: e.g. catalytic converters or pneumatic brakes.
<p>Recycle</p> 	<p>Design for materials recovery. Loss of original product's added value.</p>	<p>BP:</p> <ul style="list-style-type: none"> Well-organised federation of a significant part of the vehicle 	<p>BP:</p>

	From end-user to recycling centres.	<p>recycling industry through a specialised computer system.</p> <ul style="list-style-type: none"> • OEMs have to publish vehicle disassembly guidance according to legislation. <p>C:</p> <ul style="list-style-type: none"> • Illegal recycling channels still exist. • Recycling targets are still defined by weight. 	<ul style="list-style-type: none"> • Dismantling manuals are available for most of Volvo's trucks. • DAF has already anticipated a possible extension of the European ELV Directive (2000/53/EC) • More than 93% of all materials in a standard DAF truck can be reused. <p>C:</p> <ul style="list-style-type: none"> • HDOR vehicles are very heterogeneous, hampering the design of generic end-of-life infrastructure to recycle efficiently. • Ultimate end-of-life of HDOR vehicles in countries without proper dismantling recycling infrastructure to recover high added value components.
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4. DISCUSSION AND CONCLUDING REMARKS

653 Globally, the implementation of the circular economy, which is still at an initial stage of
654 development, has mainly focused on recycling rather than on reuse (Ghisellini et al., 2015). The
655 HDOR industry case is an exception to this trend: remanufacturing is the preferred option for the EoL
656 of HDOR vehicles, rather than dismantling and recycling. From a sustainability point of view, this is a
657 commendable and praiseworthy practice in that it offers heavy vehicles a second life. However,
658 second-hand heavy vehicles are then usually resold to emerging markets and developing countries
659 that do not have the proper technologies to dismantle, recover or recycle heavy vehicles that have
660 reached their ultimate EoL, which then become a severe burden for the environment, with loss of
661 precious metals. Developing countries lack proper waste collection and treatment systems (Diaz,
662 2017), and have a number of problems related to waste management that still need to be resolved:
663 lack of political will, absence of rules and regulations for solid waste management, insufficient funds,
664 and absence of educational programmes.

665 On the other hand, even in more developed countries in Western Europe such as France,
666 dismantling and recycling channels for heavy vehicles are in their early development stages, and it is
667 still difficult to find and identify the relevant interlocutors and right actors (ADEME, 2006; Cetim, 2014).
668 To date, materials recycling or recovery are therefore not the preferred pathways for the EoL of HDOR
669 vehicles: at the European level, both industrial operators and policy makers are not proactive enough
670 in the setting of standards related to the EoL management of HDOR equipment. In addition, the
671 profitability of dismantling infrastructures for HDOR vehicles has yet to be proved. At the moment,
672 exports of HDOR vehicles are profitable for the end-owners, but this is globally a non-sustainable
673 solution, because the importing developing countries do not possess factories to recycle properly.
674 Additionally, exports outside Europe lead to significant leakage of value for European manufacturers,
675 from strategic, economic and environmental points of view. Simply stated, the EoL of HDOR vehicles
676 is an important concrete opportunity for maintaining resources in Europe, and for securing the supply
677 of rare and precious materials from resource scarcity and price volatility, which is not fully exploited
678 today. Lastly, even if this issue is somewhat outside the scope of the present paper, European
679 countries will have to assist developing countries in preserving value from EoL equipment and creating
680 a circular economy (Diaz, 2017).

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682 Major stakeholders of the HDOR industry, such as original equipment manufacturers or EoL
683 expertise centres, are becoming increasingly aware of these missed opportunities. These challenges
684 and opportunities had also been identified and confirmed by a business development manager from
685 one of the main European construction equipment manufacturers, interviewed during our
686 investigations. OEMs are beginning to understand that the stakes are high, and adapt their offers
687 accordingly (e.g. Volvo and Caterpillar's business model evolution as detailed above). To go even
688 further and fully achieve the potential and promises of CE, the HDOR vehicle sector can learn from
689 the automotive sector in the following areas of best circular practices:

- 690 – Well-organised EoL value chain of ELV in the EU. Well-established dismantling and systematic
691 recycling procedures in ATFs, motivated and propelled by the ELV directive and EPR.
- 692 – Involvement of research and engineering expertise centres (e.g. INDRA operating in France) within
693 the EoL value chain to help close the loops of products and materials by providing state-of-the-art
694 tools, methods and software platforms.
- 695 – Transparent collaboration networks between automotive manufacturers, EoL treatment facilities and
696 intermediary third parties from the EoL value chain. For instance, collaboration between industrial
697 manufacturers all along the value chain is one of the key elements of the framework proposed by
698 Witjes and Lozano (2016) to move effectively towards CE through more sustainable business
699 models.

