Towards a Circular Dutch Heavy-Duty Vehicle Value Chain

A Multi-Level Perspective analysis of the Dutch Heavy-Duty Vehicle Value Chain following the Solution-focused Sustainability Assessment

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Thomas Spruijt

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"The current European policymakers are focused to steer the present-day into the right direction, to keep it from falling apart. However, prolonging the fragile present-day that can collapse any moment, is by no means a future" – Robert Menasse

"The world has enough for everyone's needs, but not for everyone's greed." – Mahatma Gandhi

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Executive summary

The call for a sustainable world seems to be larger than ever: climate change due to Green House Gas (GHG) emissions, biodiversity loss and resources are increasingly depleted. The heavy-duty vehicle (HDV) sector currently contributes 6% to the overall GHG emissions in Europe, vehicles are produced and often disposed of in an environmentally unfriendly way, and resource scarcity complicates its transition towards a zero emission future.

By eliminating waste and pollution, keeping products and materials in use, and regenerating natural systems, the Circular Economy is being increasingly recognised to address these challenges. To battle resource depletion, and GHG emissions and to improve the security of supply, the Dutch government has the ambition to become a fully Circular Economy in 2050.

The Netherlands is one of the major HDV-producing countries in Europe. Producing almost 100,000 vehicles in 2021, leading to an exported value of 6.3 BN euros. The production of HDVs is still an unsustainable practice. Sustainability targets are ambitious, progress is slow, or practices even become (temporarily) more polluting. On top of that, the constant innovation for fuel efficiency leads to a trade-off between use phase performance and circularity. This is amplified by the linear mindset apparent in the current value chain. The business-as-usual is producing as many vehicles as possible, with little regard for circular design and standardisation aimed at reuse.

In 2021, governmental statistics state that 255 vehicles are dismantled by Authorized Treatment Facilities (ATFs) within Dutch borders (Traa, 2022). The official numbers do not encompass the full dismantling capacity in The Netherlands, as many more End-of-Life (EoL) Vehicles (ELVs) are imported for dismantling. These vehicles consist mainly of salvaged vehicles and vehicles returned in take-back programmes. The Dutch ATFs operate efficiently and can utilise most of the components and put them on the aftermarket, even with a warranty, certified by the authority of Kwaliteitszorg Demontage. Nevertheless, dismantling is an expensive practice, driven by high labour costs and low prices for second-hand parts or secondary materials and is often financially not viable. This is amplified by the fact that the current linear way of production of new vehicles does not reflect the full costs of production as not all external social and environmental costs are included.

In general, a vehicle will almost certainly not end its life in The Netherlands. 95% will be exported as a used vehicle, even though when it is considered an ELV, or without roadworthiness certificates. Roughly 70% of European vehicles will end their life in Europe, and 30% in Low and Middle-Income Countries (LMICs). The level of dismantling within Europe is to a large extent not-documented or under unknown conditions. Illegal ATFs can dismantle ELVs for a lower price as they don't adhere to safety standards, and do not adequately dispose of hazardous substances. This significantly hampers the uptake of circular practices. Meanwhile, the oldest vehicles and ELVs are 'dumped' on LMICS, where the level of dismantling is known as subpar to European standards but significantly cheaper than in Europe. The dismantling practices are dangerous for the workman and hazardous for the environment.

In conventional Internal Combustion Engine Vehicles heavy-duty vehicles (ICEV), 95% of the GHG emission is emitted during the use phase. Therefore, from an environmental perspective, it is evident that the use phase needs to be decarbonised. Producing a Battery Electricity Vehicle (BEV) is more polluting than an ICEV, mainly due to the battery pack. Decarbonisation by electrification leads to a GHG emission breakeven point of 63,000 km of mileage given the current Dutch electricity mix.

The electrification of HDVs raises new challenges, at different places in the value chain. Increased demand for Lithium and other Critical Raw Materials (CRM) is foreseen. A shortage in supply is already envisaged as soon as 2025. The current uptake of BEVs in the heavy-duty vehicle sector is yet too slow to even come close to achieving zero emission ambitions. In 2022, only 55 BEVs were registered. Even though BEVs are considered the most mature technology, it is no 'silver bullet'. Therefore, other technologies should get more emphasis as well. Hydrogen is one technology suggested by the industry, although this is still in a juvenile phase. Regardless of the pace of uptake of zero-emission vehicles (ZEV) the ICEV will not be phased out for a long time. Following the ambitions agreed upon during COP26, the legacy fleet will exist for at least until 2035 for the majority of ICEVs. Synthetic fuels are suggested as an option by the industry to decarbonise these vehicles until they are phased out.

The transition towards ZEVs will have serious consequences for the current value chain. This thesis shows that LMICs do not even possess the infrastructure to maintain cleaner ICEVs, above EURO IV emissions standards, let alone will have the infrastructure to drive, maintain and dismantle ZEVs in the foreseeable future. This potentially leads to a vehicle that will end its lifecycle within Europe and LMICs that must rely on other, substandard Asian HDVs, with a lifetime of only 10% of the European competition.

To overcome the barriers hindering the transition of the HDV value chain towards a Circular Economy, this research gives various recommendations.

For the industry
The zero emission transition will change the value chain drastically. More stringent regulation on circularity, resource scarcity, true pricing and a lacking infrastructure in importing countries for zero emission vehicles, asks for reconsidering business models and the design of the vehicle. This can ultimately lead to a (forced) full lifecycle in Europe.

Industry players should anticipate these drastic changes through better collaboration in the value chain, by sharing information on practices, materials and whereabouts of vehicles. The reinvention of the wheel is not necessary: Dismantlers and recyclers are knowledgeable and efficient. This can be put to use to transition towards a circular HDV value chain.

For circular business models, a different design is needed. The industry should focus on retaining the value of vehicles and components. By circular design, the economic life of HDVs and their components can be increased, and with extra emphasis on design for disassembly and recycling, components can be reused for a longer time and eventually recycled as an end-of-pipe solution for closing the material loop.

A potential option with a lot of impact is to implement innovative circular business models, even if these are operating in a different business context. Caterpillar, an OEM that produces Heavy-Duty Offroad Machinery, proves such a business model to be profitable, even for highly heterogeneous equipment.

For policymakers
The most important recommendation for policymakers is to create a level-playing field between virgin materials, new products, secondary materials and circular practices. Legislation should be adapted to incentivise circular practices, e.g. by tax relief on repair and reuse, which is already in place in Sweden, and additional policies like tax on use of virgin material, or mandatory targets for use of secondary materials. Ultimately, this can be the basis for proper accounting of external environmental and social

costs. For example, in a True Pricing model. True Pricing will level the playing field for dismantling practices, and use of secondary materials. Appropriate accounting could lead to resolving the supply and demand equilibrium by the invisible hand. The industry can also be facilitated by a circularity indicator. This facilitates them in defining the circular targets that are currently ambiguous and ill-defined. This research shows that such an indicator will lead to transparency, better-defined goals and a level-playing field for circular alternatives and can create competition on sustainability performance.

Another way of facilitating the industry is by improving the traceability of the vehicle. As the conditions and practices for dismantling are often unknown, the lack of knowledge on the whereabouts of the vehicle hampers the circular design and designing circular policy instruments. This also mitigates the responsibility of the HDV from OEMs, without assigning this responsibility to others.

To become more circular it is important to look beyond the borders of The Netherlands and even beyond those of Europe. The current value chain is only able to become more circular by enhancing EoL-management in LMICs. Merely cascading Dutch high-tech vehicles is not enough. Therefore, front-running countries like the Netherlands have to invest in knowledge and infrastructure in LMIC countries. This will help these countries to improve their freight transport, without pushing them towards more pollutant vehicles of a lesser quality.

Extension of the ELV directive has the potential to provide tools for better traceability, by requiring Certifications of Destruction (CoD), using Extended Producer Responsibility for shifting responsibility for the EoL phase to Original Equipment Manufacturers (OEM) and by strengthen current import regulations in LMICs with more stringent export regulations and bans on ELV export. However, the ELV directive itself has to improve by avoiding contra-productive definitions, such as backfilling defined as a circular practice. Furthermore, the implementation of the ELV directive extension should be accelerated as much as possible. The first official draft is expected to be published in June 2023, but the actual implementation might still take years.

A pull-driven option for the government is to switch to sustainable procurement of vehicles and incentivise this practice for private stakeholders. A more facilitating option is to create opportunities for the whole value chain to collaborate, by creating temporary spaces with less restrictive competition regulation.

In general, policies should facilitate the industry towards circularity and a more circular mindset. Therefore, more research in the HDV sector should focus on finding comprehensive data on ELV whereabouts and circular practices. On top of that, research should assist the HDV sector should be in anticipating on the drastic changes in the value chain and help LMICs in their ambition for prosperity but in a circular manner.

The necessity to change to a circular mindset can be extrapolated to every other product as well. It is therefore advised for policymakers to use the findings and methods of this research to investigate the barriers and enablers for the transition towards a circular value chain for other major product categories, such as medical equipment, electronics, or textiles.

Acknowledgements

This thesis was written in partial fulfilment of the requirements for the degree of Master of Science in Complex Systems Engineering and Management at the Delft University of Technology. For now, this thesis marks the end of my academic career.

During most of my studies, both my Bachelor's and Master's, I indulged in industry characteristics and the specifics of the energy transition. Through researching circularity at Planbureau voor de Leefomgeving, I wanted to expand my knowledge of sustainability beyond the energy transition. This research showed how a deep dive into an unknown industry like the heavy-duty vehicle sector can spark the enthusiasm for its dynamics and insights.

This would not have been possible without the people around me. I want to thank my academic supervisors Zofia Lukszo and BinBin Pearce for their constructive feedback and the willingness to dive into the concept of the Circular Economy alongside me and Gijsbert Korevaar in special. His knowledge of the Circular Economy, enthusiasm about the subject and tireless guidance truly helped me make the most of my thesis research.

I also would like to thank Mariësse van Sluisveld, Kees Schotten, Ton van Dril and the people from PBL in general. Everyone was very keen on helping me during my research, with a lot of feedback and Mariësse even helping out during the focusgroup for a full day of taking notes meticulously. I think it is safe to say that everyone at PBL is warm-hearted and wants to make the world a bit better through (policy) research. Moreover, I would like to thank all the interviewees and participants from the focusgroup for their significant contribution to this research. Jordi van den Oever from Vos Truckparts for showing me how dismantling is practiced in The Netherlands, and Sjoerd Sintenie from DAF, for the numerous times he helped me out with grasping the finesse of the heavy-duty vehicle sector.

Lastly, I would like to thank my loved ones for their unconditional support, even in written form, and the lovely and much-appreciated conversations during the numerous rides to the TU Delft.

Thomas Spruijt
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1. Introduction

The call for a sustainable world seems to be larger than ever: climate change, biodiversity loss, and resource depletion are one of the many environmental crises the world is currently facing. On top of that, the COVID-pandemic and the Ukraine Crisis exposed our vulnerable dependency on materials and products (Hanemaaijer, 2023). From governments to consumers, many do not yet realise that we are in the middle of a catastrophe. A switch from fossil fuels to renewable energies alone is unfortunately not enough: natural resources and raw materials should be cherished (Mehlhart, 2023).

By eliminating waste and pollution, keeping products and materials in use, and regenerating natural systems, the circular economy is being increasingly recognised to address these challenges (Ellen MacArthur Foundation, 2021; Lieder & Rashid, 2016). To battle resource depletion, greenhouse gas emissions and to improve the security of supply, the Dutch government has the ambition to become a fully Circular Economy in 2050 (Hanemaaijer, 2021)

In this research, the following definition is adopted, adapted from Kirchherr (2017): "A CE describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing products and components, and recycling of materials in production/distribution and consumption processes, to accomplish sustainable development. This implies creating environmental quality, economic prosperity and social equity, for the benefit of current and future generations". This definition aligns with the definition of the Dutch National Programme for Circular Economy (NPCE, 2023).

The definition of the Circular Economy (CE) concept is often under debate, and it is often not highlighted that it needs a systemic shift (Kirchherr et al., 2017). However, the CE concept can act as a guideline for the operationalisation of circular practices (Kirchherr et al., 2017). The transition towards a CE cannot be achieved solely through small incremental changes, it asks for a systemic change in the whole value chain (Rli, 2015). Research should take a holistic approach and investigate how to transition to a Circular Economy, through mapping of barriers, links between value chain phases and stakeholder involvement. The transition to a circular value chain should be made across an entire value chain to ensure circular design, production, use and waste management. (Johansen et al., 2022). Hence, the concept of CE is used in this research to analyse the transition towards a circular value chain.

In 2020, the European heavy vehicle fleet counted 6.2 million heavy vehicles (ACEA, 2022b), of which 160.000 were registered in the Netherlands (CBS, 2022). Annually, 200,000 Heavy-Duty Vehicles (HDV) are taken off the road in the EU, amounting to millions of tonnes of valuable resources (Munir, 2021; Saidani et al., 2018). On top of that, HDVs, which are vehicles allowed to have a Gross Vehicle Weight (GVW) higher than 3.5 tonnes, are responsible for approximately a quarter of CO2 emissions from road transport in the EU (EEA, 2022b) and 6% of the total EU GHG emissions(EC, 2016). Without further action, the share of CO_2 emissions from heavy-duty vehicles is expected to grow by around 9 % between 2010 and 2030 (EC, 2019b).

Therefore, this research focuses on transitioning to a circular heavy-duty vehicle value chain. "The term "circular heavy-duty vehicle" refers to a theoretical product that has maximized materials efficiency, zero materials waste and zero pollution during manufacture, utilization and disposal – which differentiates it from today's zero emission vehicles" (WEF, 2020a).

1.1. The Circularity Options Inventory Network

This research is part of The Circular Options Inventory Network (COIN). COIN aims to provide public quantitative complete information on product chains to support public policy development on circularity. The network is a partnership of PBL, the Dutch Environmental Assessment Agency, with participating universities including Leiden Institute of Environmental Sciences, Utrecht Copernicus institute, University of Amsterdam, Delft University of Technology, and participating knowledge and research institutes including the Dutch National Institute for Public Health and the Environment (RIVM) and the Dutch Organisation for Applied Scientific Research (TNO). COIN aspires to be the knowledge exchange platform for Circularity for the Dutch industry, trade, and professional users. It will be used to facilitate the Circular Economy execution programs of the Dutch government. COIN aims to cover the full field of product categories, actors, and circular strategies. COIN aims to be more comprehensive than other knowledge sources, and to be acknowledged as the shared source for industry, government, user groups, technology suppliers and consultants.

1.2. Knowledge gaps

First, the current lack of state-of-the-art literature on circularity in the HDV sector is to be addressed. As mentioned before, the dearth of this literature is apparent in comparison with the automotive sector. The limited availability of data is a pressing issue and is the reason that the assessment of circularity in the heavy vehicle sector currently relies heavily on stakeholder statements (Baron, 2022).

This dearth has several reasons. The first is the lack of legislation, specifically the lack of ELV legislation for HDVs. One of the reasons for HDV's absence in the ELV directive, is the active lobby of the ACEA against extension to the HDV sector (ACEA, 2020). They state that EoL management of HDVs is a well-functioning and healthy industry, that does not need governmental intervention. Another reason is the smaller amount of heavy-duty vehicles (6,2 million) compared to passenger vehicles (246 million) and light commercial vehicles or vans (29 million) alongside the heterogeneous nature of the vehicles (ACEA, 2020, 2022c). Of the 9 million passenger ELVs, approximately 30% still have unknown whereabouts (Mehlhart, 2022). The ELV directive for passenger cars shows, even though a substantial amount of passenger vehicles still ends up in the illegal circuit, that it will improve the data collection on and insight into the EoL phase of Passenger Vehicles.

Figure 1. Shows the literature appearance of the automotive industry compared to the heavy-duty vehicle. Appendix A. Elaborates on the literature search.

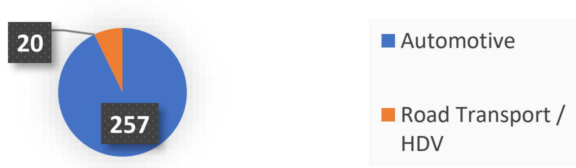


Figure 1. Literature appearance of the automotive industry in general and the HDV sector (2017-2022)

Most research has focused, so far on barriers to a CE in the automotive industry as a whole, or zoomed into certain parts of the passenger vehicle like plastics (van Bruggen et al., 2022), or the batteries (Sopha et al., 2022). A few studies have been on CE for HDVs, mostly zooming in on a certain circular strategy, for example on remanufacturing (Rönkkö et al., 2021; Zhu et al., 2014). Secondly, studies that researched the circular economy in the HDV sector have been so far a qualitative assessment of opportunities, challenges and possible strategies (De Abreu et al., 2022; Paradowska, 2017; Saidani et al., 2019; Saidani et al., 2018; Saidani et al., 2020) However, a quantitative analysis of the value chain yet remains to be done and it is also recommended to do so in order to get a better grasp of the impact of circular strategies within the sector (De Abreu et al., 2022; Saidani et al., 2018). One of the main aims of the COIN project is to map the value chains of product categories. To formulate informed strategies for the implementation of a circular economy, it is imperative to establish a thorough and coherent representation of the material flows, stocks, and waste and emissions outflows. (Krausmann et al., 2017). To fill this gap, the case of the Dutch HDV sector will be used and analysed. To the best of the author's knowledge, not yet before the value chain has been mapped specifically for the Dutch HDV sector. This research will contribute by mapping the baseline quantities of stocks and flows of materials, products and environmental impacts of the Dutch HDV sector, including the key stakeholders and decision-makers relevant for this product category.

Thirdly, most studies have a static view of the transition towards a Circular Economy. Institutional instruments are seen as enablers and technical innovations are potential CE strategies, but it is not taken into account what kind of effects these developments have on the value chain. A useful framework to define dynamics and mechanisms in transition processes is the Multi-Level Perspective framework (Geels, 2002). By using the Multi-Level Perspective framework, these developments and their effects are described.

This research enhances knowledge on the transition towards a circular HDV value chain by conducting an integrated system analysis, combining quantitative and qualitative research. It investigates the sector and material specificity of barriers and opportunities in the HDV sector. The findings have theoretical and practical implications for policymakers, industry stakeholders in the HDV sector, and researchers working towards sustainable and circular HDV systems.

1.3. Research objective and research question

The focus of transport policymaking has been more on addressing emission-related issues in the use and less on ensuring minimal waste and security of resource supply. The EC even proposed new reduction standards, to reduce the CO_2 emission by 45% in 2030 compared to 2019 (EC, 2023b). Currently, the goal is a 30% reduction in 2030. The ambitions in the NPCE (2023) show this has changed for the whole economy and aims to steer towards a Circular Economy, but no distinctive policies are in place to transform these ambitions into actions for the heavy-duty vehicle sector. Taking this into account and with the academic knowledge gaps, the research objective is formulated as:

To develop a deeper understanding of the current level of circularity in the Dutch heavy-duty vehicle sector, identifying circular strategies and enablers to overcome barriers that hamper the systemic shift towards a circular heavy-duty vehicle chain. This deeper understanding should aid Dutch policymakers and industry players in the transition towards a circular heavy-duty vehicle chain.

Stemming from the research objective, this research aims to answer the following research question:

"How to overcome the barriers to a circular value chain for Heavy-Duty Vehicles produced in The Netherlands?"

1.4. Societal relevance of this study

Hanemaaijer (2021) and the National Programme Circular Economy (2023) underline the importance of product-specific research, to create product-specific instruments. This thesis research, being the first of the COIN project, aims to establish the firm ground for the analysis of circular strategies for various value chains present in the Netherlands. The case of the Dutch HDV sector could help to establish a research methodology that allows gathering a comprehensive overview of circular strategies, barriers and opportunities to implement the strategies for various product categories that are prevalent in The Netherlands.

The OEMs active in The Netherlands produce an annual value of over 6 billion euros (CBS, 2022). This underlines the economic importance of the HDV sector for the Netherlands.

The value chain has a global character, but since two of Europe's largest producing facilities, one from DAF and one from Scania, are located in the Netherlands, The Netherlands can exert power on the whole chain. This goes for both facilities in terms of the production process. The design, for DAF, can be adapted within the Dutch borders, while for Scania the main design department is situated in Sweden.

The sector is subject to a lot of factors asking for change. Zero emission transitions, increasingly stringent regulation on emissions, and resource scarcity are putting pressure on the current regime of the incumbents in the HDV sector. This currently creates momentum for creating and researching circular options.

1.5. Link to the CoSEM Study Programme

This research is conducted as part of the master's programme Complex Systems Engineering and Management (CoSEM) at the Delft University of Technology. This programme explores innovations in complex socio-technical environments.

The HDV value chain is a complex socio-technical multiple stakeholder environment, with both private and public actors involved. On top of that, a systemic shift or transition itself is regarded as a complex socio-technical environment. The (radical) change towards a CE reflects non-optimality due to the tension between the energy transition and the shift towards a CE. Its multi-dimensional context contributes to the complexity as well. It encompasses institutional changes, market dynamics, technical developments and their interrelations that either hamper or accelerate the transition.

1.6. Outline of the report

The report has the following outline. Chapter 2. Provides the theoretical basis for this thesis, introduces the case of the Dutch HDV and concludes with the conceptual framework for this research. Chapter 0 elaborates on the methodology used to research the Dutch HDV value chain, barriers and enablers to a circular value chain. It also encompasses the research design that structures the outcomes of this thesis. Each block of the research design corresponds with one chapter in the results section. Chapter 0 reports on the outcomes of the value chain analysis. Chapter 5. Presents the barriers and enablers identified during the exploratory interviews and focusgroup. Chapter 6 synthesises these findings by comparing them to the findings in the literature (6.1) and by positioning them to the institutional developments (6.2) and zero emission transition (6.3). Section 6.5. Gives recommendations for improving the HDV value chain. Chapter 7. Reflects on the scientific methods used and the limitations of the research. This thesis concludes by answering the research questions and giving recommendations for future work in Chapter 8.

2. Theoretical background

This research utilises various theoretical frameworks to understand and describe the key leverage points in the socio-technical environment of the HDV value chain.

In this chapter, the theoretical background places the HDV value chain in the context of transition theory. To understand transitions, section 2.1 elaborates on the theoretical framework introduced by Geels (2002), called the Multi-Level Perspective (MLP). Section 2.2. Describes the circular R-framework and its embedding in the value chain, which is used to gain a deeper understanding of the HDV value chain. Section 2.3. Explains the typology used to identify barriers and enablers. Then, section 2.4. Introduces the conceptual framework that incorporates the value chain, the MLP and the typology of barriers and solutions. Section 2.4.1 elaborates on the case of the HDV. Section 2.6 concludes this chapter by introducing the sub-research questions.

2.1. The Multi-Level Perspective

Each transition progresses through various stages in which a new regime emerges and, when successful, the incumbent regime will replace: the pre-development, start-up, acceleration and stabilisation phase (Hanemaaijer, 2023). Transitions rarely develop linearly in distinctive phases. The Multi-Level Perspective (MLP) framework operates on the premise that technologies are not isolated in a social vacuum, but instead are contingent on critical socio-economic and socio-political factors that shape the process of technical change and the adoption of innovation. (Nurdiawati & Agrawal, 2022).

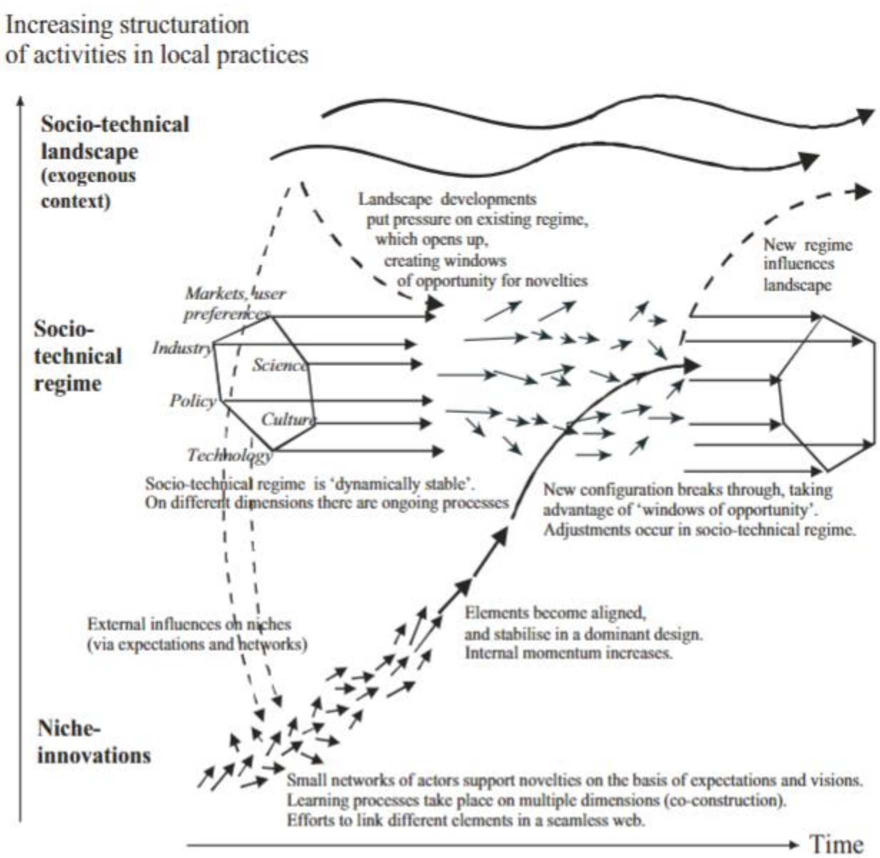


Figure 2: The Multi-Level Perspective. (Geels, 2011).

The MLP recognises a transition as a non-linear process and has a nested hierarchy in which the niche-level innovations are embedded in a socio-technical regime, that is in turn embedded in the socio-technical landscape (Geels, 2005). Figure 2. Shows the nesting and interrelations between the different levels.

The socio-technical landscape cannot be influenced by the socio-technical regime and niche level in a short time span (Geels & Schot, 2007). The socio-technical landscape includes deep and large societal values, climate change, macro-economic trends and large events, such as the Ukraine war, or other crises (El Bilali, 2019). Occasionally, these unexpected large-scale events can result in a “window of opportunity”. On the one hand, the landscape environment can push towards a circular economy: Aggravating European concerns on resource scarcity and security of supply, also due to crises of the Ukraine war and COVID-pandemic (EC, 2023a) more awareness for pollution and circumstances along the value chain (Hanemaaijer, 2023) and the imminent need to decarbonise the heavy vehicle. The reality is the landscape context might also hamper developments towards circularity, for example, due to trade-offs between fuel efficiency and material use (Saidani et al., 2018). Landscape conditions are explored in depth in Section 4.1.

The regime level represents the dominant set of rules, norms, and practices that shape the existing socio-technical system. This level is characterized by stability and the reproduction of existing structures and ways of doing things. Legislation and regulation based on landscape-level politics play a significant role in supporting or challenging dominant regimes. Incumbent regime actors, such as established firms, governments, and other influential stakeholders, have a vested interest in maintaining the status quo and resisting disruptive innovations that could threaten their position (Jackson et al., 2014). This creates a lock-in effect, which creates self-reinforcing barriers that hamper the systemic shift to a circular economy (Chizaryfard et al., 2021).

Niches are the location wherein innovations are developed, which can grow, destabilize or even change regime practices. The innovation can be anywhere in the stage from a R&D project to a mature technology.

According to Geels (2011), the niche level is the breeding ground for innovations, which have the potential to disrupt, transform or replace existing regime practices. These innovations are new technologies or socio-technical practices being developed in a protected environment. Such innovations can range from a research and development project to mature technology, as long as they do not conform to the prevailing ways of doing things, and have not yet gained dominance within the regime (van Eijck & Romijn, 2008). The niche-innovation level is used to describe the introduction of zero emission vehicles and is elaborated upon in section 4.1.2.

The MLP is a useful perspective to analyse both the top-down landscape factors and the bottom-up niche-level developments influencing the HDV value chain. Prior research has highlighted the MLP as a valuable perspective for investigating socio-technical transitions in various industries, including the automotive (Berkeley et al., 2017), or the heavy-duty vehicle industry (Berggren et al., 2015).

It recognises that a systemic shift in the incumbent automotive regime is complex, and involves multi-dimensional, interlinked and dynamic interactions between all MLP levels (Berkeley et al., 2017). However, MLP studies tend to focus on the diffusion of new artefactual technologies, while the socio-institutional, and organisational aspects are overlooked (Sarasini & Linder, 2018). Further criticism states that there is a lack of attention to actor dynamics (Markard et al., 2012). The transition from linear resource management of make, take and waste, to circular models of resource use, involves a deeper understanding of the processes and phases of socio-technical transitions (Jackson et al., 2014).

This problem is addressed by the active involvement of stakeholders. A way of involving stakeholders is by mapping the problem in an iterative multi-stakeholder learning process (Bergek et al., 2008). In 2016, (Zijp et al.) introduced the Solution-focused Sustainability Assessment framework (SfSA), an approach that allows one to gain a broad insight into the scientific and practical aspects of a problem and its potential solutions. The SfSA is enhanced by employing a 'chain approach', which seeks to engage stakeholders from various stages of a product chain to investigate the solution space from diverse perspectives. (van Bruggen, 2022). Application of the SfSA approach resulted in broad support for the proposed solution space and a better interpretation of the problem (Zijp et al., 2016). It is particularly helpful when a single risk metric would ban an activity, whilst it would be allowed, or even stimulated from a multi-metric sustainability assessment. Similar friction exists between certain decarbonisation regulations, circularity ambitions and frameworks for waste processing (Krausmann et al., 2017). The use of the SfSA will be elaborated upon in section 3.2.

The MLP functions as the basis on which the circular R-framework will be embedded. This results in the conceptual framework, introduced in section 2.4, that will be used to answer the research question.