700 However, the mere implementation of regulations is not sufficient to ensure a smooth evolution
701 towards sustainable CE. The example of waste electrical and electronic equipment (WEEE) is
702 noteworthy. WEEE, which is subject to numerous regulations in Europe (e.g. Directive 2012/19/EC)
703 is often exported, legally or illegally, “just to end up in some of the most polluted places in the world:
704 being reprocessed under lax or no regulations to recover value via acid leaching and burning, which
705 results in public health disasters and extensive environmental pollution in West Africa and South-East
706 Asia” (Velis, 2015). Industrial operators (e.g. engineers, managers, designers) must be able to rely
707 on a state-of-the-art literature on integrating and implementing circular practices. For instance, Lieder
708 and Rashid (2016) proposed a framework to be used as a CE implementation strategy in the context
709 of the manufacturing industry. More broadly, Moreno et al. (2016) developed a conceptual framework
710 for circular economy design strategies (e.g. design for resource conservation, design for slowing
711 resource loops, or design for whole systems design). This therefore gives guidance for practitioners
712 wishing to design for new circular business models in practice.

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714 Future research needs to go further and make a more quantitative assessment of the remaining
715 distance that has to be gone to reach full CE for HDOR vehicles and associated spare parts. Saidani
716 et al. (2017) provide guidelines for the design and development of new frameworks, tools and
717 indicators for measuring product circularity. More specifically, Di Maio et al. (2017) propose a new
718 value-based indicator to assess the performance of actors in the supply chain in terms of resource
719 efficiency and CE. Quantification of missed value buckets for European HDOR actors should then be
720 an enabler for both the European Commission, in considering a new regulated framework for HDOR
721 vehicle EoL, and European industrial practitioners to exploit these opportunities gainfully. With this
722 purpose, CIDER Engineering, an engineering centre dedicated to dismantling, recycling and
723 remanufacturing heavy equipment and vehicles, performed a technological watch, in France and in a
724 few strategic European countries, to (i) evaluate the quantity and deposit of EoL and second-hand
725 HDOR vehicles, and (ii) identify last owners and intermediary third parties in the EoL value chain.
726 According to experts from ADEME and in agreement with experts in the HDOR industry, the access
727 to key information, such as the exact materials composition of an EoL HDOR vehicle, the current
728 deposit stocks or the efficiency of EoL channels handling HDOR vehicles, would help bring the EoL
729 processing of HDOR vehicles into a greener economy. It would also be useful to have real-time
730 forecast information about the wear and tear of HDOR components in order to prevent the failure of
731 key components, schedule more accurate preventive maintenance, and thereby contribute to circular
732 economy implementation in practice. Further research to evaluate the environmental impact of the
733 possible loops for each HDOR component and material will be needed to enlarge the limited amount
734 of literature documenting this subject to date (Niero and Olsen, 2016). Each possible HDOR EoL
735 scenario has its own consequences on the criteria of sustainability (economic, environmental and
736 social). Also, stakeholders have their own goals and preferences regarding these criteria. The authors
737 stress the value of all research, both theoretical and applied, experimental projects and any other
738 initiatives that could hasten the drafting of suitable directives for end-of life HDOR vehicles, and help
739 develop innovative processes and new control of procedures for their EoL management.

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741 **ACKNOWLEDGEMENTS**

742 Particular thanks are due to all the experts from the automotive and HDOR industries we met during our
743 investigations, for their time, support and invaluable shared information. The authors also thank the reviewers
744 for their precious and highly constructive comments.

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746 REFERENCES

- 747 ACEA-European Automotive Manufacturers Association, 2015. ACEA Position Paper on Circular Economy. September 2015.
748 ACEA-European Automotive Manufacturers Association, 2016. Facts about the Automobile Industry. Available online (1
749 November 2016): <http://www.acea.be/automobile-industry/facts-about-the-industry>
750 ADEME, 2006. Etude sur la fin de vie de tous les moyens de transport en France, à l'exception des véhicules couverts par la
751 directive Véhicules Hors d'Usage. Etude réalisée par BioIS pour l'ADEME, Novembre 2006.
752 Banaite, D., 2016. Towards circular economy: analysis of indicators in the context of sustainable development. *Social*
753 *Transformations in Contemporary Society*, 2016 (4), ISSN 2345-0126 (online)
754 Bocken, N., Bakker, C., De Pauw, I., 2015. Product design and business model strategies for a circular economy. *Sustainable*
755 *Design & Manufacturing Conference*, Seville, 12-14 April 2015.
756 Cetim, 2014. Filière de fin de vie et de déconstruction des engins lourds. Note veille, Matériels de Travaux Publics, Mines et
757 Forage, Septembre 2014.
758 Chapman, A., Bartlett, C., McGill, I., Parker, D., Walsh, B., 2010. A snapshot of the remanufacturing industry in UK in 2009.
759 CRR, Centre for Remanufacturing and Reuse, UK, August 2010.
760 Chemineau, L., 2011. Développement d'une méthode d'éco-conception basée sur la modélisation et l'évaluation des filières de
761 valorisation : application au secteur automobile. PhD Thesis, Sciences de l'ingénieur [physics]. Ecole nationale
762 supérieure d'arts et métiers - ENSAM, 2011. French. <tel-00600682>
763 CIRAIQ, 2015. Circular Economy: A Critical Literature Review of Concepts, Bibliothèque et Archives nationales du Québec
764 (BAnQ), August 2015. ISBN 978-2-9815420-0-7.
765 Clarke, R. J., 2005. Research Models and Methodologies. HDR Seminar Series, Faculty of Commerce, Spring Session 2005.
766 Creswell, J. W., 2003. Research design: qualitative, quantitative, and mixed methods approaches. Thousand Oaks, CA: Sage
767 Publications, 2nd Edition.
768 Creswell, J.W., Plano Clark, V.L., 2007. Designing and Conducting Mixed Methods Research. Thousand Oaks, CA: Sage.
769 Despeisse, M., Kishita, Y., Nakano, M., Barwood, M., 2015. Towards a Circular Economy for End-of-Life Vehicles: A
770 Comparative Study UK – Japan. *Procedia CIRP*, Volume 29, 2015, Pages 668-673, ISSN 2212-8271,
771 <http://dx.doi.org/10.1016/j.procir.2015.02.122>.
772 DfT-Department for Transport, 2016. Non-Road Mobile Machinery (NRMM) definition. Available online (1 November 2016):
773 <http://www.dft.gov.uk/vca/enforcement/non-road-mobile-mach.asp>
774 Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: A market value
775 approach, *Resources, Conservation and Recycling*, Volume 122, July 2017, Pages 163-171, ISSN 0921-3449,
776 <http://doi.org/10.1016/j.resconrec.2017.02.009>.
777 Diaz, L.F., 2017. Waste management in developing countries and the circular economy. Editorial, *Waste Manag. Res.*, Vol.
778 35(1) 1–2.
779 Diener, D., Tillman, A.-M., 2015. Component end-of-life management: Exploring opportunities and related benefits of
780 remanufacturing and functional recycling. *Resources, Conservation and Recycling* (0921-3449). Vol. 102, p. 80-93.
781 Diener, D., Tillman, A.-M., 2016. Scrapping steel components for recycling - Isn't that good enough? Seeking improvements in
782 automotive component end-of-life. *Resources, Conservation and Recycling*, Volume 110, July 2016, Pages 48-60, ISSN
783 0921-3449, <http://dx.doi.org/10.1016/j.resconrec.2016.03.001>.
784 Diener, D., Willander, M., Tillman, A.-M., 2015. Product-Service-Systems for Heavy-Duty Vehicles – An Accessible Solution to
785 Material Efficiency Improvements? *Procedia CIRP*, Volume 30, 2015, Pages 269-274, ISSN 2212-8271,
786 <http://dx.doi.org/10.1016/j.procir.2015.02.027>.
787 Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles. Official
788 Journal of the European Communities (21 October 2000).
789 Directive 2001/116/EC of 20 December 2001 adapting to technical progress Council Directive 70/156/EEC on the approximation
790 of the laws of the Member States relating to the type-approval of motor vehicles and their trailers.
791 Directive 2002/151/EC: Commission Decision of 19 February 2002 on minimum requirements for the certificate of destruction
792 issued in accordance with Article 5(3) of Directive 2000/53/EC of the European Parliament and of the Council on end-of-
793 life vehicles.
794 Directive 2002/24/EC of the European Parliament and of the Council of 18 March 2002 relating to the type-approval of two or
795 three-wheel motor vehicles and repealing Council Directive 92/61/EEC.
796 Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic
797 equipment (WEEE).
798 Directive 2003/138/EC: Commission Decision of 27 February 2003 establishing component and material coding standards for
799 vehicles pursuant to Directive 2000/53/EC of the European Parliament and of the Council on end-of-life vehicles.
800 Directive 2005/293/EC: Commission Decision of 1 April 2005 laying down detailed rules on the monitoring of the reuse/recovery
801 and reuse/recycling targets set out in Directive 2000/53/EC of the European Parliament and of the Council on end-of-life
802 vehicles.
803 Directive 2005/64/EC of the European Parliament and of the Council of 26 October 2005 on the type-approval of motor vehicles
804 with regard to their reusability, recyclability and recoverability.
805 Directive 2008/33/EC of the European Parliament and of the Council of 11 March 2008 amending Directive 2000/53/EC on end-
806 of-life vehicles, as regards the implementing powers conferred on the Commission.
807 Directive 2008/35/EC of the European Parliament and of the Council of 11 March 2008 amending Directive 2002/95/EC on the
808 use of certain hazardous substances in electrical and electronic equipment (RoHS).
809 EASAC-European Academies Science Advisory Council, 2016. Indicators for a circular economy. EASAC policy report 30,
810 November 2016. ISBN: 978-3-8047-3680-1.
811 EC-European Commission, 2010. Critical Raw Materials for the EU. Report of the Ad-hoc Working Group on defining critical raw
812 materials, June 2010.
813 EC-European Commission, 2011. Roadmap to a Resource Efficient Europe. Communication from the commission to the
814 European parliament, the council, the European economic and social committee and the committee of the regions,
815 Brussels, Belgium, September 2011. SEC (2011) 1067 final.
816 EC-European Commission, 2014a. Towards a circular economy: A zero waste programme for Europe, September 2014.
817 EC-European Commission, 2014b. Ex-post evaluation of certain waste stream Directive. Final Report, 18 April 2014, Bio
818 Intelligence Service, Arcadis, Institute for European Environmental Policy.