This research contributes to the state-of-the art literature on MLP in the following ways:

- It takes the niche-level innovation as an influence on the current regime, alongside the developments in the socio-institutional landscape. This underlines the importance of the socio-institutional and organisational aspects, which are often overlooked.
- By combining a value chain analysis with a stakeholder chain approach, more focus is also on the interdependency between the various actors in the system. By using the SfSA approach, the potential of actor dynamics and interlinkage will be used to gain innovative insights.

2.2. R-Framework and embedding in the value chain

The value chain of the Dutch heavy-duty vehicle is a socio-technical regime. To describe the current state of the socio-technical regime, its current best practices and strategies to become more circular, the R-framework, and its embedding in the value chain are used.

The R-framework is a modification of the Ladder van Lansink, a priority order for waste treatment methods (Potting et al., 2017). Reducing material use is possible by implementing various circularity strategies (R-strategies). Various R-frameworks have been proposed. For example, the 3R-framework (Reduce, Reuse, Recycle) (Ghisellini et al., 2016), or the 4R-framework introduced in the Waste Framework Directive, with the added Recovery strategy (Commission, 2008). The most nuanced one is the 9R-framework, introduced by Potting et al. (2017). This framework is used in most Dutch policy documents and research from PBL (Hanemaaijer, 2021). Hence, Potting's 9R-framework will be considered in this research as the normative R-framework.

Figure 4: The embedding of the R-strategies in the HDV value chain (Potting et al., 2017) Figure 3. Shows the various strategies, prioritised hierarchically, following the Ladder van Lansink (Potting, 2017). Higher up the ladder means that the strategy is superior to a lower strategy, in terms of material circularity, or material reduction. These can be categorised into four categories, following the categories of Hanemaaijer (2023):

1. Narrow the loop: Smarter product use and manufacturing by using less material by avoiding the use of the product (R0: Refuse), increasing the utilisation of a product (R1: Rethink), or producing the product more efficiently (R2: Reduce)
2. Slow the loop: Product and component life elongation through reuse (R3: Reuse), maintaining the product (R4: Repair), Restore an old product (R5: Refurbish), using the discarded product or its parts in a new product with the same function (R6: Remanufacture) or use the product or its parts for a different function (R7: Repurpose).
3. Close the loop: Avoid leakage of materials by processing materials to obtain the same (high grade) or lower (low grade) quality (R8: Recycle).
4. Substitution: Replace finite, critical materials with renewable (e.g. biomaterials) or alternative less critical materials.

Another possible way of useful application of materials is the incineration of materials with energy recovery (R9: Recovery). Energy recovery "ends" the resource cycle. A circular economy entails higher strategies, that keep materials in the loop (Van Buren et al., 2016). Therefore, in a circular economy, this strategy should be phased out.

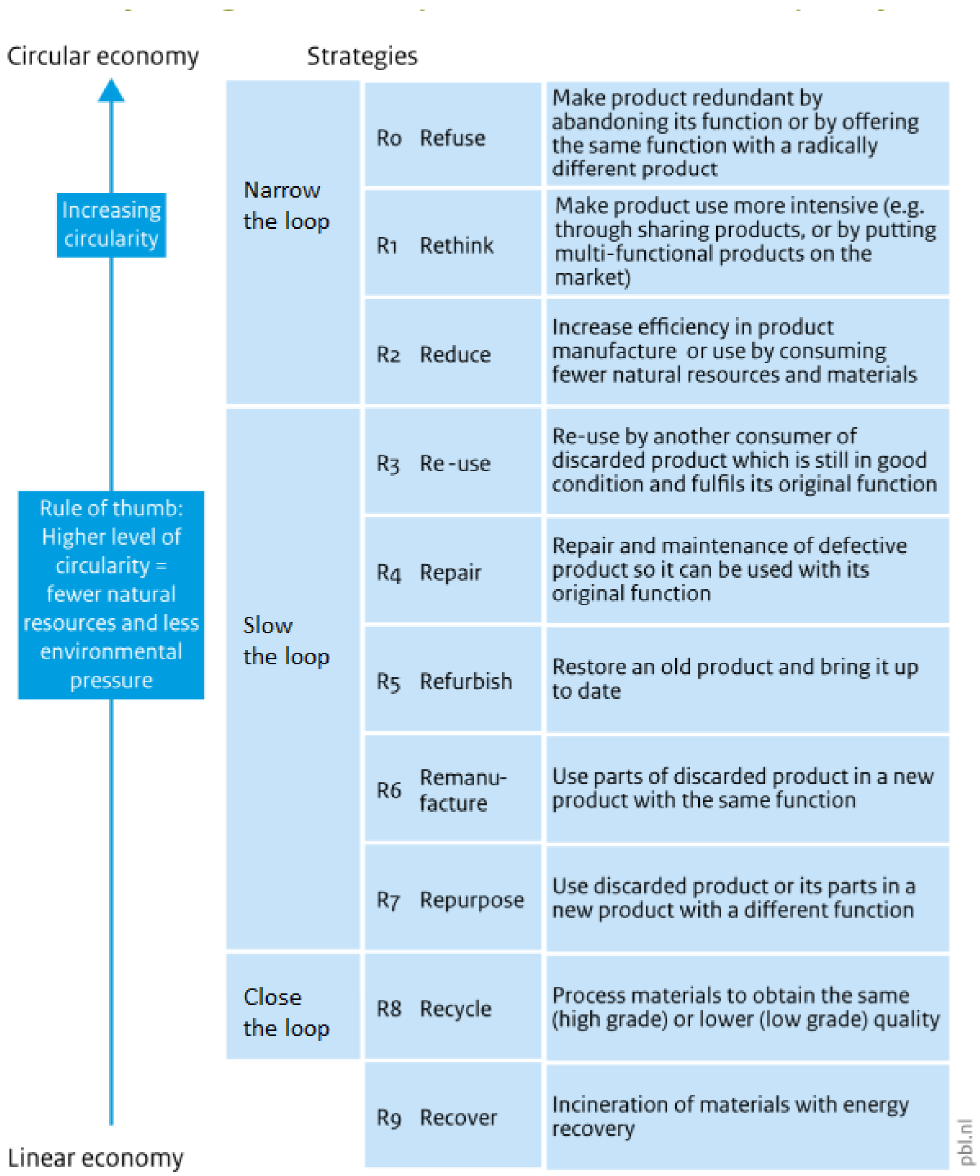


Figure 3: CE strategies, in order of priority. Adapted from Potting et al. (2017)

The R-framework is usually used to describe and group circularity strategies (Hanemaaijer, 2023; Kirchherr et al., 2017; Van Buren et al., 2016). However, (Potting et al., 2017) show that the R-framework is also useful to point out at which place of the value chain the R-strategies are relevant.

Embedding the R-framework in the value chain points out where different circularity strategies are relevant, and which chain actors play a role in those strategies (Potting, 2017). Figure 4. Shows the embedding of these strategies in the value chain of the heavy-duty vehicle.

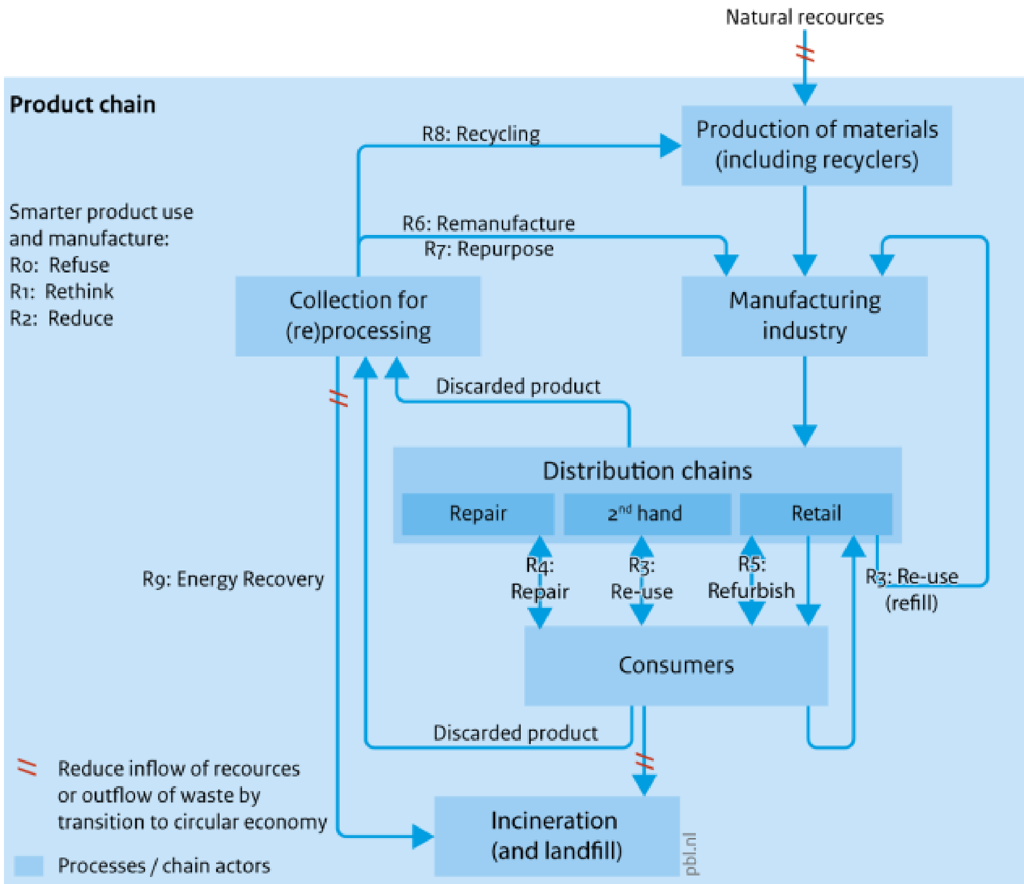


Figure 4: The embedding of the R-strategies in the HDV value chain (Potting et al., 2017).

Following Potting's method, the R-framework is able to describe the socio-technical regime of the value chain of the heavy-duty vehicle. The R-framework and its embedding are employed to analyse the socio-technical regime of the HDV sector and therefore be part of the conceptual framework introduced in section 2.4.

2.3. Barriers and enablers towards a circular economy

The combination of landscape developments such as more stringent policies, and rapid expansion of technological solutions creates risk and uncertainty amongst manufacturers and other industry players. This results in multiple barriers that act against the transition towards a circular heavy vehicle sector (Berggren et al., 2015).

Focal MLP studies suggest that in order to achieve systemic change, barriers extending well beyond technological dimensions need to be overcome (Geels, 2005). The technical feasibility of CE concepts is heavily researched but is also heavily debated being not the key barrier as it is thought to be. Dimensions such as cultural factors, institutions and economic barriers are being seen as just as significant (Berkeley et al., 2017). For example, Kirchherr (2018) identifies a 'lacking consumer interest and awareness' as well as a 'hesitant company culture' as core cultural barriers. These barriers can self-enforce and interact and are therefore often heavily interlinked (Geels & Schot, 2007; Kirchherr et al., 2018; van Bruggen et al., 2022). For example, the combination of the cultural perception barrier that recyclate is dirty and that recyclate is more expensive than virgin material, makes the transition to a CE more difficult (Kirchherr et al., 2018).

The categorisation of barriers provides insights into the level at which enablers need to be formulated (van Bruggen et al., 2022). Various categorisations of barriers exist. Kirchherr et al. (2018) conceptualised four barriers to a general CE framework. However, this framework lacked emphasis on supply chain governance. Findings suggest that little collaboration between stakeholders and the lack of data are important barriers in the HDV sector (Saidani et al., 2018). The categorisation of Sopha et al. (2022) is, therefore, more applicable with the addition of the supply chain barrier. The fifth identified social category encompasses the broader consumer markets within a society (Sopha et al., 2022). However, the cultural aspect entails more than only the perception and acceptance of consumers. For example, the lack of will or motivation to make circular choices is an important perception barrier (van Bruggen et al., 2022). Therefore, the perception barrier and the social barrier are combined in an overarching cultural barrier.

Hence, based on the decisions made above and on the existing categorisations (Kirchherr et al., 2018; Sopha et al., 2022; van Bruggen et al., 2022), five types were distinguished:

- **Technical and infrastructural barriers** regard (a lack of) technology, the infrastructure supporting the recycling process, and the knowledge and skills necessary for the proper functioning. Technical feasibility includes e.g. circular design, a (lack of) proven technology for proper EoL management and component complexity. Infrastructural barriers are ways in which infrastructure limit circularity, such as dismantling/recycle centres and Post Shredder Technology facilities and knowledge and skills necessary for the proper functioning of these infrastructures (Kirchherr et al., 2018; Sopha et al., 2022; van Bruggen et al., 2022).
- **Supply chain governance barriers:** The supply-chain governance category includes the governance of upstream and downstream processes, collaboration and communication between stakeholders in the value chain. The category also includes the information flows in the value chain (Sopha et al., 2022).
- **Economic barriers** are economic and market factors that hinder stakeholders to steer towards a CE. It includes a lack of finances, economic incentives or perverse incentives, such as low prices of virgin material (Kirchherr, 2018; van Bruggen, 2022; Sopha, 2022).
- **Institutional barriers** involve government policies and regulations, such as legal restrictions, lack of policy incentives or perverse stimulants from policy in making circular choices (Kirchherr et al., 2018; Sopha et al., 2022; van Bruggen et al., 2022).
- **Cultural barriers** are particularly barriers regarding the perception of consumers and company culture, resisting change from a linear to a circular business model. It is characterized by a lack of will or awareness to make circular choices, regardless of what is technically or legally possible (Kirchherr et al., 2018; Sopha et al., 2022; van Bruggen et al., 2022).

This research does not only identify barriers that hinder the uptake of circular practices in the HDV value chain, it also investigates enablers for overcoming these barriers. Enablers refer to factors that facilitate the implementation of circular strategies (Sopha et al., 2022). These enablers are key to overcoming perceived barriers that hinder the transition to a circular HDV value chain. The typology of the enablers is similar to the typology of the barriers.

2.4. The Conceptual Framework

This research captures the transition process in a conceptual framework (Verschuren et al., 2010) to answer the research question. The conceptual framework in Figure 5. Combines the previously introduced theoretical concepts and indicates how various factors can influence the transition towards a circular value chain. The Multi-Level Perspective provides the outline of the framework. It shows how the socio-technical regime is influenced by developments in the landscape and niche level.

The socio-technical regime of the current HDV value chain is then described with the use of the R-framework, by embedding the R-strategies in the value chain. The use of the R-framework enables to identify the points of engagement in the socio-technical regime of the HDV value chain.

The landscape developments and niche innovations are able to hamper, complicate or accelerate the system change. New regulations and innovations might be beneficial for a specific area, but hamper the progress in others. For example, often trade-offs exist between improving the performance in the use phase of the vehicle and circularity (Saidani et al., 2018; van Bruggen et al., 2022). This relation is also shown in the conceptual framework, as parameters that influence the transition towards a circular value chain. Through the combination of the R-framework and the MLP, the nuances of the lock-in effects caused by different barriers are easier to be pinpointed, and previous set boundaries are easier to be reviewed.

Barriers sustain the current practices within the heavy vehicle chain and hinder the transition towards a circular value chain. These can self-enforce and interact. The typology of the barriers is identified in section 2.3. Is used to categorise the barriers that hinder the transition towards a circular value chain.

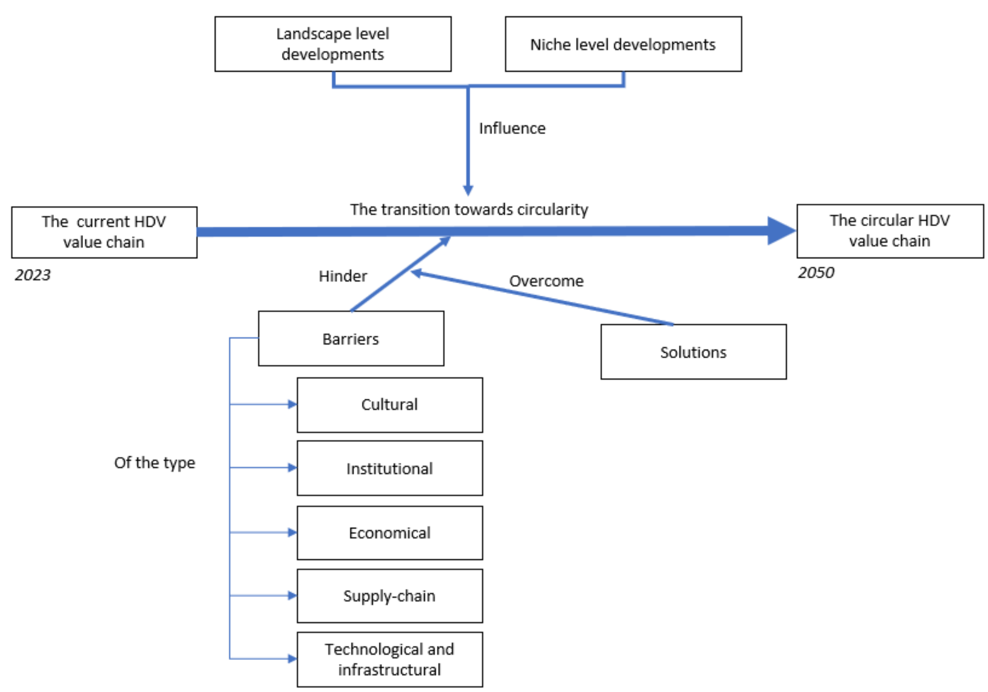


Figure 5: The conceptual framework and typology of barriers, based on the MLP (2.1.), R-framework (2.2.) and typology of barriers (2.3.)

2.4.1. Link between the Solution-focused Sustainability Assessment, the R-framework and the Multi-Level Perspective

In Figure 6. The relation is depicted between the SfSA, R-framework, MLP and the conceptual framework, that is introduced in sector 2.4. The MLP functions as a basis for the conceptual framework. Then, the R-framework is used as a start to researching the characteristics of the current value chain and the current circular practices, which are equal to the socio-technical regime in the MLP. Then, the SfSA method is used for the identification of landscape and niche-level factors that influence the transition towards a circular value chain, the barriers that are hindering the transition, and enablers to overcome these barriers. The findings of the SfSA are then related to the R-framework value chain analysis, to be able to provide insights into the dynamics of the value chain and give distinct recommendations to steer towards a CE. Hence, the SfSA findings are a vital part of this research.

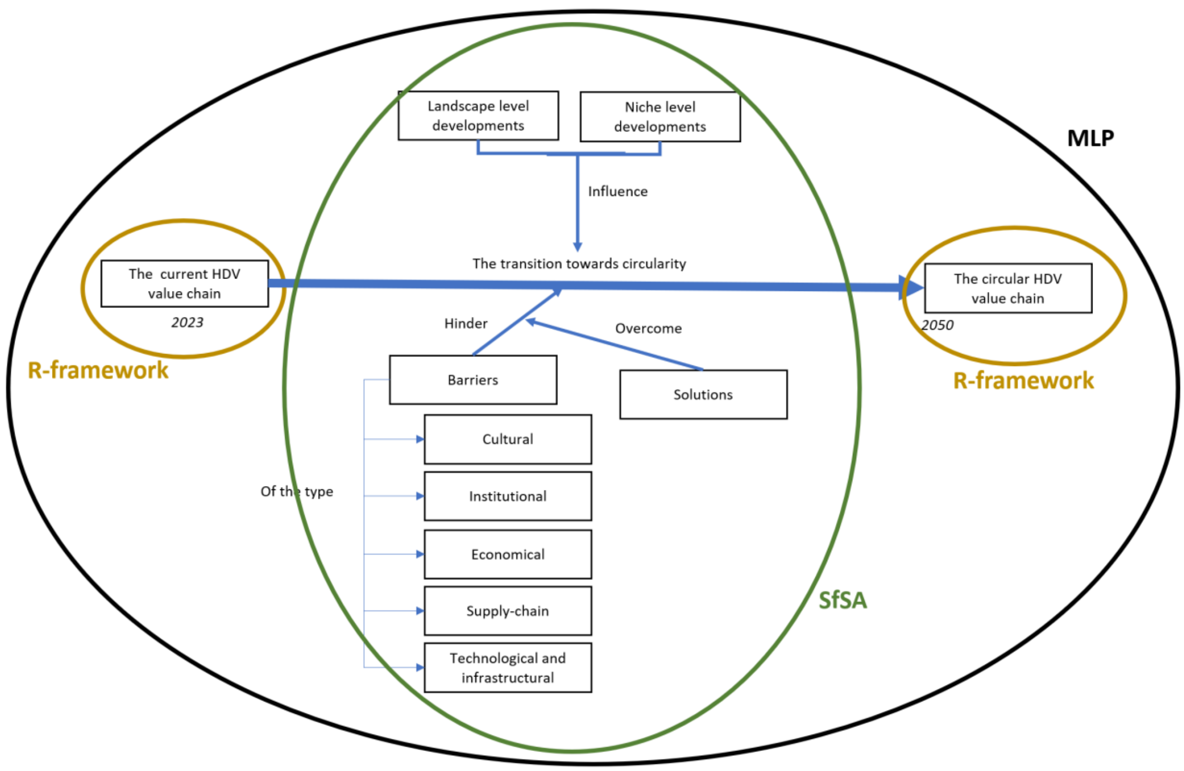


Figure 6: The relation between the SfSA, R-framework, MLP and the conceptual framework

2.5. The Case of the Dutch Heavy-Duty Vehicle

The Heavy-Duty Vehicle sector is not entirely linear. It lies somewhere between a linear and a circular economy. According to the definition of Gudde (2015), it can be defined as a chain economy with feedback loops. This means that it still involves raw material input, and a residual outflow, but also encompasses reuse of materials and components. However, this is mostly regarded as a separate optimisation step, which is an undeliberate consequence of the choices made in the phase of design, production and the use of the vehicle. In a CE, the (re)use of materials is integrated into the optimisation of the delivery of functionality (Gudde, 2015). The combination of more stringent policies and rapid expansion of technological solutions creates momentum for the necessity to research the transition towards a Circular Economy.

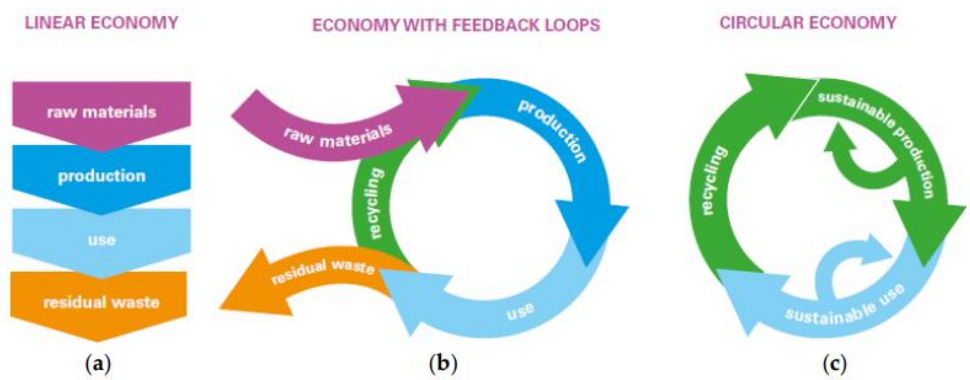


Figure 7: Three types of economies. (Gudde, 2015).

Although the lack of literature research on circularity in the HDV sector, the stakes are high in the HDV sector. First of all, the tonnage of End-of-life (EoL) HDV vehicles represents the same order of magnitude as the EoL Automotive vehicles(Saidani et al., 2018). Currently, 163.000 HDVs are part of the Dutch road transport sector (TLN, 2022). This is equal to an urban mine of 1.6 MT that is not utilised, as 95% of the HDVs do not end their life in The Netherlands (RVO, 2022). A lack of traceability causes a white spot in data on the end-of-life phase. Up to 70% of the HDVs are being dismantled in Europe, but the majority are under non-documented or unknown conditions (Munir, 2021). This is both a significant potential loss of materials and a potential environmental threat.

Secondly, the heavy vehicle sector was selected as a case study because the Netherlands is one of the biggest producers of HDVs in Europe: In 2018, 1/6th of the total European HDV production of 530.000 was produced in The Netherlands (ACEA, 2022a). The Netherlands is the ground for two major Original Equipment Manufacturers (OEMs). DAF with a European market share of 14% and Scania, also with a European market share of 14%. Together they assemble an annual amount of 100.000 trucks in The Netherlands (DAF, 2021; Scania, 2021). In 2021, the added value of the new HDV export was over 6 billion euros (CBS, 2022).

Finally, the heavy-duty sector has a significant carbon footprint. One sector that has a significant contribution to this issue is the heavy-duty vehicle sector. The heavy-duty vehicle contributes for 4% to the total emission of CO_2 equivalents in The Netherlands based on its Use phase (PBL, 2022). And about 6% of the total GHG emissions in the EU (ACEA, 2023a). The WLO (Welfare and Habitual environment) scenarios (Van Meerkerk, 2020) show that the HDV will not become superfluous in the foreseeable future, so it is safe to say that the HDV itself should get on the road towards ZE.

On top of that, production is an energy-intensive process, and operations are difficult to decarbonize (Scania, 2023). Being one of the major producing countries, the Netherlands can be at the forefront of making the heavy-duty vehicle sector steer towards a circular economy.

2.5.1. The definition

The 2007/46/EC directive divides vehicles into categories based on wheel basis, purpose of the vehicle and technically permissible maximum laden mass. The category N is used to define vehicles that are constructed for the carriage of goods, whereas the M category defines vehicles constructed for the carriage of passengers. Category O includes towing vehicles designed to be coupled with a trailer. The subcategories are based on the gross weight of the vehicle (GVW). This is the weight of the empty vehicle plus the weight of the maximum payload that the vehicle is allowed to carry. The focus of this study will be on categories N2, N3, O3 and O4:

- Category N_2: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3,5 tonnes but not exceeding 12 tonnes.
- Category N_3: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 12 tonnes.
- Category O_3: Trailers with a maximum mass exceeding 3,5 tonnes but not exceeding 10 tonnes.
- Category O_4: trailers with a maximum mass exceeding 10 tonnes

Ambiguity exists in terms of categorising based on maximum-laden mass. Organisations have different categories and even within organisations definitions differ (see CBS). Table 1. Shows the categorisations.

Table 1: Various organisations and their categorisation of HDVs

Organisation	Term	*Light*	*Medium*	*Heavy*
ACEA	Commercial Vehicle (CV)	LCV <3.5t	3.5t< MHCV < 16t	16t< HCV
CBS	Freight Vehicle	-	3.5t < x	-
CBS (International trade statistics)	Freight Vehicle / Trailer	< 5t	5t < x < 20t	> 20t
EU	N (Vehicles)	N1 < 3.5t	3.5t < N2 < 12t	12t < N3
	O (Trailers)	3.5t < O1	3.5 < O2 < 10t	10t < O3
RVO	Truck	3.5-7.5t	7.5-16t	16-23t
	Truck Special			>23t
	Trailer	-	16-23t	23t < trailer

The ambiguity troubles data gathering and combining data points of different sources. This ambiguity needs to be dealt with, even though this might lead to small discrepancies in the data analysis. To deal with this ambiguity, two types of definitions are used:

- For the value chain analysis, the clustering of RVO (2022) is used. This clustering results in homogeneous categories.
- For the remainder of the research, all vehicles designed for the carriage of goods and having a GVW exceeding 3.5 tonnes and for the International Trade Statistics of CBS exceeding 5 tonnes will be considered as one category: >3.5t. This will be referred to as a heavy vehicle, or heavy-duty vehicle (HDV).

2.5.2. Geographical scope

The Netherlands has traditionally been a major player in logistics and transport for the rest of Europe. With strategically located ports like the Port of Rotterdam, the largest port in Europe, it transits over 60% of the incoming goods (CBS, 2020). With around 700 million tonnes of transported goods each year, road transport takes account for 39% of the added value of the whole transport sector (Wijnen, 2021). Commercial Vehicle production in the Netherlands consists primarily of HDVs, a significantly lower amount of buses and no production of vans (Statista, 2022). Due to the nature of the COIN project, which aims to map circularity within product chains, a production phase in the Netherlands is of importance. Hence, this research will focus on the product chain of HDVs. DAF is currently the market leader in terms of new HDV registrations in The Netherlands with a share of 31% (ING, 2018). In 2020, amid the COVID-pandemic, DAF produced 42.000 (semi-)heavy trucks and had a worldwide turnover of €5,6 billion (FD, 2022a). Another key player in the Dutch HDV sector is Scania, with a current production capacity of almost 90.000 trucks for worldwide distribution (FD, 2022b).

Due to the international character of the HDV market, international regulations and an end-of-life phase that mostly takes place in other European member states, the geographical scope would not be broad enough if the Dutch boundaries would be chosen to demarcate. Hence, the choice is to scope around the Dutch Heavy-Duty Vehicle. This encompasses vehicles that are either produced, registered at some point in their lifecycle, or traded within the Dutch boundaries.

2.6. Sub research questions

In order to provide a structured answer to the main research question (mRQ), a series of sub-research questions (sRQs) is formulated. These sRQs serve as a means to delineate and organize the various components of the mRQ and facilitate a comprehensive answer.

sRQ1: What does the current value chain of the Dutch heavy vehicle look like?

sRQ2: What circularity strategies are currently prevalent in the heavy-duty vehicle sector and which other ones have the potential to contribute to the road towards a circular economy?

sRQ3: What are the barriers and influential developments to the transition to a circular heavy vehicle value chain?

sRQ4: How can enablers help to overcome the barriers towards a circular heavy-duty vehicle chain?

3. Methodology

Chapter 3. Describes the applied strategy to answer the sub-research questions posed in section 2.6. The research approach and its rationale are presented in section 3.1. Section 3.2 elaborates upon the used SfSA methodology and the embedding of various research methods. The research design will be discussed in section 3.3. Finally, the data collection methods will be elaborated in 3.4.