- 819 EC-European Commission, 2015. Closing the loop, an EU action plan for the Circular Economy, Communication from the
820 commission to the European parliament, the council, the European economic and social committee and the committee of
821 the regions, Brussels, Belgium, December 2015.
- 822 EC-European Commission, 2016a. Resource Efficiency. Available online (1 November 2016):
823 http://ec.europa.eu/environment/resource_efficiency/index_en.htm
- 824 EC-European Commission, 2016b. End of Life Vehicles. Available online (1 November 2016):
825 <http://ec.europa.eu/environment/waste/elv/index.htm>
- 826 EC-European Commission, ERN-European Remanufacturing Network, 2015. Remanufacturing Market Study, for Horizon 2020.
827 Chapter 9: Heavy-Duty and Off-Road equipment, November 2015.
- 828 EEA-European Environment Agency, 2015. Circular economy in Europe - Developing the knowledge base. 37 pp., 21 x 29.7
829 cm, ISBN 978-92-9213-719-9, doi:10.2800/51444.
- 830 EEA-European Environment Agency, 2016. More from less - Material resource efficiency in Europe. 151 pp., 21 x 29.7 cm,
831 ISBN 978-92-9213-736-6, doi:10.2800/240736.
- 832 El Halabi, E., Third, M., Doolan, M., 2015. Machine-based Dismantling of End of Life Vehicles: A Life Cycle Perspective.
833 *Procedia CIRP*, Volume 29, 2015, Pages 651-655, ISSN 2212-8271, <http://dx.doi.org/10.1016/j.procir.2015.02.078>.
- 834 EMF-ElLEN MacArthur Foundation, 2013a. The Circular Economy Applied to the Automotive Industry. Available online (1
835 November 2016): [http://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram/the-circular-economy-](http://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram/the-circular-economy-applied-to-the-automotive-industry)
836 [applied-to-the-automotive-industry](http://www.ellenmacarthurfoundation.org/circular-economy/interactive-diagram/the-circular-economy-applied-to-the-automotive-industry)
- 837 EMF-ElLEN MacArthur Foundation, 2013b. Towards the circular economy - Economic and business rationale for an accelerated
838 transition.
- 839 ERTRAC-European Road Transport Research Advisory Council, 2012. European Roadmap, Heavy Duty Truck. Report,
840 September 2012.
- 841 Eurostat, 2016. End-of-life vehicles statistics. Available online (1 November 2016): [http://ec.europa.eu/eurostat/statistics-](http://ec.europa.eu/eurostat/statistics-explained/index.php/End-of-life_vehicle_statistics)
842 [explained/index.php/End-of-life_vehicle_statistics](http://ec.europa.eu/eurostat/statistics-explained/index.php/End-of-life_vehicle_statistics)
- 843 Farel, R., Yannou, B., Bertoluci, G., 2013. Finding best practices for automotive glazing recycling: a network optimization model.
844 *Journal of Cleaner Production*, Elsevier, 2013, pp.446-461, doi: 10.1016/j.jclepro.2013.02.022.
- 845 Froelich, D., Haoues, N., Leroy, Y., Renard, H., 2007. Development of a new methodology to integrate ELV treatment limits into
846 requirements for metal automotive part design. *Minerals Engineering*, 20, 2007, pp. 891–901.
- 847 Garcia, J., Millet, D., Tonnelier, P., 2015. A tool to evaluate the impacts of an innovation on a product's recyclability rate by
848 adopting a modular approach: automotive sector application. *International Journal of Vehicle Design*, Inderscience, 1,
849 pp.1-18.
- 850 Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? *J.*
851 *Clean. Prod.* 143, 757-768.
- 852 Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of
853 environmental and economic systems. *J. Clean. Prod.* 114, 11-32.
- 854 Gnimpieba, Z., Nait-Sidi-Moh, A., Durand, D., Fortin, J., 2015. Using Internet of Things Technologies for a Collaborative Supply
855 Chain: Application to Tracking of Pallets and Containers. *Procedia Computer Science*, Volume 56, 2015, Pages 550-557,
856 ISSN 1877-0509, <http://dx.doi.org/10.1016/j.procs.2015.07.251>
- 857 Hagelüken, C., Lee-Shin, J., Carpentier, A., Heron, C., 2016. The EU Circular Economy and Its Relevance to Metal Recycling.
858 *Recycling* 1, no. 2: 242-253.
- 859 Hill, N., et al., 2012. EU Transport GHG: Routes to 2050 II. The role of GHG emissions from infrastructure construction, vehicle
860 manufacturing, and ELVs in overall transport sector emissions. Available online (1 November 2016):
861 www.eutransportghg2050.eu
- 862 Husnjak, S., Peraković, D., Forenbacher, I., Mumdziew, M., 2015. Telematics System in Usage Based Motor Insurance.
863 *Procedia Engineering*, Volume 100, 2015, pp. 816-825, ISSN 1877-7058, <http://dx.doi.org/10.1016/j.proeng.2015.01.436>.
- 864 IBM Global Business Services Automotive, 2009. Truck 2020 transcending turbulence. Executive Report 2009, IBM Institute for
865 Business Value.
- 866 ICCT-International Council on Clean Transportation, 2015. Overview of the heavy-duty vehicle market and CO2 emissions in the
867 European Union. Working Paper, December 2015.
- 868 ICCT-International Council on Clean Transportation, 2016. European Vehicles Market Statistics. Pocketbook 2015-2016.
- 869 IDIS-International Dismantling Information System, 2016. Available online (1 November 2016):
870 <http://www.idis2.com/index.php?action=home&language=english>
- 871 INDRA Automobile Recycling, 2016a. Available online (1 November 2016): http://www.indra.fr/en/recycling_engineering.html
- 872 INDRA Automobile Recycling, 2016b. Available online (1 November 2016): <http://www.indra.fr/en/IT-solutions.html>
- 873 Intel, 2015. Internet of Things Sensors Add Intelligence to Trucks. Available online (1 November 2016):
874 <http://www.intel.com/content/www/us/en/internet-of-things/customer-stories/saia-trucking-adds-intelligence-with-intel.html>
- 875 IPCC-Intergovernmental Panel on Climate Change, 2014. Climate Change 2014: Impacts, Adaptation and Vulnerability:
876 Regional Aspects. Cambridge University Press.
- 877 IPCC-Intergovernmental Panel on Climate Change, 2015. Climate Change 2014: Mitigation of Climate Change (Vol. 3).
878 Cambridge University Press.
- 879 Japke, O., 2009. Practice Guidelines, Development of a framework for assessing the economic benefits of remanufacturing.
880 CRR, Center for Remanufacturing & Reuse, UK.
- 881 Kiser, B., 2016. Circular economy: Getting the circulation going. *Nature*, 531, 443–446, 24 March 2016.
- 882 Kwak, M., Kim, H., 2016. Modeling the Time-Varying Advantages of a Remanufactured Product: Is “Reman” Better Than “Brand
883 New”? *J. Mech. Des* 138(5), 051701, Mar 11, 2016, 18 pages, Paper No: MD-14-1736; doi: 10.1115/1.4032808
- 884 Lacy, P., 2015. Growth, Innovation and Customer Value through the Circular Economy. *Accenture Strategy*, 2015.
- 885 Lieder, M., Rashid, A., 2016. Towards circular economy implementation: A comprehensive review in context of manufacturing
886 industry. *J. Clean. Prod.* 115, 36–51.
- 887 Ma, J., Kwak, M., Kim, H. M., (2014). Demand Trend Mining for Predictive Life Cycle Design, *J. Clean. Prod.*, 68, pp. 189-199.
- 888 Ma, J., Okudan Kremer, G., 2014. A Systematic Literature Review of Modular Product Design (MPD) from the Perspective of
889 Sustainability, *Int J Adv Manuf Technol.* 86: 1509. doi:10.1007/s00170-015-8290-9.
- 890 Manitou Group, 2016. Handling your world. Annual Report 2015. May, 2016.
- 891 Matexchange, 2016. Available online: (accessed on 1 November 2016): <http://www.matexchange.fr/>
- 892 MGI- McKinsey Global Institute, 2013. Resource Revolution: Tracking global commodity markets. McKinsey Sustainability &
893 Resource Productivity Practice, September 2013.
- 894 MGI-McKinsey Global Institute, 2015. Europe's Circular Economy Opportunity, Report, September 2015.