3.1. Research approach

This thesis research utilises a mixed-methods approach to analyse the HDV value chain. This research approach involves collecting and analysing both quantitative and qualitative data, which can be conceptually and analytically integrated to provide insight into the research question (Tashakkori & Creswell, 2007). A quantitative analysis is needed to provide a better understanding of the current flows and stocks and the potential impact of circularity strategies on the Dutch HDV sector.

However, the limited availability of data is a pressing issue and is the reason that the assessment of circularity in the heavy vehicle sector currently relies heavily on stakeholder statements (Baron, 2022). On top of that, the transition towards a circular HDV value chain identifies as a complex or wicked problem. It is a problem that reflects non-optimality, and trade-offs among conflicting goals such as between the drive for use performance and circularity, in a multi-stakeholder and multi-perspective environment (Zijp et al., 2016). The SfSA is a mixed-method approach that uses a multi-stakeholder perspective to explore solutions to complex problems like sustainability transitions (Zijp et al., 2016). Hence, the Solution-focused Sustainability Assessment (SfSA) is used to explore stakeholder and science-supported insights in the HDV value chain.

The use of this methodology is also beneficial because it is important not to only focus on barriers, but also on ways to overcome the barriers. The SfSA generates the solution space together with the value chain based on the identified barriers. However, the transition to a circular HDV value chain is an extremely complex problem. Dealing with such a complex problem involves identifying enablers that facilitate ways to overcome barriers, rather than creating bite-sized ready-to-be implemented solutions. Solutions imply that there is a single best option. Hence, this research will produce a set of key enablers, rather than straightforward solutions.

van Bruggen et al. (2022) used the Solution-focused Sustainability Assessment, to gain insight into the transition towards a CE for plastics in the automotive industry. Qualitative analysis is used to identify circularity strategies, barriers and opportunities for implementing the selected circular strategies. Saidani followed in 2018 a mixed method research to analyse and compare the heavy vehicle industry with the automotive and used this to seek convergence in findings and find overlapping different facets of the industries. The case of the Dutch HDV sector could help to establish a framework that can be used for further research on circularity strategies in value chains. For example, Saidani et al. (2020) used as well a case-study approach to gain a deeper understanding of the level of circularity in a product category.

It is important to note that the whole research is and will benefit from an iterative process. This gives the opportunity to refine the findings, test them with expert knowledge and additional research, and elaborate upon them via new pathways. Hence, sRQ2-sRQ4 will be part of cyclical and iterative research.

3.2. The Solution-focused Sustainability Assessment

The Solution-focused Sustainability Assessment (SfSA) approach provides a systematic stepwise qualitative approach in the context of sustainability transitions. The first two steps are pre-assessment and developing solutions. Van Bruggen used in 2022 this approach, complementary with an added 'chain approach' to create a solution space to overcome barriers for plastics in the Automotive industry. In this 'chain approach' all stakeholders along a (circular) product chain are brought together in an interactive and transformative approach (van Bruggen et al., 2019). A risk that is inherently The SfSA was used for the identification of barriers and enablers. This builds on the work of van Bruggen et al. (2022), that used the SfSA to identify barriers and solutions for plastics in the automotive industry. The use of the MLP complemented the method by asking the focusgroup to actively think of developments that might influence the value chain, which reduces the static nature of the SfSA.

The research methods are based on and embedded in the SfSA.

Figure 8. Below shows the process steps of the assessment.

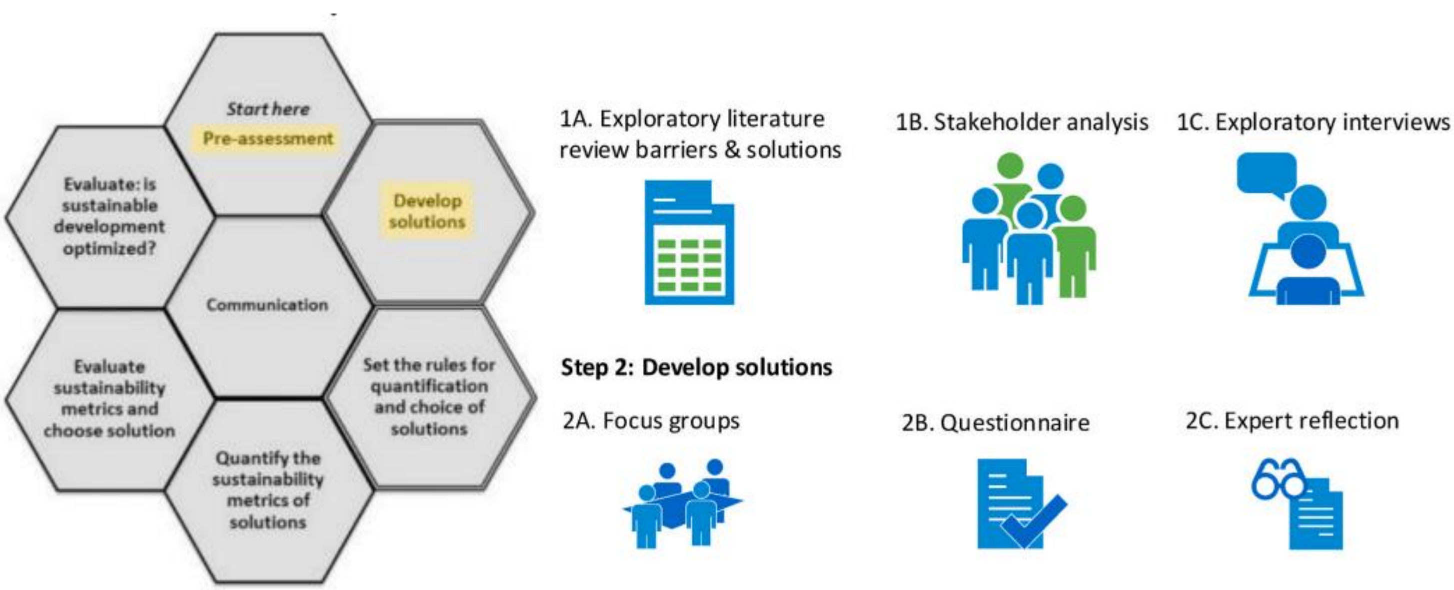


Figure 8: Steps of the SfSA on the left (Zijp et al., 2016), with the detailing of the sub-steps added by van Bruggen et al. (2022)

The approach of van Bruggen et al. (2019), does not include a value chain analysis. This step is added to get an insight into the stocks, and flows of the current HDV value chain. This data shows which value chain phases are of relevance and which interventions do have the potential to impact significantly. The corresponding steps of the SfSA method are highlighted in between brackets for each sub-research question.

For ***sRQ1***, literature and desk research is used. By obtaining data from industry reports, International Trade statistics, literature and policy documents, the stocks and flows in the HDV value chain are mapped. A stakeholder analysis (**1B)** helps to map the value chain, its phases and its actors.

For ***sRQ2-sRQ4***, the same approach is used, following the SfSA method. First, an exploratory literature review (**1A)** is conducted to identify best practices and potential circular strategies, barriers and enablers and solutions. Both grey and white literature will contribute, as the knowledge of circularity in the HDV value chain is rather industry than scientific-driven. The exploratory literature review builds a knowledge base on the research topic. (Earley, 2014). This offers not only practical insights, but also strengthens the position of the researcher in the CE debate in the HDV value chain. The researcher will be able to conduct interviews more thoroughly and coordinate and extract more knowledge from the focus group. Then, exploratory interviews (**1C)** are conducted to expand the knowledge of the current state of circularity in the HDV value chain. The final data is collected in the organised focus group (**2A)**. Research shows that a focus group helps gain support for solutions and policy measures, whilst also adding novel insights on top of the literature findings (van Zijp, 2016; van Bruggen, 2022). Hence, the use of the focusgroup is threefold: It 1. Helps to identify barriers and developments not known in the current state-of-the-art literature. 2. Proposed solutions are agreed upon by the sector itself, and therefore provide a stronger support base for policymakers if they want to implement the said proposed solutions. 3. It strengthens the network in the HDV sector, to enhance the much-needed collaboration for a systemic change towards a CE.

The stakeholder analysis is used to identify important stakeholders that are able to contribute to the debate in the focus group. Finally, stakeholders have vested interests and this might (subconsciously) influence results (Porter & Shortall, 2009). Therefore, the results are validated through an Expert Reflection (**2C)**. The Questionnaire (**2B**) is excluded from this research, due to a limited time frame.

3.3. Research design

A variety of methods has been employed to address each sub-research question. Figure 9. Provides an overview of each research step, how this research step relates to a sRQ, the data gathering method that is used and to which step this relates in the SfSA method.

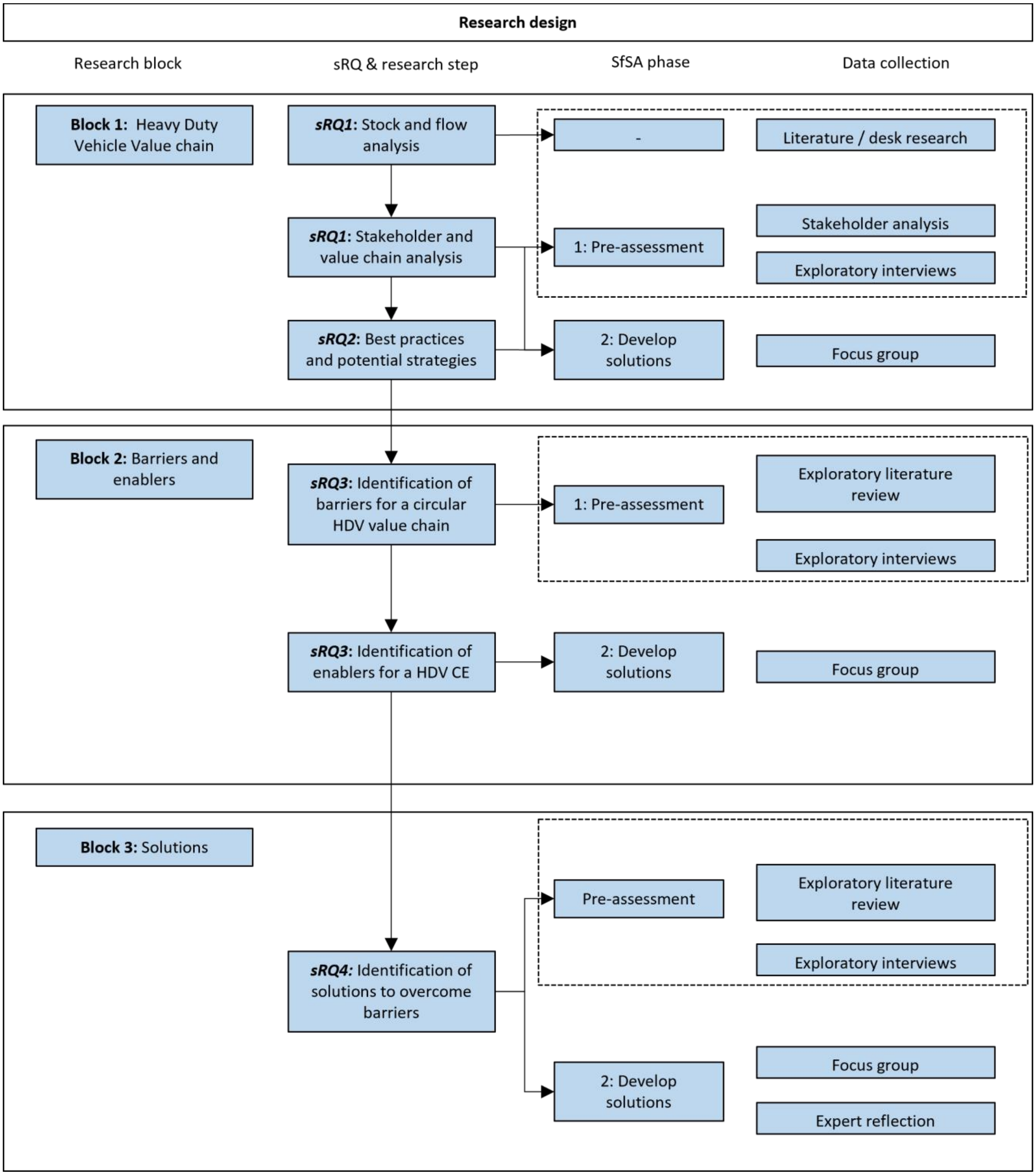


Figure 9: Thesis research design

3.4. Data collection methods

This section elaborates on the data collection methods applied to this research. The choice for the multiple data-collection methods follows the data collection steps as shown in the research design.

3.4.1. Exploratory literature review

The exploratory literature review identified barriers to circularity in the HDV sector. The review is not exhaustive and is neither meant to be. It serves as both a starting point to gain an understanding of the value chain and its dynamics and a basis to review the findings of the focusgroup.

To investigate the current state of the literature on the circular economy in the HDV sector, the following query has been used included in the title, abstract and key: (“End-of-Life Vehicle” OR Circular Economy) AND (Lorry OR Truck OR “Heavy Vehicle” OR “Heavy-Duty Vehicle” OR “Road transport”). Peer-reviewed articles were identified up to the year 2022 through the Elsevier Scopus database.

To identify the relevant articles, two criteria are used for screening. First, eleven articles were selected based on the abstract for a general relationship between CE and the automotive. Second, the article must review barriers to a circular economy. Hence, seven of them are reviewed in depth. Additionally, the snowballing method was applied to further investigate important CE and HDV papers (marked with a *). Furthermore, stakeholders recommended several articles that were relevant to the matter (marked with a **). Table 2. Shows an overview of the selected articles

Table 2: Overview of selected articles

Author	Title	Year	Automotive / HDV	Type
*ACEA	Position paper on CRM	2023	Both	Industry report
**Baron et al.	Improving EoL treatment	2022	Both	Industry report
**Baron & Loew	Coverage of all relevant vehicles by the ELV directive	2022	Both	Industry report
De Abreu et al.	Role of CE in Road Transport	2022	Automotive	Journal article
*EU	Revision of the ELV directive	2021	Both	Government Report
**Munir	End-of-Life Heavy-Duty Vehicles	2021	HDV	Thesis
Paradowska	Challenges for CE in Road Transport	2017	Automotive	Journal article
Ronkko	Remanufacturing HDV: a pilot Study	2018	HDV	Journal article
Saidani et al.	CE and HDV: Comparison with automotive	2018	Both	Journal article
Saidani et al.	EOL management in the US	2019	HDV	Journal article
Saidani et al.	ELV HDV: lessons learnt from a pilot study	2020	HDV	Journal article
*Sopha et al.	Barriers for EVB implementation	2022	Automotive	Journal article
**Van Bruggen et al.	Data	2022	Data	Journal article
**Van der Zaag	Vehicle MFA	2019	Both	Thesis
*WEF	Data	2020	Data	Industry report
Zhu	Barriers to engine remanufacturing in China	2014	HDV	Journal article

3.4.2. Stakeholder selection

Stakeholders were identified by reviewing scientific and grey literature as well as news articles and by using search engines. In addition, 'snowball sampling' was used to identify relevant respondents for exploratory interviews, the focusgroup, and the expert reflection.

Each of the interviewees or participants of the focusgroup was carefully selected based on four criteria. The first is *relevance to the value chain of the organisation.* The organisation should be actively involved in the value chain of the heavy-duty vehicle and be representative for its part of the value chain. Multiple organisations can be relevant in different ways. For example, two different organisations, both operating as dismantlers, have been selected for exploratory interviews, given the different nature of their company. The first is a private dismantler, dismantling vehicles of Scania, DAF & MAN. The second is a dismantler affiliated with a specific brand. During the focusgroup, the Dutch branch organisation for dismantling participated as well. This gave a full view of the different dynamics in the Dutch dismantling industry. The organisation should also be *relevant for the research on circularity within the HDV sector*. Because this research's goal is to provide knowledge for Dutch policymakers and industry players, the organisation should be *relevant for The Netherlands.* This means that it should operate in The Netherlands. The fourth criterium is *the role in the company of the interviewee / focusgroup participant*. The person should have sufficient knowledge on topics related to a Circular Economy and preferably be in the position to exert power in order to steer the company towards a Circular Economy. This also means that multiple persons from the same company can be interviewed or participate in the focusgroup. For example, two persons from the same OEM were interviewed, one as head of Eco-design, and an Environmental Management Specialist. Another example is two individuals employed at the same company, participating in the focusgroup. One was the global head of circular economy, while the other was the head of the Dutch fleet of approximately 1200 trucks.

3.4.3. Exploratory interviews

According to step 1C of the SfSA, exploratory interviews were conducted to get further insight into the context of the HDV sector before convening the planned focusgroup. Interviews are displayed in a non-personal way to ensure anonymity in Table 3. The categorisation was based on the type of organisation, their role in this organisation, and the code for referring to the interview.

Table 3: Overview of interviewees

Organisation	Role	Coding
RIVM	Developer SfSA	(RIVM, personal communication, 19-01-2023)
DAF	Head eco-design	(DAF, personal communication, 02-02-2023)
DAF	Environmental Specialist	(DAF, personal communication, 08-02-2023)
Scania	Head recycling BENELUX	(SVR, personal communication, 13-02-2023)
Vos truckparts	Co-owner	(Vos truckparts, personal communication, 15-02-2023)
Scania	Researcher CE	(Scania CE, personal communication, 16-02-2023)
Université Paris-Saclay	Researcher CE HDV	(Saidani, personal communication, 17-02-2023)
ILT	Specialist waste logistics	(ILT, personal communication, 20-02-2023)
IenW	ELV Policy Officer	(IenW, personal communication, 16-03-2023)

3.4.4. Focusgroup “circularity in the heavy vehicle sector”

For this step (2C in the SfSA), a focusgroup is selected via consultation of interviewees of exploratory interviews and value chain analysis. The focusgroup was organised following the Chatham House rules. Hence, quotes and opinions cannot be related to a specific person. Table 4. Provides the list of participants, their organisation and the role within this organisation, and if applicable, the value chain phase this organisation represents.

Table 4: Overview of focusgroup participants

Role	Type of organisation	Value chain phase
Head of Eco-design	OEM	Production / design
Head of vehicle fleet	Waste transport and recycling	Use phase
Co-owner	Non-OEM affiliated dismantling facility	ELV management
Manager	OEM-affiliated dismantling facility	ELV management
Director	Branche Organisation for automotive dismantling	ELV management
Head of EV recycling	Executive organisation for automotive recycling	Recycling
Head of CE	Waste management / upcycling	Recycling
Specialist waste logistics	Governmental body	NA
Policy researcher on climate, air and energy	Knowledge institute	NA
Policy researcher on climate, air and energy	Knowledge institute	NA

All the participants can be linked with the incumbent regime of the current HDV value chain. The vehicle is a valuable product, which makes it harder for an innovator to start a new business. Therefore, niche-level innovations mostly happen in-house at incumbents. However, radical systemic shifts open sometimes windows of opportunity for new actors. For example, Zepp Solutions is a start-up active in fuel-cell technology applications and will launch a functional hydrogen-powered zero emission vehicle in late 2023 (Zepp Solutions, 2023). Due to time constraints, these actors were not included in the focusgroup.

4. Value chain analysis

This chapter analyses the various characteristics of the Dutch HDV value chain. First, section 4.1. elaborates on the various developments that influence the HDV value chain. Section 4.2. shows the baseline flows and stocks involved in the Dutch HDV sector. Sector 4.3. elaborates on the different value chain phases and various best practices exercised in these phases. Sector 4.4. investigates several circular strategies.

4.1. Developments in the HDV value chain

To identify the developments influencing the value chain, two levels of influence of the MLP are used: The top-down, landscape category, and the bottom-up niche level innovations. In the pre-assessment phase, the landscape category of institutional development and the niche-level innovation of zero emission vehicles emerged as influential developments. This innovation is a driver for change in the current HDV value chain but raises new challenges as well. During the focusgroup, the participants agreed that these were the categories of developments that either hamper or accelerate the transition.

Two categories of developments are identified that influence the transition towards a circular economy. The first is the top-down, landscape category of institutional developments. Regulations, that recently came into force, and coming regulations will either accelerate or hamper the transition. The second category is the bottom-up, niche-level innovations of zero emission vehicles. This innovation is a driver for change in the current HDV value chain but raises new challenges as well.

4.1.1. Institutional developments

The heavy vehicle sector is subject to several complementary regulations. These regulations exist of emission regulations (e.g. the EURO VI norm) and transversal regulations, applicable to both the automotive and the heavy-duty sector(e.g. the WEEE directive).

Table 5. Shows the current and upcoming regulations that apply to the HDV sector, and are in link with the circular economy.

Table 5: Current and coming regulations applied to the HDV sector and in link with the circular economy

Regulation types	Current regulations	Coming regulations
End-of-Life regulation	None	ELV Directive 2000/53/EC
Extended Producer Responsibility	None	Included in the ELV directive
Emission regulation	EURO VI Norm VECTO/CO_2 emission standards	EURO VII Norm ZE stadslogistiek (Dutch)
Transversal regulatory frameworks to both the Automotive and the HDV	EPR for tyres, oils, batteries, electrical and electronic equipment (EEE); WEEE waste directive (Directive 2002/96/EC) REACH (1906/2007 EC)	
Additional, complementary or other policy frameworks in link, directly or not, with CE	ECOWAS import regulation (2020) Waste Framework (Directive 2008/98/EC)	3R-approval inclusion (Directive 2005/64/EC)

The research on the institutional environment by Saidani et al. (2018) was the starting point for this table. To elaborate, and update this research, interviews were used to gather the latest insights and to steer into new directions, such as information on the revision of the ELV directive (IenW, personal communication, 16-03-2023).

Apart from the legal necessities such as the REACH, emission regulations and transversal regulatory frameworks (ECOWAS, Waste Framework Directive), no further regulations enforce more sustainable management of the EoL heavy vehicle. For example, the RoHS (Directive 2011/65 EC), controlling the restriction of Hazardous Substances does apply to passenger cars, but not to heavy vehicles. Article 2, paragraph 4(f) states: “This Directive does not apply to means of transport for persons or goods, excluding electric two-wheel vehicles which are not type-approved”. This is contradictory to the findings of Saidani et al. (2018): his research concluded that the RoHS was a transversal regulatory framework. Similarly, the HDV is currently exempted from the 3R-type approval directive.

This does not necessarily mean that OEMs do not use certain directives as guidelines. For example, DAF uses the ELV directive to measure its recycling performance (DAF, 2022a).

4.1.1.1. The End-of-Life Vehicles Directive

To date, there is no overall end-of-life regulation concerning the heavy vehicle industry. However, the End-of-Life Vehicle (ELV) directive, 2000/53/EC, is currently under revision. The European Commission is scheduled to publish the official proposal for the revision in June 2023 (Spiegeler, 2023). Because it will almost certainly include ELV management, it will be of major impact on the HDV sector.

The current ELV is limited to passenger cars and light commercial vehicles that weigh up to a total weight of 3.5 tonnes. It sets targets for reuse, recycling, and recovery: for each vehicle, a minimum of 85% of reuse and recycling rate and a minimum of 95% of reuse and recovery rate for each vehicle. It also includes the Extended Producer Responsibility (EPR) which encompasses the following propositions, summarised by Saidani et al. (2018):

- Free take-back of end-of-life vehicles (ELVs) and used tyres since January 2007;
- Producer obligation for providing not only take-back of ELVs through accessible networks of authorized treatment facilities (ATFs) and collection points;
- Availability of dismantling manuals;
- Database for the automotive sector: International Dismantling Information System (IDIS);
- Public Responsibility: the registered owner of a vehicle, when intending to discard that vehicle as waste, is required to bring that vehicle to an ATF for appropriate treatment and recovery;
- Certificates of Destruction: Since January 2007, on the deposit of an end-of-life vehicle at an ATF, the operator of that facility shall issue a certificate of destruction to the registered owner.

The current ELV has a few shortcomings, the highlights are shortly summarized:

- The scope of the present directive leaves out over 35 million heavy vehicles (ACEA, 2022c), 2022);
- The absence of a separate target for reuse (Baron, 2022);
- Better coherence with the European Green Deal and the Circular Economy Action Plan, notably in eco-design to facilitate the reuse, and use of recycled content materials in manufacturing vehicles (Baron, 2022);
- Promotes downgrading and even backfilling as a recycling practice (EC, 2021);
- Lacking European Certificate of Destruction (CoD) system, quality of data and consequently a lack of traceability (ARN, 2022);
- Current IDIS faces difficulties in comprehensive data analysis (Lijzen, 2023).

4.1.1.2. The 3R directive

Even though the HDV is still exempted, OEMs use the 3R directive (Directive 2005/64/EC) as a guideline for good business (DAF, 2022a). One of the main issues within this directive is the theoretical recyclability being not necessarily (or practically not) similar to the practical recycling rates. To highlight this issue, the figure below shows the approval process for a vehicle in the 3R (Reuse, Recycle, Recover) using the ISO 22628:2002 calculation:

> *The ISO 22628: 2002 calculation is based on the weight of all components or parts of a specific material are summed up. The ISO makes a distinction between components and materials that are reused, recycled or recovered. However, only recycled and recovered components and materials are reported on.*
>
> *The assessment of recyclability is done on a yes/no approach: When a material is considered recyclable (level 4 and above), its full amount is counted towards recycling. A level 4 of recycling technology readiness level accounts for a laboratory scale readiness, whereas type approval authorities recommend at least level 6 (technology demonstrated in relevant environment) and above as an appropriate level (Yifaat Baron, 2022).*

During the revision of the ELV directive, the European Commission considers merging the 3R type approval and the ELV directive (EuRIC, 2021). This ensures a better alignment of the production phase and EoL phase to improve circularity along the whole value chain.

4.1.1.3. The Euro standards for emission

EURO VI to EURO VII

The latest standard for heavy-duty vehicles – EURO VI – was introduced in 2013. It underwent several updates, of which the latest – EURO VI-E – in 2020 (ACEA, 2023c). By renewing the fleet with vehicles compliant with the VI norm, an 80% reduction of NOx is feasible. At the end of 2022, the European Commission proposed a stringent revision: the Euro VII standard. A study conducted by Aeris Europe, on behalf of ACEA, shows that the additional impact of the new standard is only limited to a 2% NOx reduction and also a limited $PM_{2.5}$ reduction for heavy-duty vehicles (AERIS, 2021). Apart from tailpipe emissions, it also addresses non-exhaust particle emissions from e.g. tyres and breaks.

The elimination of harmful emissions has been a significant and challenging task for those involved in the heavy vehicle industry. While expensive after-treatment devices and high-pressure injection systems all help to improve environmental performance, they also substantially raise costs (Berggren et al., 2015). As an illustration, Scania invested more than 1 billion euros in the development of engines compliant with Euro VI standards (Scania, 2011).

ACEA (2023c) states that the implementation of the new norm could drastically delay the transition to zero transmission due to the increased costs of R&D, and non-feasible implementation deadlines. This is an interesting view, although not necessarily from a neutral point of view, as ultimately the goal is to decarbonise the use phase as quickly as possible. This shows that the decarbonisation transition not only causes friction with the transition to a Circular Economy; it can also cause friction with itself.

CO_2 emission standards

In (2019b), the EC introduced regulation 2019/1242, setting the CO_2 emission performance standards for new heavy-duty vehicles. With the "Vehicle Energy Consumption Tool" (VECTO), an emission label is issued based on the fuel use and CO_2 emission of the complete vehicle. The current regulation requires a reduction of 15% in 2025 and a 30% reduction in 2030. A new proposition for CO_2 reduction standards is based on the VECTO output. These new standards require a reduction in CO_2 emissions compared to 2019 levels by 45% in 2030, 65% in 2035 and 90% in 2040 (EC, 2023b).

It also encompasses an incentive that awards OEMs for each vehicle produced with a CO_2 emission less than half of the reference of the sub-group to which it belongs, reported in the previous year. This should incentivise innovation.

4.1.1.4. Import regulation

Not only European countries are moving towards a safer and cleaner fleet. Since 2020, 15 countries in West Africa, united in the Economic Commission of West African States (ECOWAS), implemented more stringent import restrictions. Imported vehicles need to adhere to the minimum emission standard of EURO IV, or not be older than 10 years (ILT, 2020). Countries have a period of 10 years to implement this directive. Additionally, in 2021, East African countries have proposed a similar directive.

4.1.1.5. Zero Emissie Stadslogistiek (ZE citylogistics)

The zero emission stadslogistiek regulation is one of the most important Green Deals of the Netherlands, which is ahead of EU regulation. In 2025, 30 cities will implement ZE zones (Kamp, 2018). The goal is to have full zero emission logistics in 2030. This will reduce the CO_2 emission by 1 MT in 2030, and will vastly improve the air quality, because traffic is the largest source of pollutants in cities (Kamp, 2018).

A modal shift is anticipated, city logistics will be outsourced, or suburban hubs will be used for logistic transfers(Panteia, 2021). It is therefore likely to assume that fewer ZE vehicles will enter the ZE-zones than the conventional vehicles are doing in the current zones. Assumed is that, of the current vehicle fleet of 14.500 conventional vehicles that enter the ZE zones more than 5 times a year, approximately 65% of the truck fleet and 90% of the trailer fleet will still need to supply the ZE zones. This results in a total of 11.676 ZE vehicles, in place needed in 2030 (Panteia, 2021).

4.1.2. The road towards zero emission in the use phase

The Use phase is for 90%-95% responsible for the total emissions of conventional ICEVs (Scania, 2021). To achieve a circular heavy vehicle, one of the main challenges of the transport sector is to become zero emission. To accomplish a ZE transport sector, various approaches are available.

4.1.2.1. Projection of the ambition

The ambition is clear. In 2050, the HDV should operate carbon neutral. A Memorandum of Understanding signed by the COP26 states that the goal is to have 30% of the new HDV sales be zero emission by 2030, and 100% in 2040 (Rijksoverheid, 2021).