- 895 Michelin, 2016. Michelin Challenge Bibendum Community, Vehicles and the Circular Economy. Available online (1 November
896 2016): <https://community.michelinchallengebibendum.com/docs/DOC-2364>
- 897 Millet D., Yvars P.A., Tonnelier P., 2012. A method for identifying the worst recycling case: Application on a range of vehicles in
898 the automotive sector. Resources, Conservation and Recycling, Volume 68, November 2012, Pages 1-13, ISSN 0921-
899 3449, <http://dx.doi.org/10.1016/j.resconrec.2012.07.002>.
- 900 Moreno, M., de los Rios, C., Rowe, Z., Charnley, F., 2016. A Conceptual Framework for Circular Design. Sustainability, 8, 937.
- 901 Niero, M., Olsen, S.I., 2016. Circular economy: To be or not to be in a closed product loop? A Life Cycle Assessment of
902 aluminium cans with inclusion of alloying elements, Resources, Conservation and Recycling, Volume 114, November
903 2016, Pages 18-31, ISSN 0921-3449, <http://doi.org/10.1016/j.resconrec.2016.06.023>.
- 904 NSTSCE-National Surface Transportation Safety Center for Excellence, 2012. Market Guide to Fleet Telematics Services,
905 Creating a Consumer's Guide to Currently Available Aftermarket Solutions. Tammy E. Trimble & Darrell S. Bowman,
906 December 2012.
- 907 Parto, S., Loorbach, D., Lansink, A., 2017. Transitions and institutional change: the case of the Dutch waste subsystem. In:
908 Industrial Innovation and Environmental Regulation.
- 909 Poulidakos, L.D., Heutschi, K., Soltic, P., 2013. Heavy duty vehicles: Impact on the environment and the path to green
910 operation. Environmental Science & Policy, Volume 33, November 2013, Pages 154-161, ISSN 1462-9011,
911 <http://dx.doi.org/10.1016/j.envsci.2013.05.004>.
- 912 Recycling, 2016. Available online (1 November 2016): <http://www.recycling.com/downloads/waste-hierarchy-lansinks-ladder/>
913 Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and setting
914 up a European Chemicals Agency
- 915 Reuter, M.A., van Schaik, A., Ignatenko, O., de Haan, G.J., 2006. Fundamental limits for the recycling of end-of-life vehicles.
916 Minerals Engineering, Volume 19, Issue 5, April 2006, Pages 433-449.
- 917 Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to Assess Product Performance in the Circular Economy? Proposed
918 Requirements for the Design of a Circularity Measurement Framework. Recycling, 2, 6.
- 919 Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: Alternative
920 concepts for trans-disciplinary research. Environmental Development, Volume 17, January 2016, Pages 48-56, ISSN
921 2211-4645, <http://dx.doi.org/10.1016/j.envdev.2015.09.002>.
- 922 Sievers, H., Tercero, L., 2012. European dependence on and concentration tendencies of the material production. Polinares, EU
923 Policy on Natural Resources, March 2012.
- 924 Simic, V., 2013. End-of-life vehicle recycling - A review of the state-of-the-art. Tehnički vjesnik – Technical Gazette 20. 2. 2013.
925 p. 371-380.
- 926 Simic, V., 2015. A two-stage interval-stochastic programming model for planning end-of-life vehicles allocation under
927 uncertainty. Resources, Conservation and Recycling, Volume 98, May 2015, Pages 19-29, ISSN 0921-3449,
928 <http://dx.doi.org/10.1016/j.resconrec.2015.03.005>.
- 929 Snodgrass D., 2012. Sustainable development – Our focus & commitment. Cat Reman, Septembre 2012.
- 930 Toyota, 2016. Available online: <https://www.toyota-europe.com/world-of-toyota/feel/environment/better-earth/recycle>
- 931 Tukker, A., 2015. Product services for a resource-efficient and circular economy – a review. Journal of Cleaner Production,
932 Volume 97, 15 June 2015, Pages 76-91, ISSN 0959-6526, <http://dx.doi.org/10.1016/j.jclepro.2013.11.049>.
- 933 Tukker, A., Cohen, M. J., 2004. Industrial Ecology and the Automotive Transport System. Journal of Industrial Ecology, 8: 14–
934 18. doi:10.1162/1088198042442324
- 935 UNECE-United Nations Economic Commission for Europe, 2016. Heavy-Duty Vehicles Classification in Europe. Available online
936 (1 November 2016): <http://www.unece.org/trans/main/wp29/wp29wgs/wp29gen/wp29classification.html>
- 937 USDoE-US Department of Energy, 2013. Energy Efficiency & Renewable Energy, Workshop Report: Trucks and Heavy-Duty
938 Vehicles Technical Requirements and Gaps for Lightweight and Propulsion Materials. February 2013.
- 939 USDOT-US Department of Transportation, 2014. Study of the Impact of a Telematics System on Safe and Fuel-efficient Driving
940 in Trucks, April 2014.
- 941 USITC-US International Trade Commission, 2012. Remanufactured Goods: An Overview of the U.S. and Global Industries,
942 Markets, and Trade. Chapter 4: Heavy-Duty and Off-Road (HDOR) Equipment, Investigation No. 332-525, USITC
943 Publication 4356, October 2012.
- 944 Velis, C.A., 2015. Circular economy and global secondary material supply chains. Editorial, Waste Manag. Res., Vol. 33(5) 389–
945 391.
- 946 Velis, C.A., Vrancken, K.C., 2015. Which material ownership and responsibility in a circular economy? Editorial, Waste Manag.
947 Res., Vol. 33(9) 773–774.
- 948 Volvo Group, 2015. The Volvo Group Annual and Sustainability Report 2015. Report, pp. 22.
- 949 Volvo Truck Corporation, 2012. Disassembly instructions, complete vehicle. Service Information, Volvo Truck Corporation,
950 Göteborg, Sweden, 2012.
- 951 Walker, G., Manson, A., 2014. Telematics, urban freight logistics and low carbon road networks. Journal of Transport
952 Geography, Vol. 37, pp. 74–81.
- 953 Walnum, H.J., Simonsen, M. 2015. Does driving behavior matter? An analysis of fuel consumption data from heavy-duty trucks.
954 Transportation Research Part D: Transport and Environment. Volume 36, May 2015, pp. 107–120.
- 955 Walsh, B., 2013. Remanufacturing in Europe – The business case. CRR, Centre for Remanufacturing and Reuse, UK, May
956 2013.
- 957 Weiland, F.W., 2014. European remanufacturing of heavy-duty and off-road vehicle components (including tyres): a hidden
958 giant? FWJ Consulting, May 2014.
- 959 Wells, P., Orsato, R. J., 2005. Redesigning the Industrial Ecology of the Automobile. Journal of Industrial Ecology, 9: 15–30.
960 doi:10.1162/1088198054821645
- 961 Wilts, H., Von Gries, N., Bahn-Walkowiak, B., 2016. From Waste Management to Resource Efficiency - The Need for Policy
962 Mixes. Sustainability, 8, 622.
- 963 Witjes S., Lozano R., 2016. Towards a more Circular Economy: Proposing a framework linking sustainable public procurement
964 and sustainable business models. Resources, Conservation and Recycling, Volume 112, September 2016, Pages 37-44,
965 ISSN 0921-3449, <http://dx.doi.org/10.1016/j.resconrec.2016.04.015>.
- 966 Yi, H.-C., Park, W.J., 2015. Design and Implementation of an End-of-Life Vehicle Recycling Center Based on IoT (Internet of
967 Things) in Korea. Procedia CIRP, Volume 29, 2015, Pages 728-733, ISSN 2212-8271,
968 <http://dx.doi.org/10.1016/j.procir.2015.02.007>.
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APPENDIX A - QUESTIONNAIRE