Figure 10 illustrates the ZE ambition, with the corresponding milestones. Assumed is that annually, 16,000 new vehicles are sold in The Netherlands, for vehicles with a replacement rate of 10 years.

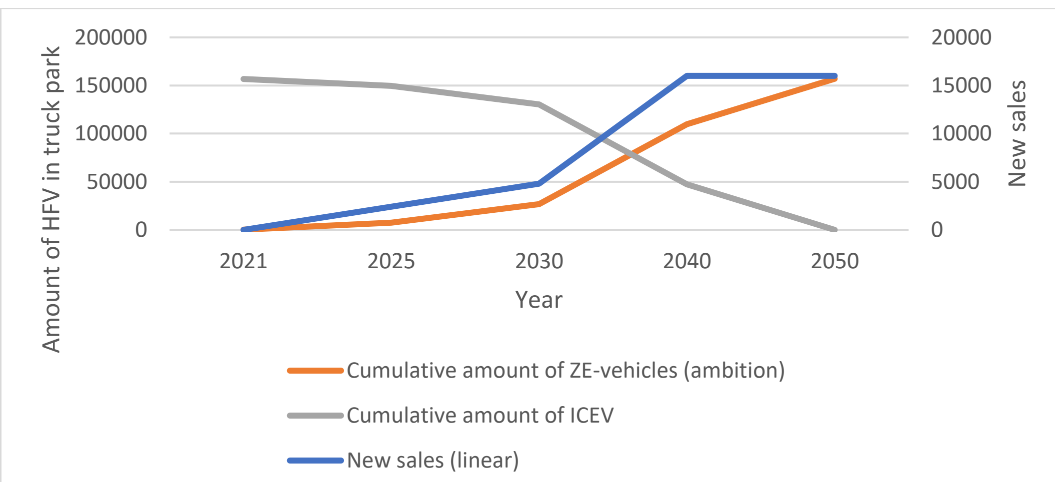


Figure 10: Zero emission Fleet ambition 2021-2050, data from *(TLN, 2022)*

Following these assumptions, a total amount of 7400 ZE vehicles have to be sold in 2025 to be on track to 5,000 vehicles sold in 2030. In 2022, a total of 192 ZE vehicles were registered in the Netherlands (RVO, 2022). A couple of things can be concluded from this picture. It is an extreme increase in ZE sales that is needed to achieve the set goals. Apart from this being a huge challenge, in terms of willingness to purchase, supply by OEMs and also supporting infrastructure such as charging infrastructure (TLN, 2022), it also causes a significant outflow of ICEVs. Furthermore, the ICEV will have the highest share in the Dutch HDV fleet until at least 2035. This means that these need to be alternatively fuelled as well.

4.1.2.2. ZE technologies

Three categories of ZE technologies are currently prevalent. The most mature technology is biofuel. Very easily implemented, as most ICEVs can run on biofuels up to 100% without major alterations (Scania, 2021). This would reduce the GHG emissions from the total life cycle of a vehicle by up to 81% (Scania, 2021). However, issues and scepticism exist as biofuels often are linked to competition with feedstock for food. Searchinger et al. (2008) states that clearing land for fuel crop production creates a “carbon debt” between 17 to 420 years to overcome with emission savings by biofuel use (Geyer, 2016). On top of that, using crops for electricity production might double the crop-to-wheel conversion efficiency and therefore larger life cycle energy and GHG benefits. Direct PV-to-wheel conversion would even be more effective, as the conversion efficiency of photosynthesis is typically below 1% (Geyer, 2016). However, it can function as a means for the transition towards a zero emission fleet, by helping to reduce GHG emissions and improve the EU’s security of supply (EC, 2019a)

Hydrogen-powered vehicles, either via fuel cell or combustion engine are another technology. Currently, 8 Dutch vehicles are powered by hydrogen. All these vehicles were converted from conventional vehicles (RVO, 2022). Transport of hydrogen is difficult and the purity of hydrogen for fuel cells will lead to high prices for hydrogen. Hence, hydrogen is considered less promising than e-fuels, a technology that will not be cost-efficient until early 2040 (D. Tol & P. Paschinger 2023). Some companies see fuel cell technology as a suitable option for long-haul transport (NOW GmbH, 2023).

There is no single best technology to decarbonise road transport. However, BEVs perform well on many metrics such as costs, emissions and value chain efficiency and are therefore considered one of the most promising alternatives (D. Tol & P. Paschinger 2023). Furthermore, it is the most prevalent ZE technology in the Dutch HDV fleet (RVO, 2022). This is due to the maturity of the technology and the ability to be implemented for regional and distribution transport (NOW GmbH, 2023). Therefore, in this research, the focus of decarbonisation technologies will be on BEVs.

4.1.3. Consequences of institutional changes and electrification

The identified developments are current and coming regulations, such as the ELV directive extension, ECOWAS import regulation, and Zero Emissie stadslogistiek. institutional developments and technological innovation of BEVs.

Following the MLP, the top-down institutional developments and the bottom-up niche-level innovation of electrification will influence the incumbent socio-technical regime of the HDV value chain. It is expected, that the landscape factors will exert pressure on the current regime, which can create a window of opportunity for niche-level innovations (Geels, 2002). However, both types of developments have the potential to either accelerate or hamper the transition towards a CE value chain.

Therefore, these developments will be tested in the focusgroup and used in the value chain analysis to determine the possible effects on the value chain.

4.2. Baseline flows and stocks

The size and the composition of the Dutch stock of HDVs depends on a few different flows. Figure 11. Shows the schematic stocks and flows.

- The stock increases due to new registrations and the import of used vehicles.
    - A new registration is a vehicle of which the admission date and the date of first registration are similar.
    - A vehicle is labelled used when the admission date differs from the first registration date.
- The stock decreases due to the export of used vehicles, dismantling, or other, unknown reasons (Traa, 2015)

Figure 11: Stocks and flows in the Dutch HDV fleet (adapted from (Traa, 2015)).

The development of the stock and its flows is shown in the figure above. However, this does not draw the full picture of the flows. The Netherlands is a large producer of heavy vehicles. Two major OEMs, DAF and Scania, have their largest production facility located in The Netherlands. The Netherlands imports also a large number of vehicles intended for export. Section 4.2.4 elaborates on the international trade.

4.2.1. Heavy-duty vehicle stock in the Netherlands

The fleet can be defined by various characteristics. For this research, the following characteristics will be elaborated upon: The total stock, GWV segments and Emission standards, fuel type and age.

Stock development between 2014-2022

The HDV fleet consists of a variety of vehicles. Almost 80% of the fleet consists of vehicles heavier than 16 tonnes. Figure 12. shows the total HDV fleet between 2013 and 2013. The share of lighter vehicles has a decreasing trend, which can be explained by the fact that heavier vehicles are more efficient in terms of the amount of freight to be carried versus the fuel it consumes. Subsection 4.3.4.1. Highlights various performance statistics of HDVs.

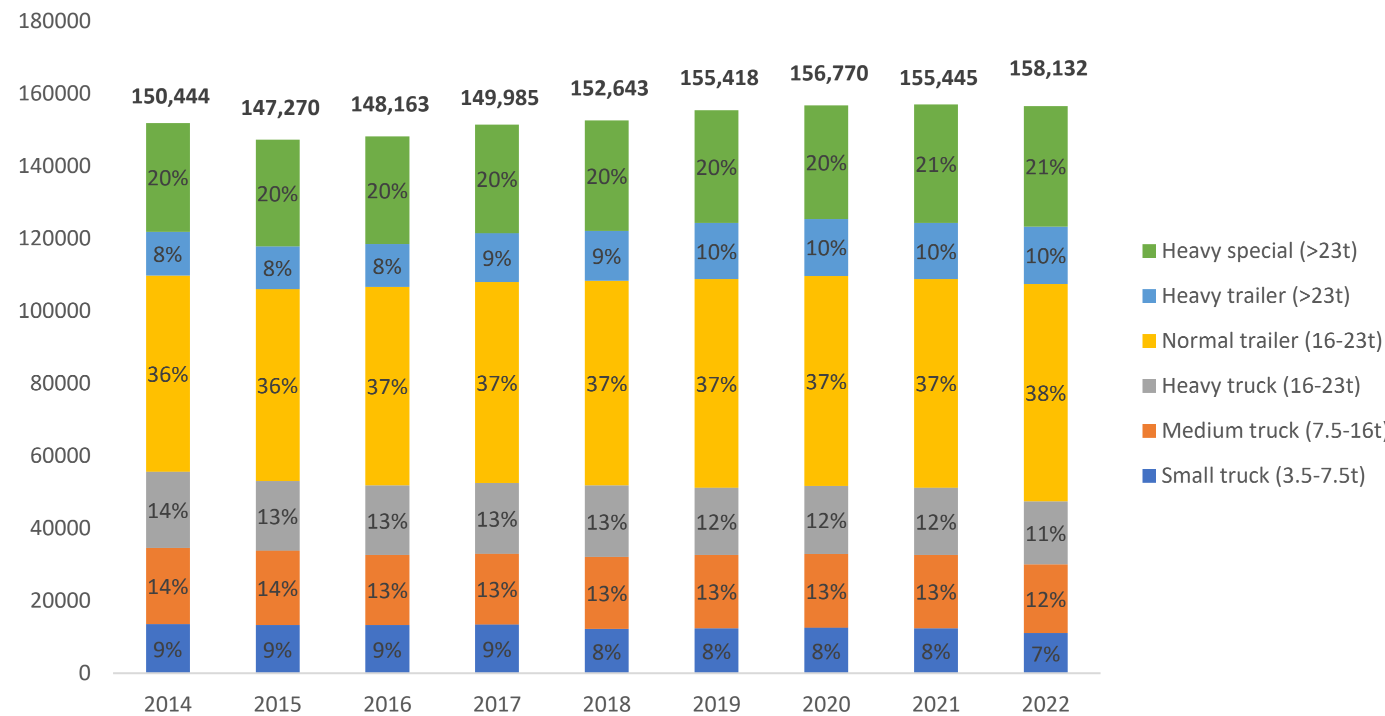
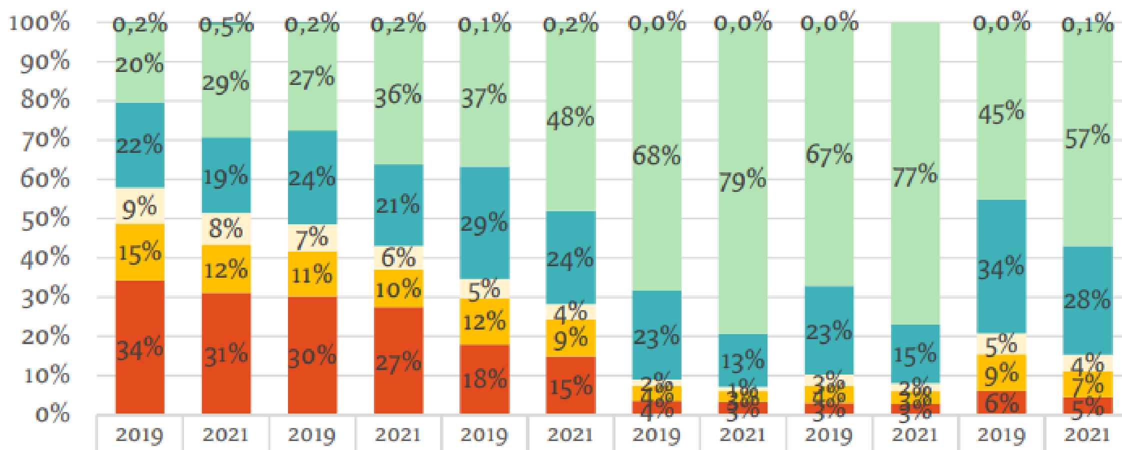


Figure 12: Dutch HDV fleet composition between 2014-2022. Adapted from (RVO, 2022).

Fuel type and emission standards

The current fleet exists almost solely from diesel-powered vehicles (98.6%) (Traa, 2022). In 2021, a negligible amount of 65 Zero Emission (ZE) vehicles was sold, adding to a total of 192 ZE vehicles (RVO, 2022) (RVO, 2022). This accounts only for 0.1% of the fleet.

The European Emission standards, elaborated upon in paragraph 4.1.1, divide the fleet based on their emission level. Figure 13. Shows the emission standards divided per segment for the years 2019 and 2021.



	Small truck (3.5-7.5t) 2019	Small truck (3.5-7.5t) 2021	Medium truck (7.5-16.t) 2019	Medium truck (7.5-16.t) 2021	Heavy truck (16-23t) 2019	Heavy truck (16-23t) 2021	Normal trailer (16-23t) 2019	Normal trailer (16-23t) 2021	Heavy trailer (>23t) 2019	Heavy trailer (>23t) 2021	Heavy special (>23t) 2019	Heavy special (>23t) 2021
Z	30	62	36	37	13	30	9	22	1		7	41
6	2.477	3.406	5.403	6.978	6.841	8.609	40.010	47.418	10.429	12.518	14.448	18.676
5	2.657	2.293	4.708	4.031	5.334	4.265	13.273	8.059	3.513	2.449	10.904	9.107
4	1.116	942	1.359	1.150	900	712	908	609	419	307	1.686	1.333
3	1.784	1.465	2.269	1.866	2.199	1.686	2.283	1.698	685	533	2.999	2.189
ot/m2	4.201	3.690	5.970	5.326	3.350	2.692	2.095	1.962	481	463	1.961	1.497

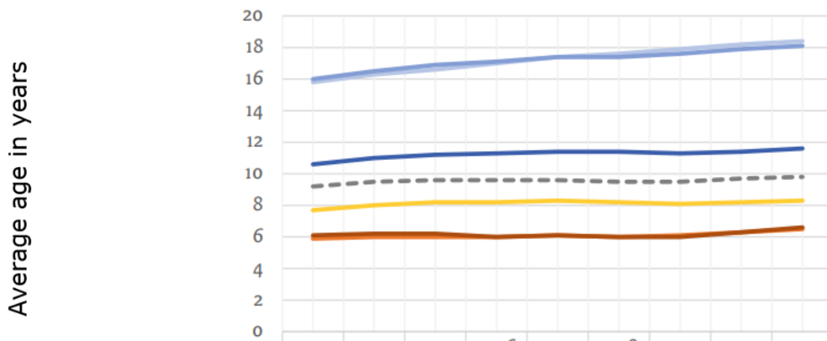
Figure 13: The HDV vehicle fleet emission standards per segment. (RVO, 2022)

The figure illustrates that between 2019 and 2021 the lower emission standard vehicles (EURO 0 – EURO V) are being replaced by mostly vehicles with a EURO VI standard. For trucks, the share of EURO VI vehicles has been significantly higher, mostly due to a quicker fleet replacement (see 4.2.2).

The uptake of cleaner technology is slower in the segment of small and medium trucks. This might become an issue in 2030. The regulation of the ZE stadslogistiek mandates all entering HDVs to be zero emission. This means that virtually all of these vehicles have to be replaced by zero emission vehicles. This will cause a big spike in new vehicle sales and a big outflow spike of (older) vehicles in 2030.

The Age of the Fleet in The Netherlands

The average age varies per segment. Figure 14. Below shows the average age of the fleet.



	2013	2014	2015	2016	2017	2018	2019	2020	2021
Small truck (3.5-7.5t)	15,8	16,3	16,6	17,0	17,4	17,6	17,9	18,2	18,4
Medium truck (7.5-16.t)	16,0	16,5	16,9	17,1	17,4	17,4	17,6	17,9	18,1
Heavy truck (16-23t)	10,6	11,0	11,2	11,3	11,4	11,4	11,3	11,4	11,6
Normal trailer (16-23t)	5,9	6,0	6,0	6,0	6,1	6,0	6,1	6,3	6,5
Heavy trailer (>23t)	6,1	6,2	6,2	6,0	6,1	6,0	6,0	6,3	6,6
Heavy special (>23t)	7,7	8,0	8,2	8,2	8,3	8,2	8,1	8,2	8,3
Total	9,2	9,5	9,6	9,6	9,6	9,5	9,5	9,7	9,8

Figure 14: Average age per HDV segment. (RVO, 2022).

The lighter HDVs have a significantly higher age compared to the heavier trucks and trailers. For some of the segments, the average age is relatively 'distorted' due to a small group of extremely old vehicles. This group of 8.500 vehicles has an average age of 49 years (RVO, 2022). With a correction by excluding vehicles older than 30 years the average age is considerably lower than in the uncorrected situation:

- Small trucks: 7 years lower
- Medium trucks: 8 years lower
- Heavy trucks: 3 years lower
- For trailers and special HDVs, the difference is insignificant

Age of the Fleet in Europe

The figure below shows the average for the different countries of the European Union and Iceland, Norway, Switzerland and the United Kingdom, retrieved from ACEA (2022c). The average age in Europe for a heavy vehicle is 13.8 years.

Figure 15: HDV age distribution in Europe. Data from (ACEA, 2022c).

The figure shows that the average age is higher in Southern European and Eastern-European countries. Vehicles are on average older than 15 years in Italy, Estonia, Portugal, Romania and Spain and in Greece even older than 21 years. These are also recipients of used vehicles from The Netherlands (ACEA, 2022c).

4.2.2. The inflow of heavy vehicles in The Netherlands

The inflow in the Dutch HDV fleet consists of new and used, imported vehicles. The inflow of vehicles amounts generally 15.000-20.000 vehicles. Various trends can cause a smaller inflow of vehicles. The sector took a big hit in 2020 which is mainly attributed to the COVID-19 pandemic, which caused a period of less economic activity.

The Figure 16. Shows the inflow of heavy vehicles in the Dutch HDV fleet between 2013-2021.

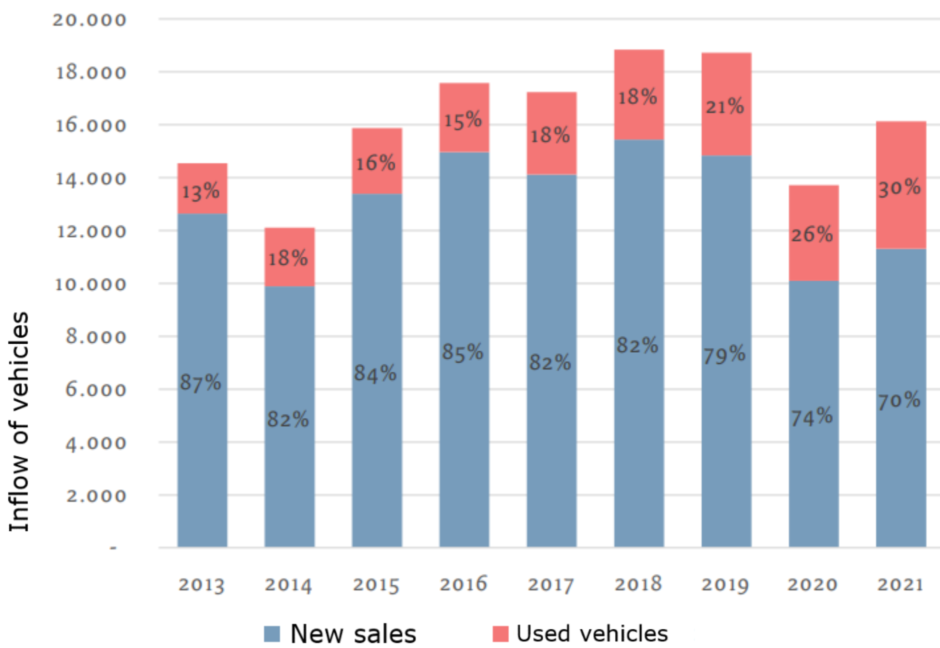


Figure 16: Inflow of HDVs in The Netherlands. (RVO, 2022).

The share of used vehicle imports increased from 13% in 2013 to 30% in 2021. Recovered quickly from this dip, the sector is still subject to factors that lead to longer use of the current fleet and a growing interest in used vehicles. The waiting time for a new vehicle is up to two years, due to, among others, chip scarcity (Vos truckparts, personal communication, 15-02-2023; (ING, 2022)). On top of that, the uncertainty of upcoming regulation for zero emission, and high fuel prices cause an uncertain investment climate (ING, 2022).

4.2.3. The outflow Dutch registered heavy-duty vehicles

Each year various commercial vehicles get discharged from the public road in The Netherlands. The following reasons are categorized by CBS: Dismantling, Export, put out of registration & other or rest. Each year (2018-2021), some approximately 60.000 commercial vehicles get discharged, of which the vast majority are vans (50.000 vs 10.000 trucks and trailers in 2020). However, the total weight is comparable of both categories (85.000 tonnes vs 83.000 tonnes in 2020). Whilst the discharge outflow is comparable in terms of weight, the dismantling of trucks and trailers in The Netherlands is very little compared to the dismantling of vans, both in quantities (12.000 vs 350 in 2020) and in weight (16.000 tonnes vs 3.000 tonnes in 2020) (CBS, 2023).

In 2021, 93.9% of the used trucks and trailers are being exported, and just 3.4% is dismantled in The Netherlands. This data shows that just a small amount of Dutch registered trucks and trailers are reaching their EoL phase in The Netherlands. Before that, they are being exported. This is underlined by the average age of trucks in The Netherlands of 9.8 years, whereas the European wide average is 13.9 years, with outliers of 21.4 years (Greece) or Luxembourg (6.7 years) (ACEA, 2022c).

The figure below shows the outflow of heavy vehicles in The Netherlands. The outflow consists of exported vehicles, dismantling, or other. Other are vehicles that leave the Dutch stock for RDW unknown reasons (Traa, 2015).

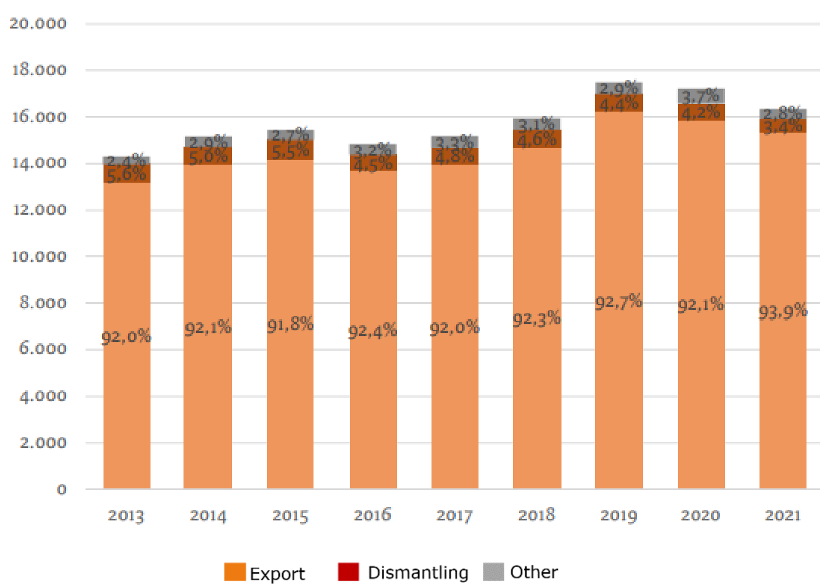


Figure 17: Outflow of Dutch HDVs between 2013-2021. (RVO, 2022)

The outflow fluctuates around 15.000 vehicles per year. From the figure can be concluded that hardly any HDV ends their life in the Netherlands. The majority of the vehicles being dismantled in the Netherlands are salvage vehicles (Vos truckparts, personal communication, 15-02-2023) or vehicles being traded-in, for example due to ill configuration (SVR, personal communication, 13-02-2023).

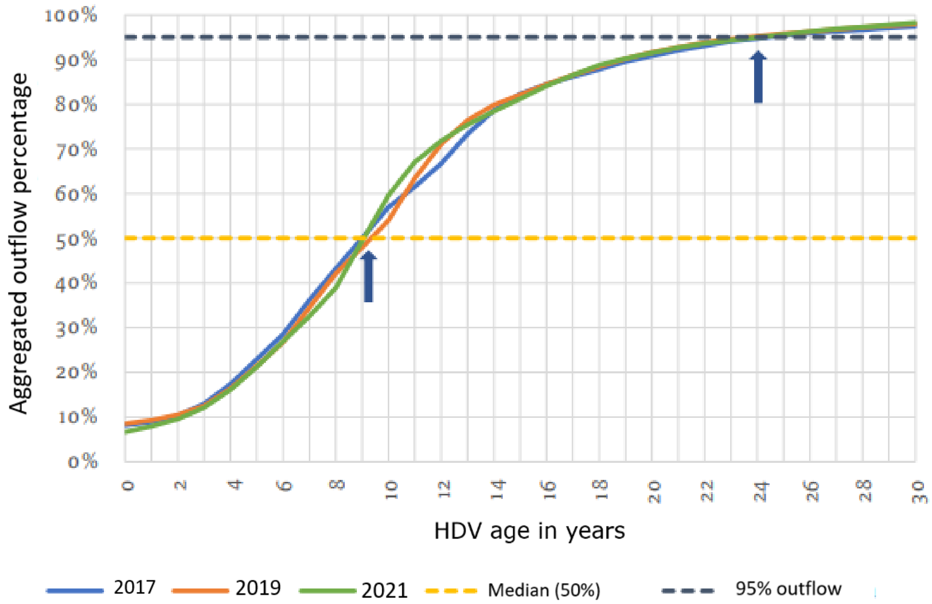


Figure 18: Age distribution of HDV outflow for 2017, 2019, 2021 (RVO, 2022)

Figure 18. Shows the age distribution of HDV outflow for 2017, 2019 and 2021. The medians provide two interesting insights. The first is that, 50% gets exported before the vehicle reaches an age of 10 years. These are the vehicles that are considered by OEMs not to have reached the end of their technical life. Second, the next segment, between the two medians, shows that the economic life of a vehicle is extended way beyond the reliability lines of OEMs. In the absolute sense of lifetime elongation, this is a good phenomenon. However, it may be argued that extending the economic life far beyond the technical life results in unrecoverable damage and hence results in a loss of valuable material.

4.2.4. The International trade of heavy-duty vehicles

The Netherlands is a larger imported and exporter of both new and used vehicles. The trade has various functions. Table 6. Shows the import statistics of new HDVs in 2021.

Table 6: Import statistics of new HDVs in 2021, data from (CBS, 2022)

	Import volume (#)	Import value (x million euro)	Avg. value per vehicle (euro)
EU	12,292	768	62,489
Africa	1	0	45,000
America	2	0	83,500
Asia	-	-	NA
Oceania	-	-	NA
Total	12,295	768	62,491

The import of new HDVS comes almost entirely from Europe (>99%). This is also the case for imported used HDVs. Therefore, in this thesis research, the import flow is aggregated and considered to be from Europe only.

Table 7. Shows the export flows from the Netherlands in 2021.

Table 7: The export statistics for new HDVs in 2021, data from CBS (2022).

	Export volume (#)	Export value (x million euro)	Avg. value per vehicle (euro)
EU	68,541	5,261	76,756
Africa	2,067	166	80,237
America	1,175	101	86,158
Asia	8,404	678	80,650
Oceania	1,745	161	92,029
Total	81,932	6,366	77,704

In 2021, the export value of HDVs was equal to 6.4 billion euros. For over 80% of the exported new HDVs has an European destination. This shows that the Dutch HDV production is important for both the Dutch economy and the European HDV market

Export of used HDVs

Little is known about the international trade of used heavy- duty trucks, despite that they are responsible for a disproportionate amount of fine particles and carbon emissions (UNEP, 2021).

Using the international transport statistics of CBS, an overview can be made of the macro flows. Table 8. Shows the import and export flows of used HDVs in 2021.

Table 8: Import to The Netherlands and export from The Netherlands of used HDVs in 2021, data from CBS (2022)

Year: 2021	Volume (#)	Value (x million euro)	Avg. value per vehicle (euro)
Import	22,927	564	€ 24,614
EU	18,669	488	€ 26,157
Africa	10,645	135	€ 12,718
America	2,372	49	€ 20,731
Asia	4,255	102	€ 23,910
Total export	35,948	775	€ 21,560

The import of used trucks comes almost solely from Europe (>99%). This can be explained with the market segmentation for new trucks (solely from EU), the reign of European brands throughout Europe and the high quality standards required in Europe. Therefore, the total import is taken as one variable.

Used vehicles are imported into the Netherlands to be exported. In 2021, approximately 3,000 of the used vehicles imported, have been registered as Dutch vehicles. The rest of the imported vehicles is exported along with the outflow of former Dutch registered vehicles.

The average value of an exported used vehicle to Africa is considerably lower than the value exported to other continents. This indicates a worse condition of the vehicle. The export of heavy vehicles remains a rather undocumented business, that contributes to the global increase of air pollution by exporting old and to the environmental standards uncompliant vehicles to developing countries (UN, 2020; UNEP, 2021) (UN, 2020) Around 20% of tested vehicles fail tests for emission requirements, or even lack the APK (Dutch certificate for being legally on the road)(ILT, 2020). A significant part of the exported vehicles is very similar to the ELVs recycled in The Netherlands (EuRIC, 2021). This means that there is a big "leakage flow" of actual ELVs being exported as used vehicles to Africa involving uncontrolled and inadequate handling, with the consequence of environmental harms and a substantial loss of secondary raw materials (ILT, 2020).

The exported volume to Africa is significant. Next to the EU, African countries are the largest importer of used trucks. shows the average age of used HDVs exported to the 12 largest importing African countries.

Table 9: Age distribution of HDVs exported to the 12 largest importing countries in Africa. Data from (ILT, 2020).

Country	**Average age**	**Q3**
Burkina Faso	14.8	16.4
Côte d'Ivoire	15.7	18.3
Egypt	8.4	7.5
Ethiopia	12.0	15.3
Gambia	17.1	19.0
Ghana	14.5	18.0
Guinea	17.5	20.6
Libya	14.3	15.6
Mali	16.4	17.9
Morocco	7.7	9.7
Nigeria	18.9	22.1
Sierra Leone	20.0	22.6

Since, 2021, the ECOWAS (Economic Commission of West African States, the largest African recipient of the Dutch export of used HDVs), has stricter environmental regulations. The minimum standard of EURO 4/IV and no older than 10 years results in that over 80% of the used vehicles currently exported to the ECOWAS are no longer accepted (ILT, 2020).

This could mean that the linear value chain will change drastically, because the oldest vehicles currently still destined to end their live, will have to end somewhere else. On top that, it would mean that over 8,000 vehicles need to find another destination, or have to be recycled within the Netherlands or EU.

4.2.5. Implications of the stock and flow analysis

The Netherlands is a major HDV producer. The two OEMs that produce in the Netherlands, have together a market share of roughly 30% in Europe. Due to COVID-19 and market problems such as long waiting lists and chip shortages, the share of new sales in new registrations decreased to 70%. Although a higher percentage of used vehicles, 95% of Dutch registered vehicles do not end their life in The Netherlands, but are exported. Because of the two operating OEMs and the high share of new vehicles, The Netherlands can take on a leading role in terms of innovation, both in emission performance, as in the transition to a circular vehicle.

The Netherlands does also import a substantial amount vehicles solely with the purpose to be exported again. Over 80% of the current export to Africa does not adhere to the new ECOWAS import regulations. 20% of the exported vehicles lacks a Dutch roadworthiness certificate, or is even considered an ELV. Therefore, the ECOWAS import regulations, and extension of the ELV directive can alter the export streams of The Netherlands. Export will decrease, and more vehicles will have to be dismantled in The Netherlands, even if they have not enough value to be dismantled for profit.

The two presented figures below summarise the findings of the stock and flow analysis.

Figure 19. Shows the stock development in Europe between 2011-2018. Figure 20. Shows the stock development in the Netherlands between 2014-2020. The conclusion can be made that from the 95% that is exported from The Netherlands, 72% will end their life in Europe, and approximately 28% in other parts of the world. This underlines the importance of alignment in both Europe and the rest of the world for the dismantling phase.

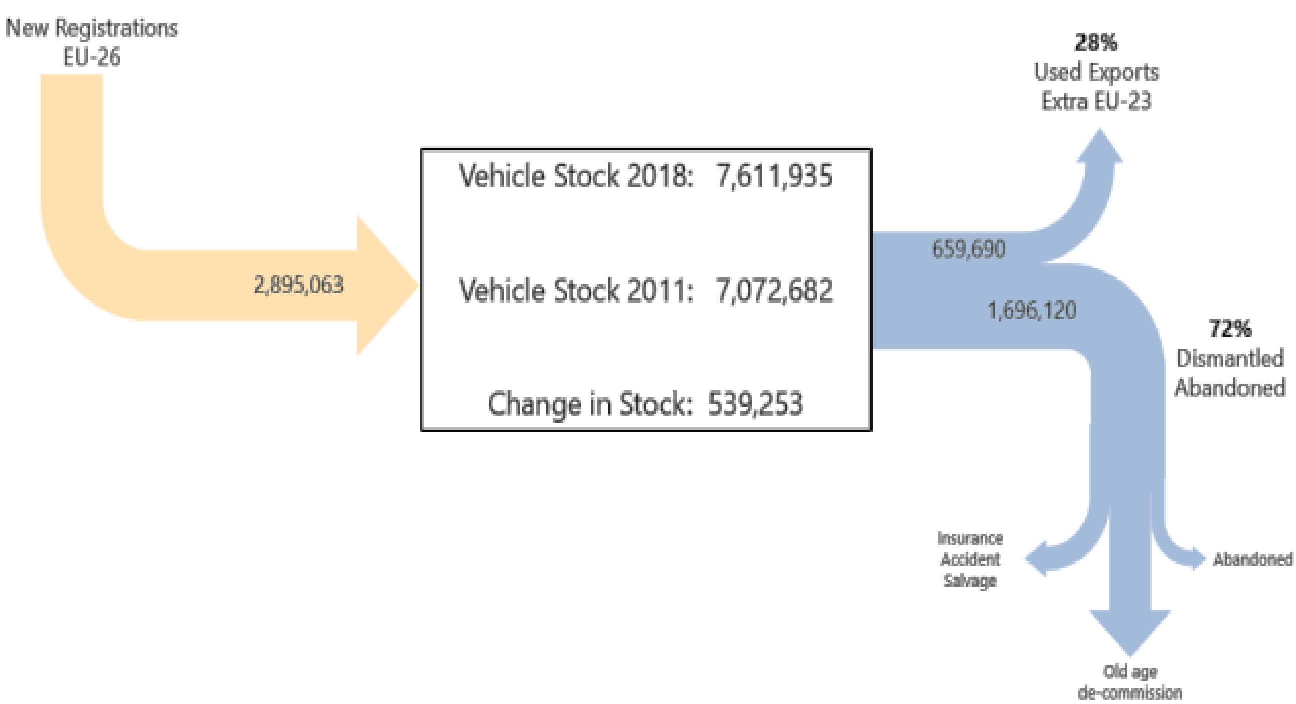


Figure 19: Stock development in Europe between 2011-2018. (Munir, 2021).

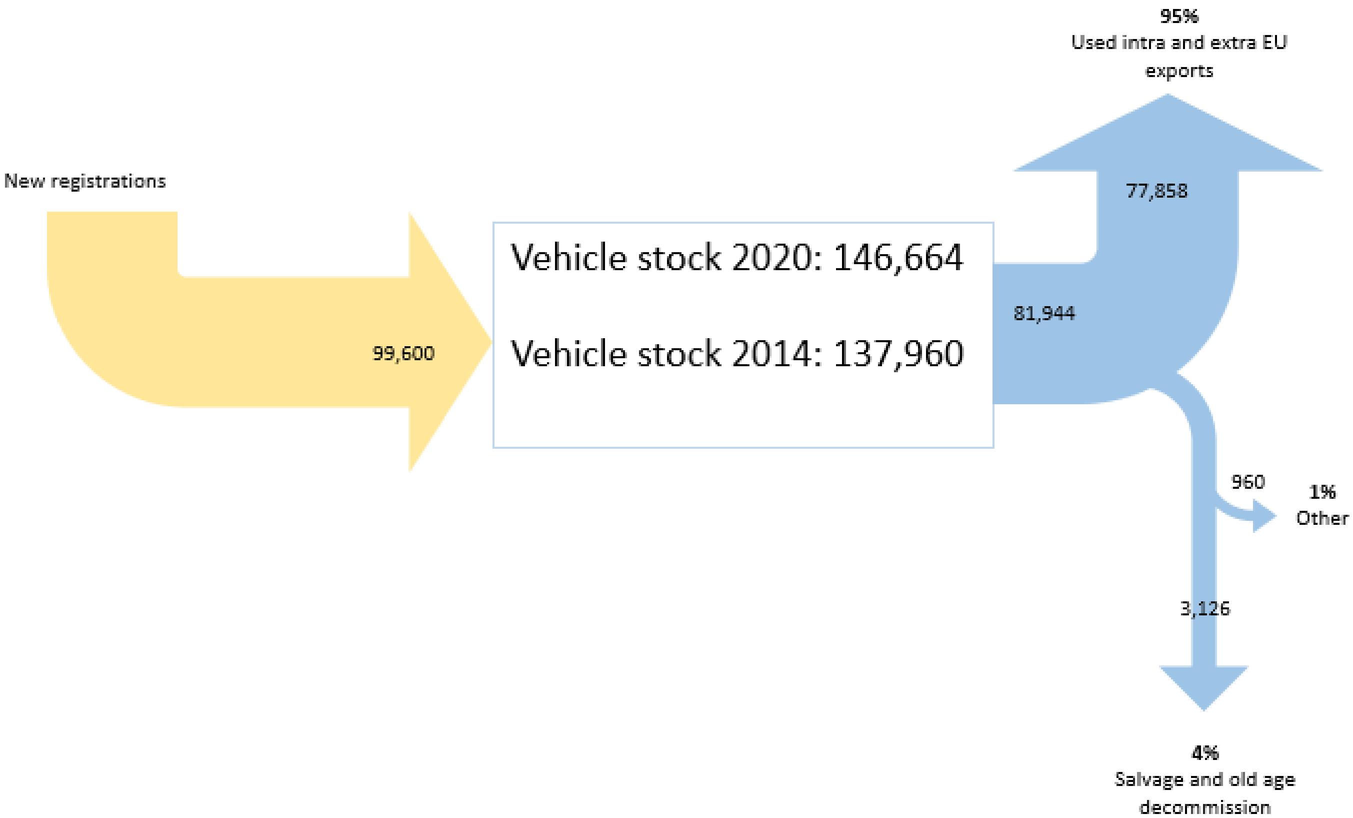


Figure 20: Stock development in The Netherlands between 2014-2020. Data from (CBS, 2021; RVO, 2022; Traa, 2022).

4.3. The Dutch heavy-duty vehicle value chain

The value chain of the Heavy-Duty Vehicle consists of various phases. Figure 21. Shows the demarcated phases and the embedded R-strategies. This is based on the general value chain and embedded R-strategies of Potting et al. (2017).

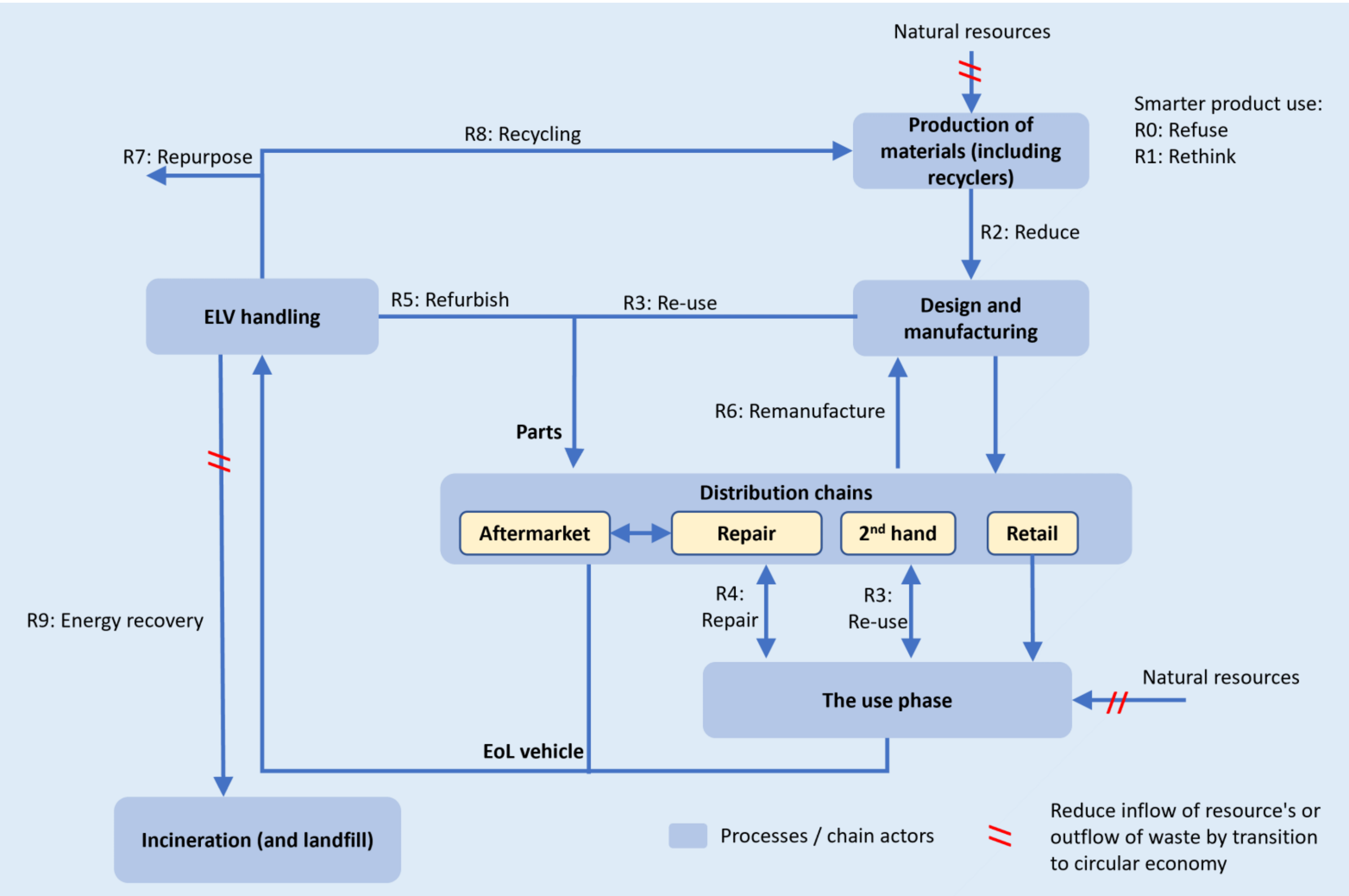


Figure 21: The Dutch HDV value chain and used R-strategies (own work based on the value chain of Potting et al. (2017))

The stock and flow analysis concludes that all value chain phases do occur to some extent in The Netherlands. The extraction of materials happens outside of the Dutch borders, and even often outside the European borders. Figure 19. And Figure 20. Show that most of the HDV ELV handling happens either in other European countries or on other continents such as Africa. This is due to the fact that the vehicles will be reused in these areas.

To explore the value chain more in-depth, the stakeholders in the Dutch HDV value chain will be analysed in paragraph 4.3.1. Then, for each phase, the characteristics, main activities and best practices will be outlined. On top of that, key issues are highlighted that are faced in these phases.

4.3.1. Stakeholders in the Dutch heavy-duty vehicle chain

In each phase, various stakeholders are operating. Often these are represented by branch organisations. Also, companies operate in a multitude of value chain phases. Companies sometimes operate within various phases. For example, dismantling companies operate as an importer/exporter of used vehicles, aftermarket actors and dismantlers at the same time. The majority of the Dutch stakeholders operate within the incumbent regime level.

Design and manufacturing. Represented by the Dutch manufacturers and importers organisation RAI, and by the European manufacturers organisation ACEA. Two of the biggest HDV OEMs do have their main production location situated in the Netherlands: DAF and Scania. These production locations are mostly assembly locations rather than component production locations. However, OEMs produce components inhouse as well.

Retail and 2nd hand. The import and export of both new and used vehicles is represented by the Dutch manufacturers and importers organisation RAI. The brands itself are responsible for the import of (new) vehicles, or via a long-lasting partnership (PON for MAN Trucks). The used vehicles are either imported by private companies, or taken-back and resold by OEMs.

User phase. The user phase is represented by the branch organisation Transport & Logistiek Nederland (Transport and Logistics Netherlands). The user is either a small transporter, a small SME with a few own vehicles, large logistics services / transporting companies, or large companies with a large operating fleet, for example RENEWI with a fleet of over 1200 dump trucks.

Repair and maintenance. Formerly represented by the Dutch branch organisation for repairment FOCWA, that merged and currently operates by the name BOVAG, the Dutch branch organisation for mobility. A BOVAG certification guarantees a certain standard of repairment. Especially new vehicles, are often under maintenance at the OEM. This mostly changes when the vehicle is depreciated.

Dismantling and aftermarket. STIBA represents the Dutch dismantling sector. Some brands, like Scania, have their own dismantling centres. Others are dismantled by private dismantlers. The amount of vehicles being dismantled exceeds the CBS statistics. This is due to the import of salvaged, undocumented vehicles. The components from dismantled vehicles are up for sale on the aftermarket. Most dismantlers provide an additional guarantee on these components. However, the certification authority 'Kwaliteitszorg Demontage' (QualityCare Dismantling), certifies the practices of the dismantlers and their output of components.

Recycling and production of secondary materials. Is represented by AutoRecycling Nederland (ARN or car recycling Netherlands). Currently, hardly any HDV reaches the recycling phase. The largest Dutch car shredder HKS reports a small annual amount of 3 HDVs being shredded (Van der Wekken, 2023, personal communication). This means that in the current value chain, recycling does not play a large role in the Netherlands.

Governmental stakeholders. The Ministry of Infrastructure and Watermanagement (IenW) governs legislation around vehicle production, use and dismantling. The European Commission also plays a big role for this matter, because the ELV directive is currently under revision and quite possibly to be extended to HDVs. The Human Environment and Transport Inspectorate (Inspectie Leefomgeving en Transport or ILT) works at improving the safe disposal of vehicles and logistics from exports.

4.3.2. The production of materials

The increasing resource scarcity and awareness of security of supply put emphasis on the production of materials. On top of that, the electrification of road transport raises new issues like demand for lithium and other critical materials.

In a circular economy, raw materials are materials that are extracted directly from nature and used to produce goods and products. Examples of raw materials include minerals, ores, and fossil fuels. Secondary materials, on the other hand, are materials that have already been used and discarded, but which can be recycled or reused to create new products. Examples of secondary materials in the HDV sector are iron and aluminium.

Due to innovations, the material composition of trucks has changed. Complex electronic systems have been introduced for monitoring and management, and composite materials for making the truck lighter and therefore more fuel-efficient (Saidani et al., 2018).

To explore the material composition of HDVs, van der Zaag (2020) uses the EcoInvent Database, a leading LCA tool. However, the EcoInvent uses data from the Volvo Truck Company dated from 2004 (Spielmann et al., 2007). A more up-to-date LCA from Scania (2021b) shows the following material compositions for ICEVs and BEVs. Each vehicle consists of over 10.000 reported materials. An average truck, allowed to carry up until 28 tonnes GWV, weighing 6.5 tonnes has the following material composition: Figure 2 shows the material composition after classification:

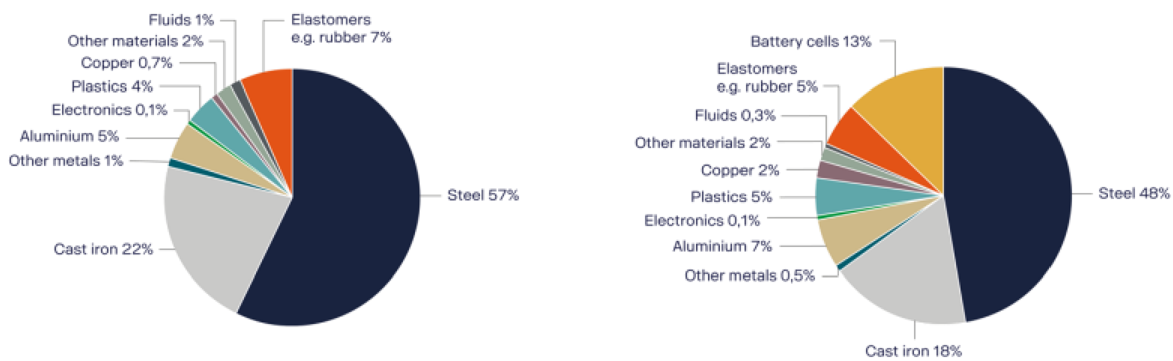


Figure 22. The material composition for the ICEV (left) and the BEV (right). Material categories expressed in percent of total vehicle weight. (Scania, 2021b)

Both vehicles are heavily dependent on ferrous metals such as cast iron and steel. The replacement of the conventional engine by an electric powertrain decreases the amount of ferrous metals used. However, this shift towards BEVs increases the strain on Critical Raw Materials, such as Lithium.

4.3.2.1. *Critical and advanced materials*

The European Commission published in 2010, and updated in 2014 work on the most at-risk and economically important materials (EC, 2014).

The elements in concern are referred to as critical raw materials (CRM) and are parts of advanced materials that are crucial in a variety of high-tech goods and machinery, not to mention goods that are essential in Europe's transition to a low-carbon economy (Peck & Jansson, 2015). Since the main components of EV batteries and traction motors are nearly entirely non-EU-sourced, the domestic sector is dependent on other nations and outside forces for their supply (ACEA, 2023b).

In a non-exhaustive list of CRMs that are crucial for the industry's move toward sustainability, ACEA listed the following (2023b):

- Lithium, battery-grade nickel, manganese, cobalt and graphite: used in the production of lithium-ion batteries
- Iridium, platinum, tantalum, cobalt and nickel: for the production of hydrogen
- REEs such as dysprosium, neodymium and praseodymium: essential for the production of permanent magnets in traction motors for electric vehicles.

The use of platinum and palladium is one of the primary CRM dependencies. According to Saidani et al. (2019), platinum group metals (PGM) are essential for new technologies like catalytic converters and fuel cells. Russia and South Africa produce the majority of the world's palladium and platinum. Palladium, which is less expensive and has more varied production regions, is replacing platinum. However, switching from one CRM to another does not lessen reliance on that CRM. Although PGM are partially recycled, they are an exception when it comes to recycling CRMs from automobiles.

PGM are recycled to some extent, but represent an exception when it comes to recycling CRMs from vehicles. For example, no dedicated procedures are in place for recovering of gold, neodymium or other CRMs in the Swedish ELV system (Andersson, M., Ljunggren Söderman, M. and Sandén A. (2014). Scarce metals in Swedish end of life vehicle recycling. SUM 2014, Second Symposium on Urban Mining). The current ELV directive is not focused on critical raw materials but more on e.g. plastic parts (Peck, 2015).

4.3.2.2. *Effect of electrification on the lithium demand*

The current state-of-the-art BEVs are powered by lithium battery packs. Heavy vehicles are considered to be on the road for 1.2 million kilometres during their lifetime. The current battery durability is not considered sufficient for these high-mileage HDVs. Battery swapping for HDVs will account for approximately up to a quarter of the gross HDV demand (Hao et al., 2019). The potential mass electrification of HDVs could increase the net lithium demand by 29% to 53% on top of the demand due to electrification of passenger cars and LDVs (Hao et al., 2019). On top of that, the IEA predicts a shortage on lithium and cobalt in early 2025 (IEA, 2021). In 2021, the annual production amounted 84 million kilos or 0.084 MT. The figure below shows the operating LCE (Lithium Carbonate Equivalent) production, the production that is under construction, the primary demand in the stated policies scenario (demand from the current policies in place), and the primary demand in the sustainable development scenario (limits the global temperature rise below 1.8°C with a 66% probability if CO_2 emissions remain at net zero after 2070).

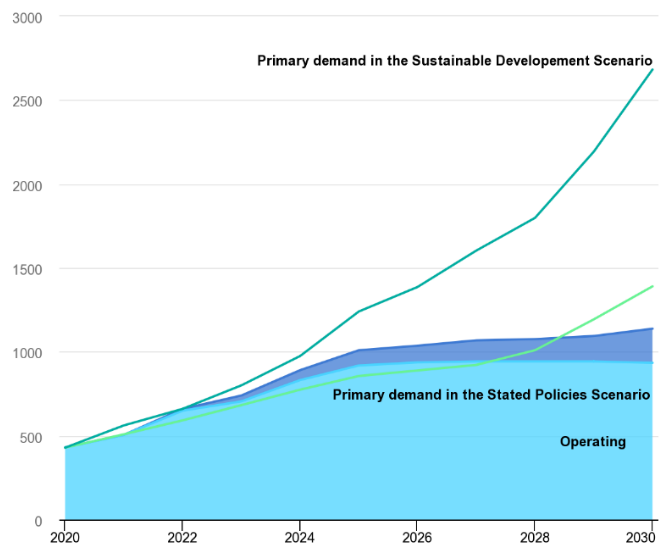


Figure 23: The committed mine production and primary demand for lithium between 2020-2030. (IEA, 2022)

Figure 23. Shows that the supply of LCE (That has a 100% assumed conversion to Lithium with a factor of 0.188) will not be able to meet demands, for the Stated Policies Scenario (in 2028) whereas it falls already behind for the Sustainable Development Scenario.

Keeping these significant resource constraints in mind, it is recommended that the decarbonisation of the HDV sector should rely on a broader mix of technologies, including fuel cell, biofuel, and natural gas vehicles. Fuel cell is reliant on CRMs as well, but is projected to be less challenging than the situation with the lithium demand (Hao et al., 2019).

Best practices:

Two main best practices are identified in the production of materials. The first is recycling. Scania only reports on a secondary material input for steel (82% primary and 18% secondary) and using the LEAD data base input for aluminium (52% primary, 48% secondary). Volvo states that approximately a third of their material input is a secondary material (Volvo, 2022). On top of that, recyclers have proven to produce secondary materials meeting virgin-grade standards. For example, secondary plastic produced from recycling can be used for safe children's toys (RENEWI, 2022b).

The second are consortia and initiatives that are promote sustainability and responsible material extraction.

- Responsible Sourcing Blockchain Network (RSBN). An open industry collaboration based on the IBM Blockchain Platform, uses blockchain technology to increase efficiency, sustainability and transparency in global mineral supply chains (IBM, 2020).
- Responsible Minerals Initiative. An industry initiative with more than 400 member companies providing tools and resources to support responsible sourcing of minerals from conflict-affected and high-risk areas (RMI, 2023).
- Global Battery Alliance. A partnership of businesses, NGOs and other industry actors working to ensure that battery production safeguards human rights and promotes health and environmental sustainability (RBA, 2022).

4.3.3. (Eco-)design and manufacturing the vehicle

Achieving circularity is not only a matter of improving on end-of-pipe practices. The design and manufacturing phase are of major importance due to choice of material, assembly for disassemble and design for lifetime elongation. The design and the production of a vehicle are heavily intertwined. Both are done in house at the OEM-level.

Manufacturing of the vehicle

If a principle of cleaner production is used, the manufacturing or production phase can be a process that is sustainable. The United Nations Environment Programme (UNEP) described this principle as a comprehensive environmental approach used in the industrial process to improve ecoefficiency and lessen environmental impact. (De Abreu et al., 2022).

Currently, two major manufacturers are operating freight vehicle production facilities in the Netherlands: DAF and Scania. Other smaller companies like Terberg and GINAF produce highly specialised vehicles or buses like VDL Bova (OICA, 2023). Figure 24. Shows the production of DAF and Scania in The Netherlands for the period of 2016-2021. Scania produces 60% of their total output in the Netherlands (Scania, 2021a). The market shares of different HDV brands is shown in Figure 25. This shows the importance of DAF for the Dutch HDV fleet. The production of Scania is more intended for the international market.

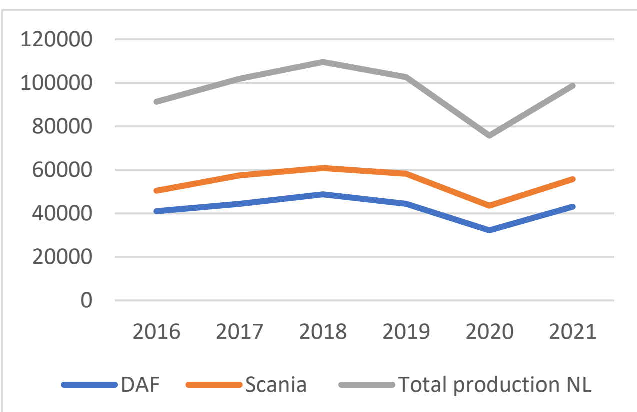


Figure 24: production of DAF and Scania in NL between 2016-2021

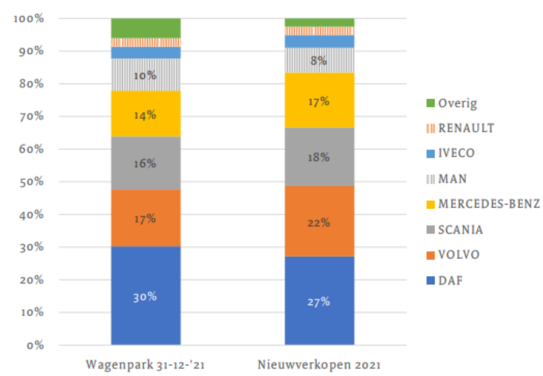


Figure 25: Fleet and new sale share per brand. (RVO, 2022)

In 2021, DAF produced an amount of 43.075 trucks in Eindhoven (DAF, 2022b). Due to the COVID-19 pandemic, the production took a big hit and therefore the latest numbers might not be entirely representative for business as usual. See Figure 24. For the fluctuation of the past few years. The maximum production capacity of both facilities are around 240 trucks a day, which is currently not met at all. Reasons are shortages in components (DAF, 2023) and chips are a limiting factor for both manufacturers (FD, 2021; Roland Berger, 2022). The figure underlines the big hit in vehicle production due to COVID-19, but also shows the production levels being almost on the old level. The 2022 numbers of DAF show even a record of 56.000 medium and heavy vehicles, which was 49.000 in 2021 (DAF, 2023).

Sustainability indicators used by production companies

To measure sustainability performance at the OEM various indicators can be used. Scania holds onto different indicators, which are based on Science Based Targets, an initiative partnered by the CDP, United Nations Global Compact, World Resources Institute and the WWF (Scania, 2021a). DAF uses indicators following the Global Reporting Initiative, the most widely used framework, defined and overlooked by the Global Sustainability Standards Board (DAF, 2022b).

Figure 26. Shows the GHG emissions from extracting raw material and refining, as well from part production, vehicle assembly and inbound logistics. 2,5 ton of GHG for both ICEV and BEV is emitted by part production, vehicle assembly and inbound logistics.

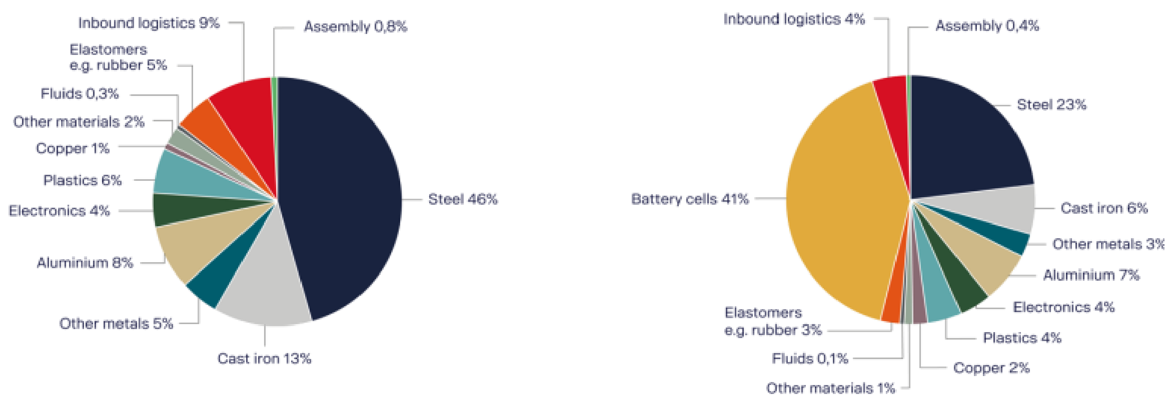


Figure 26: GHG emissions from different material categories in % of total emissions from production phase for the ICEV (left) and the BEV (right). (Scania, 2021b).