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The semi-structured interview guide used to discuss circular economy implementation with automotive and HDOR actors, was divided into four main sections:

- i. General information about the actor and company questioned, including company name, activity, size and geographical location, background, business model(s), suppliers and clients, existing collaborations, vehicle types.
Q#0: In a word, what are the current main needs and issues you have to deal with?
- ii. Regulatory aspects, including current regulations to be complied with, and anticipation of upcoming regulations.
Q#1: What are the current regulations you have to comply with?
Q#2: What are your strategies to deal with upcoming or future regulations?
Q#3: Do you have any interest in an extension of ELV Regulations to Heavy Vehicles?
- iii. Management of life cycle, including: pre-life (design, manufacturing, logistics), life (use, maintenance, upgrading), end-of-life (reuse, recovery, remanufacturing, refurbishing, recycling, disposal), and integration of emerging technologies.
Q#4: In which steps of the life cycle of HDOR Vehicles is your company involved?
Q#5: What are the highest value components or operations, in terms of cost, environmental impact, complexity, and technology? Are your systems “eco-designed”? Easy to disassemble?
Q#6: What are the types of systems that fail most often? What are the parts that require most maintenance?
Q#7: Are your systems well designed and dimensioned for your purpose of usage? What parts have evolved a lot since you have been using HDOR vehicles? What parts need some upgrade according to your experience; what could be improved to facilitate maintenance or efficiency during usage?
Q#8: Do you get any feedback during the use phase from the customer or user, for real use or perception? If so, how? If not, do you think it could be of interest for your operations?
Q#9: What is the fate of your systems (vehicles, components, materials) at their end-of-life (EoL), when they no longer function?
Q#10: Do you propose second-hand systems (vehicles, components, materials) in your business operations? Examples?
Q#11: Do you make money from the EoL of your system? How? Who with? Do you collaborate with EoL recycling channels, operators or exporters? Examples?
Q#12: Are you aware of new technologies such as Telematics, Internet of Things, and Big Data in your industrial field? If so, are you aware of the benefits they could bring to your organisation?
Q#13: Have you already implemented such devices in your systems or practices? Do you use them? What do they bring your organisation (positive or negative)? If so, what devices, for what purposes? If not, are you planning to use them in the (near) future?
- iv. Sustainability issues and circular economy positioning, including social and economic situations, environmental concerns and circular economy transition.
Q#14: What could be improved regarding the social or economic dimensions of your companies? Do you have any KPIs (Key Performance Indicators) to measure these aspects?
Q#15: Are you currently undertaking or planning to undertake any environmental actions? Examples? Have you heard of the ISO 14001 certification?
Q#16: What is the main reason, or trigger for these actions? Environmental sensitivity, economic benefits, pressure from customers or regulations, or profitability of selling green products?
Q#17: Are you aware of the Circular Economy model, and of the opportunities and benefits it could bring you?
Q#18: What could/should be done at your level to move towards a more efficient circular model?

The above generic questionnaire served as a guide but was adapted for each interview. The following companies, agencies and persons were interviewed: raw materials national expert from ADEME (French environmental agency), end-of-life transportation means coordinator from ADEME, project manager from INDRA (precursor and leading player in vehicle recycling in France), director manager from CIDER Engineering (private agency expert HDOR dismantling), director manager from TORA Location (NRMM rental company), road construction site supervisor from COLAS (major user of NRMM), sustainable development manager from MANITOU (handling equipment manufacturer).