The inbound logistics, responsible for 9% of the total emission of the production of a conventional vehicle, is due to the transport calculated per transported tonne. This includes road, short sea and train transport of production material to the factories, packaging network, transport of the vehicle to the first address and transport of spare parts to the workshops (Scania, 2021b). These emissions are rather stable in the past few years between 53-55 kg CO_2eq per transported tonne.

The total production of a ICE vehicle emits 27.5 tonnes CO_2eq. Producing a BEV emits almost twice as much (53.6 tonnes CO_2eq). This increase is due the energy intensive process of producing battery packs. The current battery cell production produces 74 kg CO_2eq/kWh(Scania, 2021b). Figure 27. Shows the GHG emissions from the battery cell production compared to the total impact per kWh installed capacity.

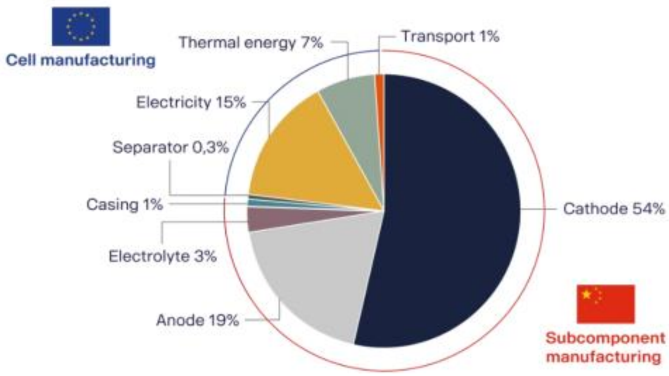


Figure 27: GHG emissions from different steps in battery cell production in % of total impact per kWh installed capacity. (Scania, 2021b)

Production of the cathode is the most energy heavy production step. Currently, the cathode and other subcomponents are produced for the majority in China. This however, imposes risks for the security of supply.

Waste and emissions created during the production phase

The data available from DAF and Scania will be compared and combined in this paragraph. The different indicator frameworks have different ways of reporting the performance. Three metrics are used to show the sustainability performance of the production phase at both companies: The energy use, emissions, and waste. A limitation is that Scania does not report facility specific. Thus, these are average statistics, not being specific for the Dutch production facility in Zwolle.

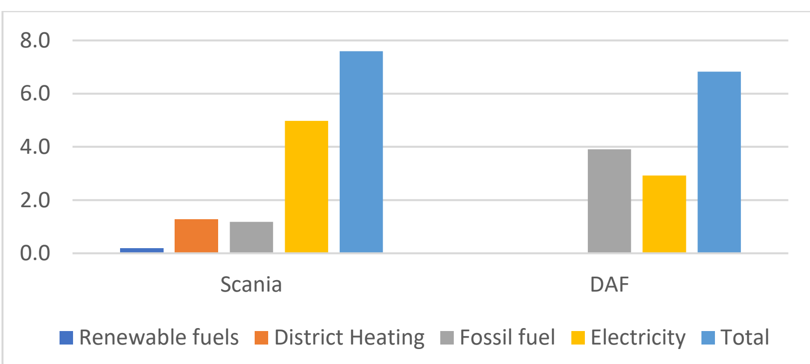


Figure 28: The energy consumption per vehicle in MWh/vehicle. Data from (DAF, 2022b; Scania, 2021a)

DAF uses per vehicle 6.8 MWh of energy; Scania 7.6 MWh/Vehicle. Electricity and district heating are the main energy sources for Scania. The energy mix of DAF is still heavily reliant on fossil fuels (gas). Therefore, the transition to phase out fossil fuels will be a challenge for both the Westerloo facility that produces the cabs, as for the production facility for the vehicles in Eindhoven. A challenge for Scania is to reduce their total amount of energy used per vehicle. This has increased from 6.9 MWh/vehicle to 7.6 MWh/vehicle.

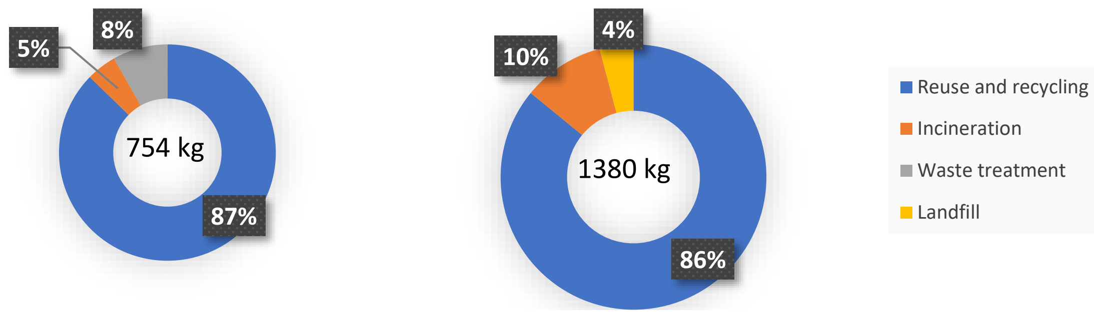


Figure 29: The waste handling for DAF (left) and Scania (right) in 2021. Data from (DAF, 2022b; Scania, 2021a)

Scania produces considerably more waste per vehicle than DAF. The amount produced has also increased, from 1.28 tonnes per vehicle in 2017, to 1.38 tonnes per vehicle in 2021. On top of that, waste of Scania is still sent for landfill, a practice that DAF has condemned since 2008 (Alers, personal communication, 2023). This can be considered as a best practice. The cab production facility of DAF faces a decrease in the reuse/recycling rate. From 83.9% in 2016 to 70% in 2021 (DAF, 2022b), and incinerates 14% of the cab waste. This is contradictory to the sustainability targets, aiming to improve reuse and recycling, whilst reducing incineration.

Best practices: eco-design and modularity

Eco-design can be considered as a best practice. According to the Ecodesign Work Plan (EC, 2022) the first principle of eco-design was created as the enhancement of environmental aspects of the performance of the product throughout its life cycle. As a result, the product is made to utilize less raw materials, prevent the use of hazardous components, and be durable enough to complete its design life cycle and then be accessible for recycling or reuse (De Abreu et al., 2022). Current vehicles are being designed for recycling. Even though HDVs are not yet subjected to regulations like the ELV directive, OEMs such as DAF are taking these regulations as directions to be on the forefront (DAF, 2022a). Current eco-design practices by different OEMs result in a theoretical recyclability of a vehicle of 90%, and a theoretical recuperation between 90%-95% (DAF, 2022a; Volvo, 2019). On the one hand, these rates are ambitious and a good circular practice. On the other hand, as explained in 4.1.1.2 these are theoretical recycling rates, not necessarily being practical recycling rates.

Another best practice is modular design. Modularity has been a major factor in Scania's business model (Scania, 2021a). The modularity is there to serve the customer's needs, but this high level of modularity increases the reusability of truck parts as well. On the other hand, it also can decrease the reusability, as it causes an abundance of parts that are not standardised. To illustrate: the Scania S-line has six different options for the cab outline.

4.3.4. Use phase

95% of the emissions in the lifecycle of an HDV, are emitted in the use phase (Scania, 2021a). Therefore, a lot of emphasis is on taking actions to reduce these emissions. Various strategies can lead to this reduction.

4.3.4.1. Performance statistics of the road transport

In 2020, the total transport performance of heavy vehicles amount 62.2 billion tonnekilometers, which accounts for 98% of the total transport performance of road transport. 93% of the total (93% of transported weight) (RVO, 2022). The transport performance measured in tonnekilometers is measured by the total transported freight (in tonnes) multiplied with the total travelled distance (in km). 70% of the distance travelled is done within Dutch borders (CBS, 2021). Hence, improving the emission performance of Dutch registered heavy vehicles is crucial for the Dutch ecosystem, but will also decrease GHG emissions in other regions.

The average load of a Dutch HDV is 8.4 tonnes in 2020. Corrected for the factor of kilometres of actual transportation, the average load is 11.4 tonnes per loaded kilometre (RVO, 2022). This shows theoretically room for improvement in terms of utilisation of the vehicle.

Another interesting statistic to point out is the average distance travelled per vehicle per year. Figure 30. Shows the average distance travelled per year for the age of the vehicle.

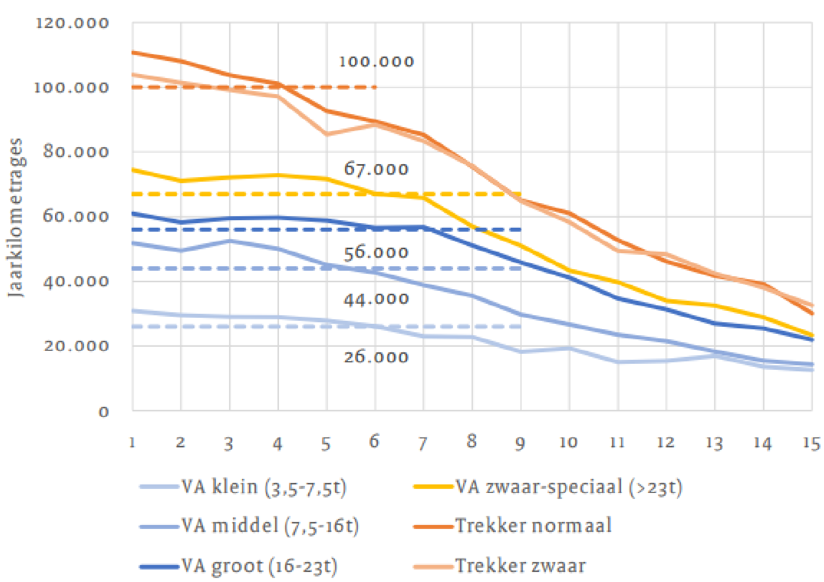


Figure 30: Average mileage over the age of the vehicle, data from (CBS, 2021), adapted by (RVO, 2022)

The figure shows implicitly how the type of ownership differs per vehicle category. The trailer, both normal and heavy, will drive 100,000 km on average in the first four years. Often, it will then be sold to a new owner, who uses it less intensive. Extreme outliers, like the trucks of bulb cultivators will drive 300,000 km to 400,000 km in a year (Peek, 2023). Considering the fact that an HDV is designed to drive roughly 1.2 million kilometres, these vehicles are at the end of their life after four years.

GHG emissions in the use phase

In 2020, the total fleet of Dutch heavy-duty vehicles emitted 7.2 billion tonnes CO_2eq (RVO, 2022). This is based on the method of fuel sold, designed by the IPCC and also used in the Klimaat en Energieverkenning 2022 ('Climate and Energy Exploration Report') (PBL, 2022).

The fossil fuel use, has significant environmental effects by emitting Green House Gases, eutrophication, terrestrial acidification and ozone creation ((Scania, 2021b). The reduction potential of electrification of the fleet is enormous.

To calculate the potential of the CO_2 reduction, the following data is used:

- Average GHG emission of 840 g/km for an average conventional Dutch HDV, equipped with an ICEV (RVO, 2022);
- Emission intensity of electricity generation in the Netherlands in 2021 (in g/KWh) (EEA, 2022a);
- Scenarios of improved electricity mixes in the EU (IEA, 2019);
- Data on GHG emissions in the life cycle of a heavy vehicle (Scania, 2021b):
    - 53.7 tonnes CO_2eq for BEV production;
    - 27.5 tonnes CO_2eq for ICEV production;
    - 2.4 tonnes CO_2eq for maintenance, 2.1 tonnes CO_2eq for decommissioning;
    - Assumption that the vehicle will drive 500,000 km during its lifetime;
    - 98.7 KWh/100 km, considering 6% Well-to-wheel losses. This means that 1 KWh converts to 1.013 g CO_2eq/km.

Table 10: GHG break-even points for various IEA electricity mix scenarios

	Powertrain	**GHG emission (g/km)**	**Use phase reduction (%)**	**Lifecycle reduction (%)**	**GHG break-even after (in km)**
Business as usual	ICEV	840	NA	NA	NA
NL 2021	BEV	422	50%	40%	62,666
EU 2021	BEV	278	67%	56%	46,493
EU 2030	BEV	206	76%	64%	41,146
EU Wind	BEV	4.8	99%	87%	31,249

Table 10. Shows that even in with the Dutch electricity mix from 2021, a BEV would reduce the GHG emission in the Use phase with 47% and reducing the lifecycle footprint with 38%. The Netherlands emits remarkably more GHG than the average Europe level (418 g/KWh vs 275 g/KWh or 424 g/km vs 278 g/km). More renewable electricity sources, means a larger reduction of emission in the Use phase. The relative share of the production phase becomes larger.

Best practices:

The utilisation of HDVs is constantly optimised. Fleet management systems register driver performance, and calculate the most efficient routes. In addition, new technologies like the Internet of Things (IoT), connected gadgets, and telematic systems are rapidly emerging. Telematic systems are automotive components that integrate wireless connectivity with remote diagnostics and automatic roadside assistance. (Saidani et al., 2018). In 2022, 66 percent of Scania's 10-year rolling fleet is connected (Scania, 2023). These system are used to manage the vehicle proactively, for predictive maintenance, driver performance, and to measure carbon impact (Scania, 2023).

Regulation encourages further optimalisation. For example, cities are reducing the transport movements in their centres. Therefore, waste transport companies started collaborating in a green collective (RENEWI, 2022a). Members of these collectives are sharing their trucks and routes to optimise routes and reduce traffic in cities. This also shows a promising increase in stakeholder and user awareness.

This shift is also underlined by an increasing interest of companies in sustainable procurement. Sustainability requirements are embedded in large tenders and even becoming more pivotal than price. For example, the municipality of Rotterdam has a requirement of sustainable transport for procured goods and services (Duurzaam010, 2020).

4.3.5. End-of-Life phase

In the Netherlands, the EoL management is done by Authorized Treatment Facilities (ATF) . Section 4.2.3 showed that only a small percentage of the Dutch-registered vehicles will reach the EoL phase in The Netherlands. Therefore, the following section elaborates on the activities of the EoL phase, both in The Netherlands and across border.

Dismantling process of trucks

Heavy vehicles are not just larger cars and therefore the dismantling and its industry is also different. The material composition is different, e.g. steel parts of a certain thickness, special equipment like a H_2/O_2 flame, is needed to cut the material (Byron & Loew, 2022). Due to the lack of standardisation, and lower volumes of ELVs, ATFs are more specialised and profit less of economies of scale.

Within the Dutch borders, the dismantling practices are of a high standard, adhering to the quality certification 'Kwaliteitszorg Demontage' (KZD) or care for dismantling quality . With the KZDplus-norm, dismantlers show that ensure the highest standards of material recycling, registration and warrantee on used parts.

OEM workshops and Dutch dismantlers, are processing for the vast majority vehicles that are either salvaged, or via an old-for-new trade (SVR, personal communication, 13-02-2023; Vos truckparts, personal communication, 15-02-2023)

Truck manufacturers like DAF or Scania produce comprehensive dismantling manuals, specifically designed for dismantling. The manuals contain all the necessary information to properly recondition and scrap the vehicle. Dismantling properly results in a theoretical recyclability of 90% (DAF, 2022a; Saidani et al., 2018) the following procedure, adapted from (STIBA, 2022) shows the dismantling process of a truck.

1. Intake vehicle
    a. Company can bid on damaged vehicle of all building years
2. Removal of hazardous substances
    a. See also Scania dismantling manual
    b. Hazardous substances get removed
    c. Fuels are for reuse
3. Dismantling of potent components and recyclable materials
    a. Dismantling of components
        i. Will be thoroughly been tested, checked and classified via the KDZ certificate
            1. 2 star and 3 star components will be stored in a stock management system
    b. Recyclable materials
4. Post Shredding Techniques
    a. Leftover wreck consisting for the majority

The reuse and recyclability of a truck differs due to various factors. The first is the state of the salvaged or returned truck and its parts. Salvaged trucks always have a certain degree of damage. The second is the age of a vehicle. An older vehicle will have been more subject to wear and tear. Another important aspect is the turnover rate of a component. The vehicles are constant developed and updated. In order to improve on fuel efficiency, durability and material input, components are constantly improved and therefore also quickly outdated. This results in a low turnover rate for many components.

All these factors are taken into account before the actual bid on an auctioned salvage vehicle. If the expected costs outweigh the potential profit, the ATF will not bid on the vehicle. The vehicle will then have a high chance of ending up in the informal economy at an illegal dismantling or repairing facility (Vos truckparts, personal communication, 15-02-2023). This shows one of the main problems for reusing parts of a vehicle or the truck as a whole. The decision making process whether a component will get back in the loop is financially motivated.

The figure below shows an salvaged vehicle, dismantled at a Dutch ATF, with in table . The table shows the various components, valued to be financially viable to reuse or refurbish. This is not for the Dutch aftermarket only. Typical Dutch dismantlers supply to the whole of Europe. If the component is too old to be used in an Dutch or European vehicle, it could still have a potential to be shipped to an developing country, e.g. in Africa. Parts with a low turnover rate, might end up eventually for recycling as well.

Table 11: Information of the salvaged vehicle

Brand	**Scania**
Type	G420
Construction year	2011
Mileage	595,255
Engine type	DC-1222
Gearbox	GRS-895R

Figure 31: Salvaged vehicle by Dutch ATF (Vos truckparts, personal communication, 2023)

Table 11. Shows the result of the dismantling process of the salvaged vehicle in Figure 31. It illustrates the circular potential of the dismantling practice. Up to 90% of the weight is able to be reused, after inspection and reconditioning when applicable. 8% will be put up for recycling, in the way described in the brackets. Just 2% is regarded as waste. It is important to note that these numbers do not prove the theoretical recyclability. The theoretical recyclability is based on the full recycling of the vehicle.

Table 13. Shows the costs and the theoretical profit for the dismantled vehicle described in Table 12. And Figure 31. It is a theoretical profit, because components might end eventually up being obsolete. The dismantling, reparation and quality assurance are labour intensive. Over 45 hours have been worked on this particular vehicle, which was in a rather good state.

Table 12: Components and their destination

Reuse (90%)		Recycling (8%)	Waste (2%)
Airconditioning	Exhaust pipe system	Cab suspension support (scrap iron)	Plastic air pipes
Airconditioning fluids	Front and rear leaf springs	Chassis frame (Scrap metal)	Plastic damaged parts
Breaks	Front shaft	Cool pack (damaged, old aluminium)	Waste left by driver
Bumper	Fuel tank	Cool pack support (scrap iron)	
Cab (possible reparation)	Gear Box	Cooling water (reuse in engines)	
Cardan shaft	Headlights		
Chassis/body	Hubs		
Clutch	Motherboards and computers		
Differential	Rear axle housing		
Engine	Wheels		

Table 13: Costs and theoretical profit for a dismantled vehicle

Costs	(€)	Profit	(€)
Purchase vehicle	10,000	Engine	8,000
Transport	500	Gear box	4,500
Dismantling man hours	1,300	Cab	4,500
Reparation and quality assurance man hours	1,625	Differential	1,500
		Other parts	3,000
Total	13,425	Total	21,500

Dismantling at unauthorized facilities

95% of the Dutch registered HDVs will not end their life in The Netherlands, of which 70% will be treated as an ELV somewhere in Europe, and 30% will end their life outside of Europe. The quality of dismantling varies significantly between ATFs and unauthorized facilities, and in between unauthorized facilities. Cases are known that in LMICs the dismantling will take place next to the road, where the vehicle stranded. To drain the fluids, which are hazardous substances, a trench will be dug to let it flow (Vos truckparts, personal communication, 15-02-2023). However, due to the limited data available, it is unknown whether these cases can be extrapolated to all illegal facilities. The data issue and lack of traceability are widely regarded as an barrier for the circular economy (Appendix C.)(Baron, 2022; EC, 2021; Munir, 2021; Saidani et al., 2018)

Best practices

The Dutch ATFs are considered to be at the forefront of the industry. They operate with high levels of efficiency, minimizing waste by repurposing components and materials. The ATFs provide warranties for the components, certified by a certification authority such as Kwaliteitszorg Demontage (KZD, 2013). They also provide bottom-up deposit schemes to maintain the intrinsic value of components as long as possible. For instance, a deposit-scheme is used for old electronic equipment (Appendix C.).

4.3.6. Distribution

The distribution phase is one of the pillars of the circular economy within the HDV value chain. Channels are used by actors to distribute new vehicles, but for a CE more important, also redistribution of both used vehicles and parts, repairing and refurbishing.

The secondary market, including the remanufacturing, refurbishing and reuse is operating quite well. The remanufacturing of heavy-duty and off road equipment (HDOR) is estimated to have a very positive benefit. It safes an annual 855 MT of materials and 3458 MT of CO_2-equivalents (Parker, 2015). It should be noted that performing comparative LCAs for manufactured vs. remanufactured goods is famously challenging due to challenges identifying the exact parameters for assessment. In 2012, the HDOR remanufacturing industry is valued in the Benelux on 160M € (Parker, 2015).

Best practices

Scania Vehicle Recycling (SVR) has optimised their used parts logistics process. The used parts are distributed via the distribution network of new parts, to minimise the footprint of the used parts.

Discarded parts, straight from manufacturing, are being used for the aftermarket. On top of this supply, SVR dismantles salvaged vehicles and vehicles from a take-back scheme, to use these components for the aftermarket. This supply is able to meet the current demand of aftermarket parts bought by official shops from OEM Scania. To reduce logistic burdens, this is sent along with the newly manufactured parts (SVR, personal communication, 13-02-2023)

The used truck centres are another best practice. Annually, DAF takes more than 12,000 vehicles back through a variety of channels, such as rental fleets, lease contracts and Buy-Back residual value guarantee (Peters, 2021). These are then, after rigorous checks reintroduced on the market, including a warrantee. This cycle repeats until the end of their lifecycle.

A problem for the remanufacturing of HDVs and their components Is the heterogeneous character (Saidani et al., 2018). However, the business model of Caterpillar shows that remanufacturing of highly heterogenous vehicles can be made profitable. An external study showed the reduction potential of remanufacturing compared to manufacturing new parts. Remanufacturing resulted in 65-87% less GHG emissions, 65-87% less energy use, and 80-90% less raw materials (Caterpillar, 2023).

4.4. Circular strategies

Along the value chain, various activities can already be identified as circular practices. These strategies have the potential to contribute to reduction of material intake in the value chain. The studies of van der Zaag (2020) at PBL, and the study of Accenture done for the World Economic Forum (2020b) are used for the outline of the potential strategies, after which the strategies were tested in the focusgroup. Research van der Zaag (2020) calculates the impact of various strategies on the primary material intake. The main limitation is the research assumes the full lifecycle being within the Dutch borders, which is not the case for the HDV. Therefore, his results are more an indication of the impact of the strategies on the primary material intake.

Electrification (van der Zaag, 2020; WEF, 2020b): Has the potential to significantly reduce the resource use in the use phase. However, This strategy has significant implications for the value chain, e.g. increasing material demands, increasing emissions during the production phase and influences the fleet stock development. Due to lacking data on electrification of HDVs, van der Zaag was not able to calculate the electrification of HDVs. However, the electrification of delivery vans is expected to increase the primary material demand by 43% (van der Zaag, 2020). In this research, electrification is regarded as a niche-level innovation, to better describe the influence on the value chain.

Improved utilisation of the vehicle (van der Zaag, 2020; WEF, 2020b): New business models like sharing are promising for increasing utilisation of cars. Cars are currently non-idle for roughly 98% of their lifecycle (WEF, 2020b). HDVs are quite the opposite, because in order to be as cost efficient as possible, logistic optimisation is key. Furthermore, trailers are for 61% owned by professional freight transporting companies (Panteia, 2021), which act as an intermediary transport providing service.

Even though, logistic optimisation is already part of the business for road transport, 20% of the transportation is still empty. Even though this is mostly due to inherent incompatibility of two-way trade in a globalised economy, significant improvements can be made (Ambel, 2017; Brancaccio et al., 2017)

Elongation of lifespan of the vehicle (van der Zaag, 2020; WEF, 2020b): Elongation of the lifespan of an HDV is considered the circular strategy that contributes most to reduction of the primary material intake (Appendix C.; (van der Zaag, 2020; WEF, 2020a).

Considering the observed regression trend of a longer lifespan of passenger cars in the past 20 years, van der Zaag assumed in 2020 an linear increase in vehicle lifespan by a factor of 1.5 in 2050 compared to 2017. The average age of an HDV is assumed to be 17 years. By increasing this to 25 years in 2050, the primary material demand from HDV production can be reduced by 40% (van der Zaag, 2020). In the current thesis research on circularity in the HDV sector, this is merely an indicator of the potential of lifetime elongation.

Elongation of lifespan of the component (WEF, 2020b): The lifetime elongation of components is the next step of today’s reality for the HDV. A good example of the effects of lifetime elongation is the business model of Caterpillar. An external study showed the reduction potential of remanufacturing compared to manufacturing new parts. Remanufacturing resulted in 65-87% less GHG emissions, 65-87% less energy use, and 80-90% less raw materials (Caterpillar, 2023).

Substitution of primary materials (WEF, 2020b): The use of secondary material can reduce the primary material intake significantly. The impact calculation of substituting primary materials by secondary materials is out of scope for this research. The research of Saidani et al. (2019) gives an example of the benefits of secondary material substitution for the critical material Platinum (Pt), in HDV applications such as the catalytic converter. Saidani found a leakage of approximately 15 tons of Pt in the European market in 2017. Although in-use dissipation accounts for around a quarter of the losses, inadequate collection and unrestricted exports account for 65% of them. (Saidani et al., 2019). Research shows that halving the platinum leakage, and using the secondary material as a substitute for the raw material input, would prevent an energetic consumption of 1300 TJ and a reduction of 250 kilotonnes CO_2-equivalents (Saidani et al., 2019).

Modal shift (van der Zaag, 2020): Few alternatives exist for road transport, as inland and railroad shipping do not have the same characteristics for usability (van der Zaag, 2020). The WLO scenario analysis underlines this, because the vehicle stock will even increase slightly (Van Meerkerk, 2020). Therefore, this strategy is not considered in this research.

4.5. Sub conclusion

The value chain analysis offers insight in the both the stocks and the flows, and the characteristics of the value chain phases. It shows that the production of materials and components, and the assembly of the vehicle is still energy and GHG emission intensive. This becomes increasingly more important, because the focal impact shifts from the use phase to these phases due to the decarbonisation of vehicle use. The dismantling of HDVs is an efficient process in Dutch ATFs. However, roughly 95% of the vehicles are exported before they reach the end of their life.

Several strategies have the potential to reduce the material inflow in the Dutch HDV sector. Lifetime elongation of the vehicle contributes the most to reducing the material inflow. A case study of Caterpillar showed that remanufacturing of components decreases drastically the material inflow, energy use and GHG emissions during the production compared to new manufacturing (Caterpillar, 2023). However, these are all theoretical impacts of strategies, or a proven strategy, but in the business of Heavy-Duty Offroad Machinery. The next chapter will identify barriers that hamper the uptake of these circular strategies.

5. Barriers and Enablers to a circular Heavy-Duty Vehicle Value Chain

Chapter 5 elaborates on the barriers that hamper the transition to a circular heavy vehicle chain and the enablers to overcome these barriers. Both barriers and enablers are generated and tested during the focusgroup 'circularity in the heavy vehicle sector'. Section 5.1 elaborates on the identified barriers and section 5.2 provides enablers to overcome these barriers.

5.1. Barriers

This section categorises the identified barriers that hinder or slow down the systemic change towards a circular heavy vehicle chain. The barriers are based on explorative interviews and the results of the organised focus group.

Based on section 2.3, the barriers are categorised as technological and infrastructural, supply chain governance, economical, institutional and cultural barriers. Table 14. Gives the overview of the experienced barriers to a Circular Economy in the HDV sector. These are identified during the focusgroup. The table shows the phases for the points of engagement to overcome the barriers, and also for which R-strategies these are barriers form a hinderance.

Table 14: Overview of barriers to a Circular Economy in the HDV sector identified during the focusgroup.

#	Type of barrier	Stakeholders in value chain	Barrier for which R-strategy
	Technological and infrastructural		
1	Trade-off between circularity and use performance	Design, producer	Reuse, repair, recycle
2	Lack of design for circularity	Design, producer	Reuse, repair, recycle
3	Lack of standardisation	Design, producer	Reduce, reuse
	Supply chain governance and information		
4	Lack of collaboration in value chain	All phases	Reuse, repair
5	Lack of collaboration between member states	Government	Reuse, recycle
6	Unknown where-abouts of ELVs and used trucks	Producer, government	Reuse, recycle
7	No data on impact of CE strategies	Producer, EoL	Reuse
	Market and economical		
8	Empty freight transport	User	Rethink, reduce
9	Cheap virgin materials	Government	Reuse, recycle, substitute
10	Expensive labour	Dismantling, recycling	Reuse, repair, recycle
11	Hard to achieve economies of scale and scope	EoL	Reuse, recycle
12	Investment risks	All phases	All R-strategies
	Institutional		
13	No ELV regulation	Government	Reuse, recycle
14	Perverse or lack of right incentives	Government	All R-strategies
	Cultural		
15	Linear thinking and linear business models	Producer, recycling	Reduce, reuse, recycle
16	Lack of user awareness for CE	User	Rethink, reuse
17	Hesitance towards innovation	Producer	Reduce, reuse

The government is not necessarily part of the value chain. However, some barriers are to be addressed by governmental organisations. One can argue that the government can engage in all issues. However, shifting all responsibility towards the governmental is too simplistic and will not help in the transition towards a CE.

The identification of barriers shows that in all value chain phases points of engagement exist to improve circularity. However, the results of the focusgroup imply that the most of the barriers (36%) are to be addressed in the design / production phase. Figure 32. Shows the distribution of the engagement points in the value chain phases.

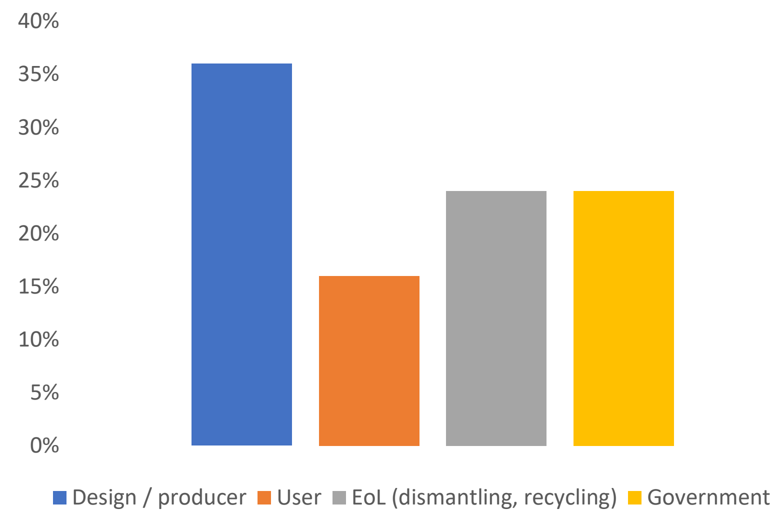


Figure 32: Distribution of engagement points in value chain phases.

The engagement points in the design / production phase are very important. In this phase, the vehicle is designed, alongside with the business model and the OEMs are dictating therefore the whole market. A lot of issues, for example during dismantling or recycling, are in theory to be solved on the OEM level. Both users and government can exert pressure on the producers. The government can design policy measures, whereas users can exert pressure by switching to more sustainable procurement.

It is also important to develop a better understanding on to what extent the barriers are hindering the various R-strategies. ‘Higher’ R-strategies are suggested to reduce material use more than ‘lower’ R-strategies. The strategies of reuse, refurbish and remanufacture are not often distinguishable in the HDV sector. It hardly occurs that components are reused without any inspection, and replacement of parts that are subject to wear and tear. This is even more applicable to the whole vehicle. It will hardly reused without inspections, refurbishing and remanufacturing, to guarantee a used vehicle of the highest quality. Figure 33. Shows what percentage of barriers is hindering the uptake of different R-strategies.

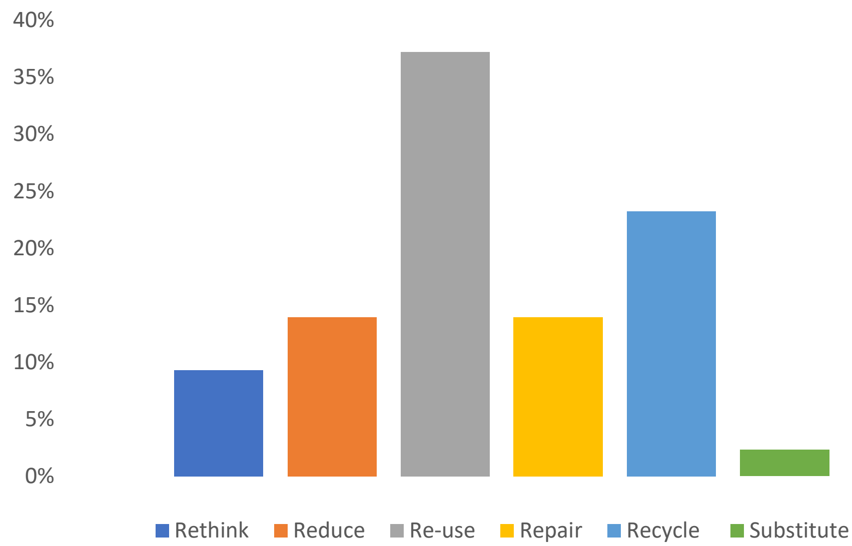


Figure 33: Hindrance rate of barriers for different R-strategies.

Figure 33. Shows that the barriers hinder reuse the most, by all types of barriers. Technical reusability, supply chain governance, cheap virgin materials, no ELV directives and linear thinking etc. All are making the reuse of components and vehicles more difficult. This is important, because lifetime elongation from both vehicles and components are considered to have the biggest effect on (raw) material intake. Other R-strategies face less barriers. For example, rethinking endures less pressing issues. This can be explained by the fact that in the case of the HDV, the use of the vehicle is rather optimised. Reduce is also a strategy that has been exercised thoroughly for a long time, due to striving for performance optimisation. However, the reducing during the production phase is less successful, also considering the emission and waste generation statistics, elaborated on in section 4.3.3. Reuse, repair and recycle share various barriers that cause hindrance, such as expensive labour, lack of circular design or lack of collaboration in the value chain. Recycle is a rather end-of-pipe solution. Because just a small amount of vehicles reach the EoL phase in the Netherlands, this is a less apparent issue for Dutch stakeholders. The only barrier that is identified for substitution is the low price of virgin materials. This leads to secondary materials being not economically feasible.

5.1.1. Technological and infrastructural barriers

A significant trade-off remains between practices facilitating R-strategies, such as circular design for dismantling, reuse and high-grade recycling, and emissions during the Use phase. For instance, elongating the lifetime of an HDV may mean that a less efficient vehicle is used for a longer period. In the case of combustion engines, 95% of the emissions during the vehicle's life cycle occur during usage (Scania, 2021a). Therefore, small improvements in this phase can result in significant reductions in fuel consumption and emissions. To achieve these goals, the industry has made considerable strides in fuel efficiency and emission reduction, leading to increased complexity in vehicle components. Modern components are more electrified and smart, and mono-materials have been replaced with lightweight composites. Additionally, various materials are often joined together using glues or welding techniques, making disassembly more challenging and reducing the overall rate of high-grade recyclability. Electrification, wielding and composites make it also harder to reuse components.

Another significant challenge of this trade-off is that vehicles and their components are quickly outdated. Emission standards going from EURO I to EURO VI in 20 years, show older ICEVs being outdated rather rapidly. Zero emission technologies are still in their early stages, resulting in fast innovation that exacerbates this effect. This also results in a lack of standardization, with only a few items such as dynamos, brakes, or stabilizers being standardized among brands and models. Innovations are fast, but the lifecycle of an HDV is long. Reliability lines of OEMs require a lifetime of at least 8 years or roughly 1M-1.5M km in distance on the road (Peters, 2021). But reality is that the vehicle is often used for 20 years and beyond (see Figure 15. For the average age of HDVs in Europe). It is difficult for OEMs to anticipate for proper dismantling by designing something that will end its lifecycle after 20 years. Except from a couple wear parts, components are designed to last the full lifetime. In the meantime, innovations are quick.

Insufficient emphasis on design for circularity to facilitate dismantling increases the time and complexity of the dismantling process, and reduces the rate of high-grade recyclability. Recyclers' sorting categories are often challenging for mechanics to follow, exacerbating this problem. Consequently, composite and mixed materials are frequently rejected and ultimately incinerated, further reducing the recyclability rate.

Even considering all issues mentioned above, the Dutch facilities responsible for dismantling (HDVs) are considered to be at the forefront of the industry. They operate with high levels of efficiency, minimizing waste by repurposing components and materials. The example of the salvaged vehicle in Figure 31. Shows that only 2% of the vehicle is meant to be recycled. Everything else is in the state to be reused. However, 95% of all Dutch registered vehicles don’t end their life within the borders of the Netherlands (RVO, 2022),. The vehicle has a high chance to end up in a non-authorized facility, that doesn’t have the infrastructure, or knowledge to dismantle the vehicle properly. This can significantly affect the circularity in the HDV value chain.

Apart from lacking infrastructure to dismantle ELVs properly, Low and Middle-Income Countries (LMICs), do not have the infrastructure to use and maintain newer vehicles. Consequently, newer vehicles, like EURO IV or EURO V, are imported, but then completely stripped from any advanced technology, and are equipped with old, more pollutant motors, as old as EURO I. Hence, it is important to keep in mind that LMCIs are heavily reliant on older European vehicles. LMCIs are not able to utilise newer vehicles in an appropriate way, let alone that they will be able to use used BEVs in the foreseeable future.

5.1.2. Supply chain governance

Collaboration within the supply chain, both horizontally (between organizations in the same value chain phase) and vertically (between organizations of different value chain phases), can be improved to enhance circularity. For instance, data lacks on the composition of components, and it is hard for non-OEM affiliated dismantling facilities to get full legal information on the right replacement of malfunctioning equipment. The lack of collaboration between dismantlers and designers, results in a design less suitable for reuse and recycling. Apart from that, reuse and recyclability is hampered due to the lack of knowledge on the reusability of components. The exact rate of wear is hard to predict and due to the absent standardisation, it is unsure which component can be used where. Coordination within entities at OEMS are a limiting factor as well. Whereabouts of components and circular practices are often unknown. Furthermore, IT systems are a highly standardised, the systems are not made for circular practices such as the use of remanufactured products in new vehicles (Scania CE, personal communication, 16-02-2023).

Outside of the Netherlands, the whereabouts of end-of-life vehicles (ELVs) and used trucks are often unknown to both authorities and OEMs, making the transition towards more circular practices difficult. 70% of the ELVs end their life within the borders of Europe (Munir, 2021). However, there is no data on the EoL management of the vehicles, which has several consequences. The first consequence is that the current state of circularity within the value chain is unknown. Non-authorized facilities do not need to comply to safety, recycling and health guidelines and are therefore opposing circularity. This represents an environmental risk. However, there is not even an estimation of the quality of dismantling in other countries. Secondly, OEMs do not know how e large volumes of materials and vehicles flow. Hence, it is hard to adapt design practices to the main standards of dismantling. The lack of cooperation between member states and there vehicle registration systems amplifies this problem. The problem of 'missing vehicles' represents significant materials losses from the European system and it needs to be avoided that ELVs are exported as used (and therefore usable) vehicles outside of the EU.

Apart from that, the environmental and material impact is unknown of certain strategies like remanufacture, reuse or recycle. A trade-off exists between the benefits of a CE strategy, like remanufacture, and the increased footprint of component transport to a remanufacturing facility. Other, 'lower' CE strategies, like recycling, can turn out to be the environmental more preferred option. This issue is embedded in a larger problem. The whole value chain has issues with the vagueness of circularity. Currently, the transition towards a CE sets an ill-defined goal, and the lack of Key Performance Indicators hampers this transition.

5.1.3. Economic and market barriers

Utilisation of the HDV can always be improved, empty freight transport is still a loss of resources. However, HDVs have a higher utilisation rate than passenger cars, which are non-idle for over 98% of their lifetime. Consequently, this means that downtime, for example due to malfunctioning, or maintenance, is extra costly. Therefore, reliability of the vehicle and its components is of utmost importance. Often, a larger module is being replaced, even only if a smaller part is defect and it is often the more economic option to replace instead of repair and to be on the road again as quickly as possible.

To reduce downtime is not the only reason why CE strategies are often not economically preferable. The price of secondary materials and used components usually cannot compete with their virgin and new counterparts. The price of virgin material is too cheap, and does not reflect the true costs of production. On top of that, labour is expensive. Most CE strategies, like dismantling of complex components are labour intensive and time-consuming, which makes the business case worse.

Furthermore, economies of scale and scope are difficult to achieve. The volume of annual ELV vehicles is relatively low, and heterogeneous, both in type, and in location where the vehicle reaches the end of its life.

It is also challenging to determine the right time to invest in new zero emission technologies as innovations are rapid and market developments can render technologies quickly outdated. For example, LNG was considered a relatively emission-friendly substitute for ICEVs. However, the volatility of gas prices due to the Ukraine crisis has made this fuel type too expensive and uncertain. This lead to a mass amortisation of this fuel type.

5.1.4. Institutional barriers

Various institutional barriers hinder the transition to a circular economy, taking on various forms. The first barrier is a lack of proper regulation. At present, there is no legislation governing the end-of-life treatment of HDVs, which retain their value for a long time. Consequently, no proper incentives apart from a certain degree of cost optimisation exist to promote circular practices for end-of-life vehicles (ELVs) and reduce emissions across the borders of the Netherlands and the European Union. Although some regulations such as the ECOWAS import regulation on vehicles older than ten years or less than the EURO V standard have been implemented (ILT, 2020), there is no component import/export regulation. This encourages the replacement of cleaner technologies such as EURO VI engines with more pollutant older types.

In addition to a lack of regulation, poorly designed regulations can be ineffective. For instance, the Extended Producer Responsibility (EPR) in the current ELV directive for passenger vehicles does not incentivize original equipment manufacturers (OEMs) to improve dismantling. The EPR imposes a standard recycling fee to be paid by OEMs, but because it is not a progressive scale, and ELV handling is not their responsibility, no incentive exists to design vehicles for better dismantling and recycling. Cross-border EPR is also currently not enforced.

Regulations can also (in hindsight) create perverse incentives, such as weight-based requirements that do not consider the volume or value that may not be recycled due to the large weight share of ferrous metals in a vehicle. Regulation can also cause greenwashing, which can mislead consumers. For example, the current ELV demands a recyclability rate of 85%, including downcycling materials to inferior second lives, or even backfilling, which is regarded as a "recycling practice" (EC, 2021).

Furthermore, regulation can be too stringent, impeding communication and cooperation in the value chain both horizontally and vertically. For instance, some participants in an organized focus group had to approve their participation on several levels within their organization to minimize the risk of violating competition law. Consumption tax (VAT) also acts as a barrier to the circular economy, leading to stacked taxes collected on the new product, again on the used product, and once more on labour, such as repair or maintenance. Export bans can also be too stringent. Banning export of old vehicles or components can hamper the transition towards a circular economy. Old types might be outdated in our developed economy. But, replacing pollutant vehicles with a less pollutant one is still an improvement and contributes to lifetime elongation.

5.1.5. Cultural barriers

The transition to a circular economy in the HDV sector faces several cultural barriers. The foremost of these is the linear system and associated company culture. Although there are existing circular economy (CE) practices in place, they are based on cost efficiency rather than on a circular mindset. Producers of components and vehicles tend to have linear business models that oppose lifetime elongation by reuse or another strategy to slow the loop. Therefore, by facilitating more circular business models, there is a risk that the business-as-usual might be cannibalised. This emphasizes the need for a shift in mindset towards a circular economy.

Another cultural barrier to the transition is the lack of interest in sustainable HDVs. Hence, the willingness to pay a premium for sustainability is marginal. This lack of willingness can be attributed to several factors, including a lack of financial resources and a lack of understanding of the environmental benefits of circular practices.

A barrier that is understandable, but nevertheless significant, is the focus on scope 3 emissions by HDVs, which account for 95% of the environmental impact during the Use phase (Scania, 2021a). However, it is essential to note that other phases of the HDV lifecycle are still highly polluting and contribute to the overall environmental impact of the sector.

Hesitance towards innovation is another barrier to the transition, especially if it does not seem to have an immediate effect. For example, it can be challenging to persuade OEMs to invest in circular design when there is a consensus that the vehicle will end up as anonymous car fluff regardless. Furthermore, thinking in problems rather than in solutions hampers the transition towards a circular value chain. Overcoming these barriers will require a collective effort from stakeholders, policymakers, and consumers alike.

5.2. Enablers to increase circularity in the HDV value chain

Different types of barriers have been identified and throughout the focus group, enablers have been explored to overcome the identified barriers.

5.2.1. Technical and infrastructure enablers

The quality of the output at the End-of-Life phase is dependent on the design of the vehicle. Therefore circular design is vital to achieve circularity.

A **circular design** facilitates the reuse, remanufacturing, and recycling of components and materials. Three aspects of circular design stand out: Lifetime elongation, modularity and design for recycling.

Lifetime elongation has a large potential to reduce the material impact of the HDV. By remanufacturing, repairing, and remanufacturing, both vehicle and components should reside in the loop as long as possible. One way is to improve the durability of the components.

Another way, is by increasing the **modularity** of the vehicle. Innovations are quick and components are also subject to a heavy use. Most of this innovation has historically been in the powertrain. The transition towards zero emission transport emphasises even more on drivetrain innovation. Most likely, innovations will follow-up rapidly, causing technology to be quickly outdated. It would be unnecessary to buy a whole new vehicle, if just the drivetrain has been improved. A more modular design would reduce the impact of quickly outdated drivetrains, will keeping the rest of the vehicle intact. Modularity can also make the dismantling less time consuming because the vehicle will be easier to disassemble.

Design for recycling will increase high-grade recycling by using more mono-materials, or by using materials that have a proven high recyclability. There is often a trade-off between the need to improve performance during the Use phase, e.g. by replacing mono-materials with lighter materials, such as composites or polymers, and design for recycling.

5.2.2. Supply-chain governance and information enablers

To facilitate and encourage circular practices, both in the beginning (e.g. Circular Design) and in the end (dismantling and recycling), improved knowledge and information is essential.

Data on the end-of-life phase of the HDV could greatly improve circular practices. One obstacle for practical circular design improvements is the lack of data on the large flows of ELVs. It is unknown to where, how and to what extent HDVs are dismantled in the EU. It is hard for both policymakers and OEMs to act if the current state of circularity in the value chain is unknown.

Insight in the performance of CE strategies is necessary to steer towards the right strategies. The impact of secondary materials and components and preparing them for use compared to their new counterparts is necessary to look into.

For further optimisation, the use of **material passports** is suggested. Material passports allow for the optimisation of recycling processes.

A Circularity indicator is a key element in the transition to a circular economy. It helps to measure circular performance of organisations and is able to set clear goals (WBCSD, 2022). Until now, most competition is on vehicle reliability, driver comfort and fuel efficiency. Reporting on ESG goals shows already that non-economic indicators can create competition as well. This renders organisations that fall behind to become quickly obsolete. The European Commission has currently 17 circularity indicators under revision. Choosing an overarching indicator is a delicate process, as a (in hindsight) wrong indicator could steer the transition into the wrong direction and/or be susceptible for greenwashing.

5.2.3. Economic enablers

Sustainable procurement is an important tool, especially if it is exercised by parties with market power, like the government or large corporates with a substantial intern logistics component. Procurement criteria can include indicators besides the market price of a vehicle.

A systemic shift is needed for the circularity transition. **New Business Models** (BM) have the potential to cause a systemic shift. Other BMs force the OEMs to think differently about their product. For instance, Caterpillar’s non-road mobile machinery Business Model includes a take-back programme with a **deposit scheme and voluntary product take-back** (Ellen MacArthur Foundation, 2017). A key component of Caterpillar's successful BM is its incorporation of the entire lifecycle of the product in the design process to ensure sound financial processes throughout all stages. This exemplifies that new BMs that hold the OEM responsible for the end-of-life phase can improve circularity across the entire value chain.
Another compelling new BM is **Product-as-a-Service (PaaS)**. Logistics companies are primarily interested in the use of Heavy-Duty Vehicles (HDV) to provide their services, rather than owning them. The shift of OEMs from vehicle suppliers to service providers would necessitate a rethinking of the vehicle's lifecycle, as they would retain ownership. Consequently, designing for dismantling would become routine to optimize End-of-Life Vehicle (ELV) handling.

The consensus during the focus group was that **True Pricing** is the most impactful enabler. The current market price for a vehicle does not reflect the true costs made along the value chain, because environmental and social costs are not accounted for. True Pricing refers to the market price and unpaid external costs, such as underpayment, loss of biodiversity and carbon emissions (True Price, 2019). True Pricing could significantly change the linear business case. It is suggested that the impact of reverse logistics for e.g. remanufacturing are able to nullify the benefits of keeping products in the loop. By calculation of the (external) costs of circular practices, a full valuation can be done on their impact. This would strengthen the level-playing field.

5.2.4. Institutional enablers

Regulations play a critical role in steering the transition towards a Circular Economy. At the beginning of the value chain, **mandatory recycled content and biobased targets** are necessary to incentivize the use of secondary and biobased materials and reinforce eco-design measures. At the end of the value chain, promoting reuse and recycling is key.

The End-of-Life Vehicle (ELV) Directive serves as an example of such regulations, and is currently undergoing revision to potentially encompass heavy-duty vehicles. Within the ELV-Directive, **Extended Producer Responsibility (EPR)** mandates a removal fee that OEMs must pay for each vehicle they introduce to the market. The premium that illegal ATFs are able to pay due to lower environmental and administration costs should be countered by an appropriate fee. However, this standard fee must be re-evaluated, and a differentiated fee based on the level of design-for-dismantling implemented could incentivize proper dismantling. The European Commission aims to merge the ELV and type approval (3R) directives, which would support the implementation of CE from manufacturing to ELV treatment(EuRIC, 2021).

Furthermore, **better and clear definitions of circular practices** are critical. The definition in the ELV directive should align with the definition of recycling with the Waste Framework Directive's definition, which excludes backfilling as a circular practice(EC, 2021). Additionally, distinctions should be made between various levels of high grade and low grade recycling (downgrading).

A revision of the **Taxation framework** is also necessary to encourage circular practices, potentially through a raw material resource tax or a reuse-repair tax relief. Sweden has already implemented the reuse/repair tax relief since 2017 (Milios, 2021).

5.2.5. Cultural enablers

A Circular Economy requires **more collaboration along the value chain**. OEMs need to have better knowledge on dismantling and recycling practices to improve their circular product design. Meanwhile, ELV stakeholders need more information from OEMs to improve their activities. Therefore, information exchange and a tighter value chain should be facilitated. However, companies are hesitant for tighter collaboration due to the potential threat of violating competition regulation. Governmental bodies should provide controlled space to collaborate without violating competition regulation.

5.3. Sub-conclusion

The uptake of circular practices in the HDV value chain faces many different barriers. Based on the findings of the focusgroup, enablers are identified to overcome these barriers. The enablers have a role in facilitating successful implementation of circular strategies.

Table 15. Shows the relationship between the enablers and which barriers they are generated for to overcome.

Table 15: Overview of enablers that overcome the identified barriers

Enablers	Barriers
True pricing	Cheap virgin materials, expensive labour
Circular design	Difficulties with reuse, remanufacturing, recycling
Lifetime elongation	Excessive material outflow
Modularity	Lack of standardisation, trade-off between circularity and performance
Design for recycling	Problems with recycling
Knowledge on EoL phase of vehicles	Unknown whereabouts of ELVs, impact of CE strategies
Material passports	Problems with recycling
Circularity indicator	Impact of CE strategies, level-playing field for sustainable competition
Sustainable procurement	Investment risks, linear thinking
New Business Models	Linear thinking
Deposit scheme	Outflow of materials
Product-as-a-Service (PaaS)	Unwanted ownership, unclear ownership
Mandatory recycled content and biobased targets	Uptake of secondary material use
ELV Directive + EPR responsibility	Ownership of ELVs
Clear definition of CE practices	Perverse incentives
Revision of tax framework	Level-playing field
More collaboration along the value chain	Lack of information on circular design

A key learning from the focusgroup is the absence of data on the EoL management of HDVs hinders the transition to a circular HDV value chain. This could the start of constructive discussions on how to actively improve design for dismantling and recycling, tailored on the most common practices for dismantling and recycling. The absence of EoL data of HDVs, is caused by the lack of ELV regulation for HDVs. This link is further amplified by the fact that the ACEA, and its linear mindset, in the past has actively opposed including HDVs in the ELV directive. The case of the passenger vehicle shows that the ELV directive and its requirement for identification systems helps to identify ELVs, and EoL practices. Nevertheless, a lot of passenger vehicles still end up in the informal economy. This makes the extension of the ELV directive definitely a vast opportunity for improving data on EoL management of HDVs, but not yet an encompassing enabler to successfully transition towards a circular value chain.

The current design of the vehicle complicates circular strategies and the implementation of enablers. First of all, this research shows in section 4.4. that lifetime elongation has potentially a large impact on the primary raw material. However, the current design complicates the extension the lifetime of both the vehicle and its components. OEMs design a vehicle for a life of 8 years. The actual lifespan amounts a time closer to 20 years. Concluded can be that the vehicle is already being squeezed compared to the actual intended design life. The question is whether this should be squeezed even more in the current design.

Another proposed enabler during the focusgroup was a more modular design. However, the contemporary HDV is a highly integrated system. This makes it complicated for modular boundary definitions. An often observed effect are interactions and side effects of innovations. Innovations in one component often have a consequence for the other, e.g. in dynamic or thermal interactions, functional safety concepts or software interactions.

Hence, without any distinct altercations in the design, lifetime elongation and modularity are technical not feasible. That’s why way more emphasis and research is needed on circular design. This is even more important for the zero emission drivetrain technology, being still in a juvenile phase.

Another, more business oriented enabler is to alter the Business Model of the OEM, for example to a circular model such as Caterpillar’s. This would force the OEM to think better about the EoL phase of the vehicle, because it will retain ownership, or will get it back via deposit schemes. This is regarded by incumbents as an interesting business model, but the Caterpillar’s business context is seen as less complex due to several factors. First of all, their machinery has a rather static location (e.g. mines or working sites), and does not switch often from ownership. Secondly, it appears to have less variation in models, or at least no different types of structure build, such as garbage trucks, tankers, or loaders, produced by aftermarket parties.

The results of the focusgroup show the interlinkage between barriers, between enablers, and the relationship between barriers and enablers. Various enablers open a window of opportunity for other enablers to be put to use.

For example, comprehensive data on the EoL management of HDVs, would help OEMs to improve their circular design more accurately. This would help to increase reuse, repair, and if it has no economic value anymore, to enhance high grade recycling. This knowledge and information on the circularity performance of companies in general, could be a basis for a Circularity Indicator. Consequently, this indicator will be an enabler for defining better targets in-company, and create a level-playing field for competition on circularity, rather than price-based competition.

Another example is True Pricing. By accounting for external environmental and social costs, a more level-playing field is created for circular practices. A tax relief on repair and reuse, or an extra tax on primary raw materials, could enable companies active in the EoL management of HDVs to become more competitive with OEMs, and primary materials.

This shows that both barriers and enablers are linked with themselves and with each other. Increasing the lifetime of the vehicle would reduce the excessive material outflow. However, the lack of circular design hinders the implementation of further life elongation, due to the intended design life.

6. Synthesis

The following chapter will further integrate the previous analysis by discussing the results of the focusgroup (Appendix C.)and relating them to literature and each other. In section 6.1, the synthesis will first touch on how the results of the focusgroup relate to the findings of the exploratory literature review. Subsequently, the findings will be placed in the bigger picture of a circular economy. Various views, barriers and enablers have been captured, but how do these relate to the overarching concept of a global circular HDV value chain? Section 6.2 elaborates on the effects of Dutch and European policies on LMICs in the value chain. Section 6.3 illustrates the effects of the zero emission transition on circularity in the HDV value chain and section 6.4. Sheds a light on the chasm between efficiency and circularity. Finally, section 6.5. provides recommendations for policymakers, industry players and other knowledge users to steer towards a circular HDV value chain.

6.1. Comparison with state-of-the-art literature

Technical and infrastructural layer

The literature underlines most of the barriers identified in the focusgroup. The trade-off between innovation for usage performance and circularity is often mentioned (Baron, 2022; Saidani et al., 2018; van Bruggen et al., 2022) as well as the lack of standardisation due to the speed of innovation (Baron, 2022), This all result in lower feasibility to recycle and or reuse (Munir, 2021; Rönkkö et al., 2021)

An addition from the literature is that the limited security of recyclate supply, of a constant quality is a barrier to the application of recyclate (van Bruggen et al., 2022). Literature also mentions the high-quality standards of HDV material (ACEA, 2023b). This was not been specially mentioned in the focusgroup. This can be explained by the fact that in the focusgroup, no producer of material was present. OEMS order their materials with specific requirements, but the composition of the materials is not specifically looked into by OEMs.

It is recognized both by literature and the focusgroup that LMICs lack the proper ELV dismantling infrastructure (Saidani et al., 2018). However, through researching the influence of the landscape development of changing export conditions and regulations, a more nuanced insight in the functioning of LMICs was obtained. It is fairly obvious that LMICs do not yet possess the technology or infrastructure to facilitate zero emission vehicles. However, the argument that LMICs neither have the proper infrastructure to keep the contemporary newer generations (EURO IV-VI) vehicles on the road by maintaining and repairing is a novelty. This has quite some consequences, as the current paradigm is that as long as the forefront of the industry innovates, the lower developing countries will follow. This argument opposes the current paradigm, or at least shows that it is with a substantially larger delay than previously thought. This shows the lack of focus in the literature on the true end-of-life phase: Somewhere outside of the Dutch borders.

Another insight that is not highlighted by the literature, is that integration and electronification have far-fetched consequences. Not only for the EoL phase but for design as well. Dynamic interdependency is said to impede attempts to make the design more modular. Updating or changing a component often has its effects due to software interactions, packaging, or robustness of the components.

The only barrier identified during the focusgroup to substitution of materials was market-related: Cheap virgin materials make secondary materials economically not feasible. A serious problem with substitution is the stringent safety requirements for use of materials. These require materials to be of the highest quality standards.

Supply chain barriers
The lack of downstream knowledge due to the poor traceability of the vehicle is an issue that is described by both literature and participants of the focusgroup (Munir, 2021; Saidani et al., 2018). The focusgroup stated that this was one of the key findings, and to be looked into to enable constructive discussions. It is difficult for an OEM to exert power and prevent lower CE strategies such as backfilling and incineration. The absence of coordination along the value chain is also an intern problem at OEMs that internalised a part of the vehicle dismantling. The whereabouts of reused components are unknown, and IT systems are not standardised and not ready for reverse logistics and an inflow of reused components. This was not mentioned in the literature. Another aspect is that currently, no proper reverse logistics are in place to collect returned cores and ensure the security of supply (Rönkkö et al., 2021).

Market and economic barriers
The focusgroup argued that the most pressing barrier is that the cost of an HDV does not reflect the true costs like environmental and social externalities. General literature on circular economy (Hanemaaijer, 2023; Kirchherr et al., 2018) underlines this issue, but literature on CE at HDVs does often not explicitly state that this is one of the fundamental barriers. van Bruggen et al. (2022), mentions this barrier but did not identify any enabler from the literature. This proves that the current literature does not recognise this barrier as fundamental. This is interesting, as this finding shapes potential directions for policy measures.

Another argument pointed out during expert reflection on the findings of the focusgroup, was that the business context of Caterpillar's non-road mobile machinery (NRMM) is far less complicated than the business context of heavy-duty vehicles. Saidani et al. (2018) takes these as one category. Consequently, he sees the Caterpillar business model as a best practice for the whole sector. However, NRMM is more stationary on a single working site, is heavily over-designed and the vehicle often stays with the same owner. Hence, the Caterpillar business model cannot be copied one-on-one but can be used as best practice input for the transition of the HDV value chain.

Institutional barriers
It is evident that a lack of regulation is one of the core institutional barriers, both identified by the focusgroup and literature. The absence of regulation on ELV handling (Baron, 2022; Saidani et al., 2020), and the export of ELVs as used vehicles leaves room for opportunistic behaviour (Saidani et al., 2020). Definitions within regulations are also often mentioned in literature. The ambiguity of definitions hampers remanufacturing practices (Parker, 2015; Rönkkö et al., 2021) and non-circular practices like backfilling are still considered recycling in regulations, like the ELV directive (EuRIC, 2021).

The focusgroup adds to the literature by identification of regulations that might be too stringent, such as tax that actually impedes the uptake of circular practices, and competition regulation that hampers collaboration in the value chain.

The relief of tax on repair and reuse is already implemented in Sweden and is evaluated by Dalhammar et al. (2020). The evaluation points out that the tax relief does not have a significant impact on the repair and reuse rate for products like shoes, bikes and fridges. However, Milios (2021) states that higher-valued products might earlier be impacted than cheap alternatives. Hence, it could still be impactful for the HDV sector.

Cultural barriers
The literature identifies two main categories of cultural barriers. The first is the embeddedness of linear practices in the company culture. Components like pneumatic breaks and catalytic converters are still systematically replaced by brand new ones (Saidani et al., 2018), remanufacturing might endanger the business-as-usual of the primary market (Parker, 2015), and OEMs even might actively decrease remanufacturability by increasing complexity (Rönkkö et al., 2021). The focusgroup underlined these activities. This showed also the openness and engagement of every participant: The participants were not afraid to point out each other's shortcomings, and no offence was taken.

The second is the perception of HDV value chain stakeholders, which shows the (linear) mindset of stakeholders (Saidani et al., 2018). During the debate on the characteristics of a potential deposit fee, an interesting insight into linear thinking appeared. The following quotes are from the focusgroup:

- Deposit fees are for products with shorter cycles;
- The deposit fee should be valued on the intrinsic value of the materials of the vehicle because it will be recycled for material recovery after the taking-back;
- If the deposit fee is too high, the economic point to recycle might be earlier than the end of the economic life;
- It would be something if you would make a loss on your deposit fee

This thinking is still reasoning from a linear mindset: The vehicle will inherently end its life in a state that only can be utilized by material or even energy recovery. However, in circular thinking, the deposit fee is used differently.

The following figure illustrates the circular business model.

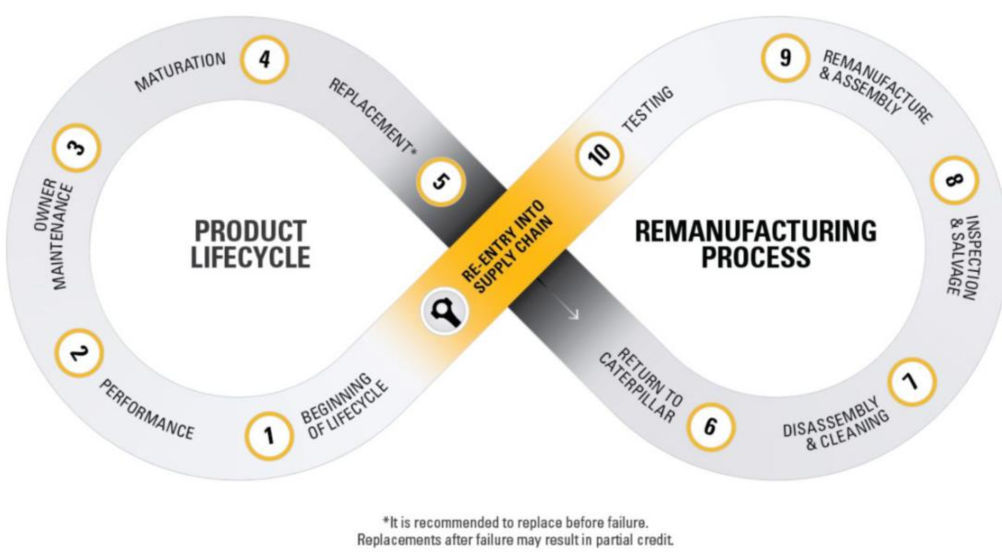


Figure 34: The circular business model of Caterpillar (Caterpillar, 2023).

After taking back the component (or “core”), determined is whether the used part is ready to be reclaimed. After remanufacturing, the product is then offered for a lower purchase price with a same-as-new warranty. In this business model, a deposit fee is an encouragement to return the vehicle or component before failure or disposal.

Linear thinking also shows in the attitude towards enablers like a more circular or modular design, or a new business model, for example, the business model of Caterpillar. Needless to say, it is clear that these top-down enablers are not to be implemented without any fuss. This argument aside, OEMs still look at the circularity transition from their perspective, which is more problem-oriented than enabler oriented. The case of the new zero emission powertrain underlines the lock-in in this perspective even more. Even though, the technology is in a juvenile phase, modularity and circular design are not actively sought after while designing these new powertrains. In the opinion of the researcher, the argument that the HDV business context is more complicated due to a wider variety (garbage trucks, tankers, conventional freight trucks etc.) than the Caterpillar machinery, does not entirely hold. First of all, these structures will outlive the truck itself two or even three times, according to the focusgroup. Secondly, the rest of the truck, cab, chassis, drivetrain, and wheels, remains the same for all these structures. Hence, bringing in this argument underlines the linear thinking of OEMs.

Berggren et al. (2015) showed that the incumbents of the HDV sector can be active on both the regime and the niche-innovation level. This thesis research underlines this phenomenon, as Scania focuses on BEVs as zero emission technology, and DAF even investigates both pathways of hydrogen fuel cells and BEVs. While their far-fetching experience in building HDVs certainly supports the advancement of these technologies, it also hampers the much needed radical systemic change. This thesis shows that the linear thinking of the incumbents causes them to fail to incorporate new circular design in their new zero emission vehicles. Even though it imposes an even a more challenging pathway to incorporate it simultaneously, in the opinion of the researcher it is needed to avoid the same lock-in that is experienced in the conventional ICEV value chain.

Hence, linear thinking and the resulting business model are large barriers towards circularity. Therefore, policy measures should specifically incentive a systemic shift to circular business models.

6.2. The effects of Dutch circular policies for LMICs

Exporting middle-aged used trucks to Eastern-European countries and even older vehicles to other areas such as the ECOWAS is a good example of an important circular strategy, maintaining and prolonging the use of the vehicle. Due to the intrinsic value of a truck, it will almost always be more profitable to export to a country that will prolong the use phase of the vehicle. However, this is also the start of a debate.

Even if justified by a market mechanism and by the necessity of older vehicles as the backbone of the transport system, shifting environmental responsibilities and issues from highly-developed countries to LMICs raises problems for a circular economy. Not only within the EU but also on a supra-continental level. It results in sustainability being a club good for higher-income countries, without eliminating resource inefficiency and emissions on a global scale (Paradowska, 2017). Therefore, the used vehicle export is not only a boon and a bane at the same time for both the CE and decarbonisation, it is also barely addressed in the state-of-the-art literature. It is often more profitable to export an ELV that is way beyond its due date than to properly scrap it in The Netherlands or the EU. Hence, exporting used and more pollutant vehicles to developing countries will only shift the burden of GHG emissions and other pollution away from developed countries. Importing countries should introduce stronger quality standards, like the ECOWAS regulation. However, in LMICs, many economies rely on used vehicles, due to their low price point, or as alternatives are often not on offer at all. In Africa, more than 60% of the vehicles added to their fleet annually are through the imports of used vehicles (ILT, 2020). Import dependency on exporting markets thus persists (WEF, 2023) and even the demand for vehicles past their economic life due date will remain, as these vehicles are cheaper. This will undercut the import policy initiatives. Therefore, unilateral action by the importing LMICs will not help to solve the problem. To truly globally decarbonize the heavy vehicle sector, developed countries should stop exporting vehicles that fail environmental and safety inspections and are no longer considered roadworthy in their own countries. The ELV Directive extension can partly solve this problem through better governance around ELVs. The directive should encompass technical and economic criteria that could define a minimum standard that should be ensured before vehicles are allowed to be exported. However, the economic value of a vehicle is a rather relative concept. In highly developed countries, vehicles are discarded before their economic life is due. An increase of 2% in fuel efficiency can already be a reason to discard an HDV, due to the intensive use and large fuel consumption of HDVs (DAF, personal communication, 28-02-2023).

The Netherlands, but also Europe as a whole are proud of their leading position in the HDV market. In the spirit of John Kennedy and its famous quote “A rising tide will lift all boats”, innovation at the highly developed forefront of the value chain will mean that these innovations eventually will seep through to the less developed LMICs. However, the cascading of used vehicles, regarded as the CE practice lifetime elongation, shows signs of malfunctioning. Vehicles with a EURO VI engine, are equipped with highly integrated and complicated electronic systems. These vehicles are imported, adhering to even the most stringent import regulations. However, LMICs often lack the infrastructure to keep these vehicles on the road. Because the systems on the vehicle are too complicated, the systems and EURO VI engines are replaced by older engines, as old as engines compliant with the EURO I standard. Therefore, it is critical to improve the infrastructure in less developed countries to achieve a circular economy. To make proper use of more advanced vehicles and engines, improvements in maintenance knowledge and infrastructure are necessary. Apart from the maintenance infrastructure, ELV dismantling infrastructure needs to be improved as well. Better knowledge and infrastructures are needed to prevent hazardous activities such as leakage of hazardous substances, improper use of tools, and dismantling without safety measures. Improving the ELV handling can also increase the quality of the resulting recyclate.

6.3. Implications of the ZE transition on the HDV value chain

In this research, electrification was chosen as the main technology for the zero emission transition. It is currently the most mature technology and is considered to have the highest potential to decarbonise the transport sector(NOW GmbH, 2023). For example, hydrogen is considered less potent than e-fuels, a technology that will not be cost-efficient until early 2040 (D. Tol & P. Paschinger 2023). However, this thesis research shows that the uptake of BEVs will not be enough to achieve the ambitious climate goals due to material scarcity, lacking charging infrastructure and insufficient grid reinforcement.

Regardless of the new type of technology, it will be of huge impact on the business-as-usual. The first impact is on the Total Cost of Ownership (TCO). For most organisations, this is leading, as long as regulations such as ZE city logistics are not mandating an emission-free vehicle. To make the TCO of BEVs break even, a decrease of up to 57% is needed (Panteia, 2021). Without this price drop, either due to the market or with proper subsidies, logistic SMEs might bankrupt logistic, because they operate with small profit margins (Appendix C.)

The second impact is on the material stock. The downside of new technologies is that they are quickly outdated in their juvenile stage. This means a huge increase in primary material demand if the business-as-usual is maintained. Furthermore, it is expected that HDVs require a battery replacement within their lifespan (Hao et al., 2019). This puts more pressure on the limited source of Lithium, which is expected to see a shortage as soon as in 2025.

The third impact identified is on the global HDV value chain. LMICs have by no means the infrastructure to adapt to new technologies like BEVs or HFCVs. In fact, the current practice is to rebuild cleaner vehicles (e.g. with a EURO V standard), towards a lower standard, even down to EURO I, to be able to maintain and use the vehicle. Developments like electrification and stricter import regulation can exacerbate this effect. Even developed countries are struggling with appropriate charging infrastructures for cars, let alone for Heavy Vehicles. The zero emission transition can result in a huge impediment to the linear business-as-usual practices because LMICs still face unreliable power supply and off-grid rural communities and consequently a lack of supporting infrastructure for ZEVs (ICCT, 2022). This can force the full HDV lifecycle, from production to dismantling, to be within the EU borders. This is a form of forced systemic shift. This can even turn out as the driver for the much-needed change. Therefore, both policymakers and industry players should anticipate this development by redesigning and preparing the lifecycle for a circular economy.

However, this might also force LMICs to shift towards other suppliers of (used) trucks, for example from Asia. This shift will hamper both the decarbonisation and the transition to a circular economy. First, the vehicles imported from Asia are mostly compliant with EURO III or EURO IV standards, which are considerably more pollutant than used vehicles from the EU. Second, these Asian types will not be awarded an EU type approval: the lifespan of Asian vehicles is roughly 100.000 km, which is only 10% of the lifetime of a vehicle approved by the European 3R Directive. This results in more vehicles produced and therefore more material demand (Appendix C.).

Another implication of the European Commission's proposed more stringent CO_2 emission standards is that it may impede the zero emission transition and indirectly the circularity transition as well. OEMs have aligned their pathways with the current CO_2 emission standards (30% reduction in 2030 compared to 2019). However, the more ambitious and stringent proposal of at least a 45% reduction in the industry, will take such a strain on research and development for ICEVs, that it will stall the research and development of zero emission vehicles such as the BEV (ACEA, 2023a). Some regard it even as a threat to the existence of the industry (NOW GmbH, 2023). Hence, the short-term goal to reduce CO_2 emissions might have to be tempered to become zero emission in an earlier stage.

6.4. The chasm between circularity and efficiency

The chasm between striving for high efficiency and circularity is not only a barrier, it also causes trade-offs. The obvious one, recognised in literature and industry, is that composites are replacing mono materials for better and more lightweight performance. This reduces the recyclability of the materials.

Lifetime elongation, by reuse, repair or remanufacturing, is considered to have a large potential to decrease the primary material inflow. However, experts point out that the current vehicle is designed for a life of 8 years, but it will likely be on the road for 15-20 years. Further extending the lifetime of the vehicle, without any altercations in the design has its consequences. Components will wear out, and vehicles will become less safe and roadworthy. Older vehicles will likely be less aerodynamic, have less cleaner engines and will therefore be less fuel efficient. A solution might be to re- and overdesign components, to be able to remanufacture them before failure, following the Caterpillar business model.

Another insight that is not highlighted by literature, is that the integration and electronification have far-fetched consequences. Not only for the EoL phase but for design as well. Dynamic interdependency is said to impede attempts to make the design more modular. Updating or changing a component often has its effects due to software interactions, packaging, or robustness of the components. Hence, it is possible that designing for circularity could reduce the high fuel efficiency of the vehicle. As long energy as is not abundant, or from a fossil source, fuel efficiency will stay a key performance indicator.

6.5. Recommendations

The insights of this research sparked the debate on the viewpoint of a circular economy and what is actually desirable. This research shows that it would be highly inefficient to accomplish a fully circular heavy-duty vehicle chain within the Dutch borders because the Dutch heavy vehicle is often discarded way before its economic life due date. Therefore, this section gives recommendations to guide practices from policymakers and to help industry players to become a thriving part of a circular HDV value chain.

6.5.1. For policymakers

The nature of the HDV value chain is diverse and international. Hence, it is important to make policies for three different levels of engagement. The first is within the Netherlands, the second is within Europe, and the third is at the global level. In general, this would encompass making the Dutch HDV sector future-proof by helping them break with linear thinking and incentivising circular thinking and business models. This is not only done on the Dutch level but also on the European and global level.

Within the Netherlands

The Netherlands has a unique position, with two major production facilities within its borders. It would be a loss of knowledge, employment opportunities and added economic value if The Netherlands fails to help these OEMs. It is also important because these OEMs have the power and knowledge to direct the whole sector to a Circular Economy.

Incentivise the production of a circular vehicle. This is done in two ways. Stimulate reduction of the environmental impact of the production phase. The production phase is still very pollutant, in GHG emissions, waste generation and other environmental impacts. It should be addressed by OEMs operating on Dutch soil because they can exert their leading position.

Increase the attractiveness of circular practices by tax relief on repair and reuse. This practice is already in place in Sweden, since 2017 and has proven its effectiveness and ability to be implemented. Additional policies like a tax on virgin material use have also to be considered and could be a step towards True Pricing. However, tax on virgin material use might weaken the competitive position of Dutch OEMs, if not exercised on a European level.

Incentivise sustainable procurement. Market power is in the current economy one of the main drivers for adjustments in business. Tenders for large orders that have criteria on sustainability, for example, a circular indicator, will create a demand-driven change. This will also help the OEMs by creating a more certain demand for zero emission vehicles that are produced more sustainably.

Within Europe

Enhance collaboration between stakeholders along the global value chain. An inter- and supranational approach to a circular economy in the heavy-duty vehicle chain is likely to be more effective. Even though two major production facilities are situated within the borders, the current life cycle of a truck hardly ends in The Netherlands. The global and international nature of the value chain makes domestic companies interrelated. To enable collaboration, competition regulation might have to be lifted under strict circumstances.

Create insight into dismantling practices as well from importing countries. Both policymakers and industry players need data on the volume flows of vehicles, and dismantling activities in countries that are on the receiving end of older vehicles. These are most likely to dismantle non-salvage ELVs. The ELV directive extension can be a suitable tool to create these insights top-down. The overview of these flows and practices can then be used by OEMs to exert more control and enhance their design for circularity. Policymakers can use this data to incentivise best practices and intervene on more specific barriers.

Create a monitoring instrument like a **Circular Indicator**. A Circular Indicator can make the transition towards a circular economy tangible. Goals can be set on practices in the production phase and for CE practices such as reuse and recycling, both by industry players and policymakers. The production phase will become relatively more pollutant if the use phase is decarbonised. Thus, this should also be monitored. The CTI can become the basis for creating new competition grounds.

Create a True Pricing model or equivalent. In the end, virgin materials are too cheap and labour is too expensive. This is due to the lack of attribution of external environmental and social costs to the production of virgin materials and new components. By incorporating these externalities the production of a vehicle will be fairly priced. This will create a level playing field for reuse of components, and secondary materials.

Extend the ELV directive to heavy-duty vehicles. The ELV directive for passenger vehicles is not yet a silver bullet. However, it could be a great start to implement Extended Producer Responsibility and to gain more knowledge on the whereabouts of vehicles during their EoL phase. The current ELV directive is currently under revision

On a global level

Invest in knowledge and infrastructure in LMICs. This research points out three reasons to invest in knowledge and infrastructure in LMICs. In general, it would be interesting to see if best practices from Dutch dismantlers are transferable to these countries.

- It is evident that used vehicles are of value in LMICs. However, it also should be acknowledged that they lag in the uptake of cleaner or eventually zero emission technologies.
- It is also clear that vehicles will end their life in LMICs, once they end up in these countries. However, the urban mine of LMICs should be utilised in an environmentally and labour-safe way, and as high grade as possible
- The whole world should become circular, not only the Western and highly-developed countries. Therefore it is important to help LMICs and help them steer away from the use of inferior and more pollutant Asian vehicles.

Stronger export ban on ELVs beyond economic/technical due date. Longevity is key, but not at all costs. It should not mean that vehicles, with an ELV status, should be exported to LMICs. Proper regulation should be in place to avoid the ‘dumping’ of vehicles considered ELVs because LMICs do not possess the power and the luxury to ban the import by themselves.

6.5.2. For the industry

Scarcity and price volatility of CRMs and other raw materials, more stringent regulation on resource use and emissions, combined with a technologically advanced product. The HDV sector is changing in a complex context. Hence, it is important to become future-proof. In light of this thesis, the advice is to think proactively about changing towards a circular business model.

Use the transition towards zero emission vehicles for the transition towards circular vehicles. The value chain of zero emission vehicles will be different from the ICEV value chain. Currently, LMICs do not possess the knowledge or infrastructure to use ICEVs with cleaner technologies (EURO V-VI). This means that in the foreseeable future, zero emission vehicles will be of no use in these countries. This forces the Dutch and European HDV sectors to close the lifecycle within the European borders. With the fast pace of technological innovations, it would be valuable to make the vehicles more modular and to investigate how a more circular business model could be viable. For example, the circular business model of Caterpillar is interesting to look into for best practices. Even though the business context of their Non-Road Mobile Machinery is different and somewhat less complicated, they successfully exercise circular business for decades. On top of that, Renault has initiated a circular truck centre. It is strongly advised to look into circular business models to keep ahead of the competition.

Do not reinvent the wheel if not necessary. A circular HDV value chain does not mean that every value chain needs to be in-house at an OEM. Dutch dismantlers and recyclers, and maintenance facilities are efficient and knowledgeable. Circularity also means making the most of everyone’s expertise, and see service or products as a service, rather than doing it all by yourself.

Increase the economic life of HDVs and their parts. The economic life of both HDVs and components should be extended as much as possible, as research shows that this has the largest effect on primary material intake.

This means that **the economic lifetime of a vehicle should be determined.** Longevity is key, but not at all costs. It should not mean that vehicles, with an ELV status, should be exported to LMICs. Proper regulation should be in place to avoid the ‘dumping’ of vehicles considered ELVs.

Improve the circular design. On top of that, designing for circularity can significantly simplify dismantling practices. This results in cheaper dismantling, and a higher potential for high R-strategies such as reuse. A circular design can be the basis of a new business models in a closed-loop system. It

7. Discussion

Section 7.1 discusses the placement of this thesis in a broader scientific context. This thesis is also subject to several limitations due to the research methodology and data availability. Section 7.2. Summarises these limitations.

7.1. Scientific reflection

This research has created a new theoretical framework of various theories that have not been combined before. This thesis has shown how the Multi-Level-Perspective, the R-framework, and barrier categorisation can be combined to provide an insightful conceptual framework to answer the main research question. By creating this framework, the thesis contributes to the system perspective of the transition towards a circular HDV value chain by identifying barriers, enablers, circular strategies, and the current state of circularity in the various phases of the HDV value chain. This was even further enhanced by the integration of the landscape and niche-level developments into the conceptual framework.

The MLP is one of the leading transition theories and is able to describe a system that is subject to factors that hinder systemic change(Geels, 2005). Using the MLP framework for the conceptual framework of this thesis, gave insights in the system dynamics that otherwise would have been lost. First of all, it shows that developments, both on the landscape and the niche-innovation level, can both accelerate and hamper the transition to a circular HDV value chain.

The presented conceptual framework contributes to existing socio-technical system theory literature, as it shows that incumbents being active on both the regime and the niche-innovation level might accelerate the technical advancement of zero emission technology, but this will not cause the radical systemic shift a Circular Economy asks for. This is why the combination of barrier identification through a focusgroup and analysis of both landscape and niche-innovation developments has shown to be valuable: Linear thinking needs to be cut down and the business model of incumbent OEMs needs to focus on circularity. Hence, it gives more depth to the findings of Berggren et al. (2015), on the successes of incumbents pursuing activities on both regime and niche-innovation levels.

The cultural context is one of the most important barriers. The systemic shift depends highly on the transformation of the perception of the value chain stakeholder, from merely business and economic values to a more inclusive perception that includes more societal and environmental aspects. This suggests in order to induce a systemic shift, internal system transformation needs to be complemented and enhanced by external factors. An external factor that is researched are regulations. For example, the current regulation on CO_2 emission reduction is accounted for by OEMs. However, the proposed, more stringent regulation might hamper the transition towards zero emission and a circular value chain greatly. This shows that short-term profit (i.e. cleaner ICEV technology), impedes the long-term goal of a circular and zero emission vehicle. Accordingly, the present thesis shows that developments, both top-down landscape, and bottom-up, can have a large influence on the transition towards a circular economy. This proves that the MLP is also useful for the identification of the influence of socio-institutional aspects, which is often overlooked by studies using the MLP.

The contemporary HDV value chain was explained as a socio-technical regime, on which the zero emission niche innovations acted as an influence. The R-framework has proven its value by identifying CE strategies and analysing the regime of the value chain. Moreover, this research also shows the ability of the R-framework to illustrate on what kind of level the circularity thinking is of the stakeholders. A lot of thinking was still rather low on the R-ladder. The R-framework proved also to be valuable for providing insight into the current state of circularity in the value chain, and the characteristics of the different value chain phases. This analysis shows that because the value chain within the Dutch borders functions efficiently, the emphasis should be on practices outside the Dutch borders. It also shows that OEMs operating in The Netherlands with their market power are able to shape the HDV value chain, with the right knowledge. However, the R-framework is also fairly rigid, because it is able to investigate the value chain, and the possible R-strategies, but it does not provide insights, into barriers, enablers and developments that influence the socio-technical regime of the value chain. Also, it does not identify why these strategies have not been implemented yet. Literature suggests that successful transitions require the overcoming of barriers that extend well beyond technological dimensions (Geels, 2005). This thesis research makes a valuable contribution as understanding why the current HDV value chain is locked in around the current business-as-usual is a critical step towards overcoming the obstacles to system transformation.

The Solution-focused Sustainability Assessment (SfSA), has proven to be a very convenient methodology to identify barriers and enablers. It provided a structural way to gain insights into the HDV value chain for nuancing the discussion on how to transition to a circular HDV value chain. This builds on the work of van Bruggen et al. (2022), that used the SfSA to identify barriers and solutions for plastics in the automotive industry. The use of the MLP complemented the method by asking the focusgroup to actively think of developments that might influence the value chain, which reduces the static nature of the SfSA. This thesis showed that this gave a better insight into how the whole global value chain needs to be modified, rather than solely the stakeholders in the 'own backyard' of The Netherlands. The use of the R-framework for the value chain analysis gave insights that would not have been obtained if only the SfSA would have been used. Research by van Bruggen et al. (2022) did not grasp the full picture dynamics of the value chain due to the absence of a thorough value chain analysis. The added step of the value chain analysis, including the stock and flow analysis, illustrated how the actors operate, showed novel points of engagement and also the under-demarcation when researching product categories.

The differences between passenger vehicles and HDVs have been made clear in existing literature and policymakers start to acknowledge the difference. This is underlined by reviewing ELV directives, previously only applicable for passenger vehicles. However, literature still sees an overlap between categories that might need nuance. For example, Saidani et al. (2018) views HDVs and Non-Road Mobile Machinery (NRMM) as one category: Heavy-Duty Off-Road (HDOR). This research shows that they differ considerably, and best practices might not be applicable one-on-one between the vehicle types. This insight can be extrapolated to the literature on the transition towards a Circular Economy in general. Practices and policies need to be adapted for specific product categories. Hanemaaijer (2023) and the NPCE have the intent for this more specific research, but this research shows that the categories need to be even more demarcated.

The identified barriers had a considerable overlap with the results of the focusgroup. This is a validation of the findings of the focusgroup. A completely different set of barriers would indicate shortcomings in the research or a wrong selection of focusgroup participants. The focusgroup identified also interesting novel barriers, that are not yet identified by literature. An example of a valuable new insight is that vehicles, even though imported as a vehicle with high emission standards, such as EURO VI, are being stripped from the high-tech parts and are converted with engines as old as EURO I. This shows that the knowledge and infrastructure in importing LMICs are not on par to start using cleaner vehicles, let alone zero emission vehicles. Therefore, the focus should shift partly to improving further down the cascading value chain, rather than innovation for small incremental increases in developed countries.

This research on the transition to a circular HDV value chain also fits in and contributes to the debate about the Circular Economy.

In his research on the definition of CE, Kirchherr et al. (2017) found that CE is seen as a concept that requires effort, particularly on the regional level. A small amount of research mentions simultaneous change at the micro (product, company), meso (eco-industrial parks) and macro (city, region, nation, and beyond) levels. This thesis research shows that for a product with the characteristics of a heavy-duty vehicle and its value chain, it yet does not make sense to scope down to the regional level. On the contrary, the biggest 'circularity wins' are to be made on the global level. The international character of the HDV, the dependency on used vehicles in LMICs, and their (in)ability to keep up with technological innovations prove that it makes sense to design and implement circular policies and strategies on a European and global scale.

7.2. Research limitations

Section 7.2. Discusses the limitations of the research.

7.2.1. Reproducibility

One of the limitations of this research relates to the reproducibility of the research. The limited availability of data is a pressing issue and is the reason that the assessment of circularity in the heavy vehicle sector currently relies on stakeholder statements (Baron & Loew, 2022). A limitation of the literature analysis that hampers reproducibility is biased selectivity. Part of the papers have been included by the snowballing approach, or as recommendations from interviewees.

The results obtained via the focusgroup are qualitative, making the findings unique to the research process. Reproducing the focusgroup will likely result in different findings. The implications of this limitation have been minimised by comparing the focusgroup findings with state-of-the art literature.

7.2.2. Stakeholder bias

The results of this research are partly based on explorative interviews and a focusgroup, that had a total of 10 participants.

All phases of the value chain have been covered by the range of participants, but due to the timeframe of this research, only incumbents have been included, and no actors operate solely on the niche-innovation level. Even though incumbents that operate on both levels are of significant importance for adopting niche-level innovations (Berggren et al., 2015), they also have vested interests in keeping retaining the business-as-usual. This strategic behaviour is also widely regarded as a barrier in literature (Saidani et al., 2018; Saidani et al., 2020; van Bruggen et al., 2022). Some of the findings of the focusgroup could be held to the light of strategic behaviour as well. For example, a key finding was the lack of data on circular practices in the EoL management which made adapting to a more circular design harder for OEMs. However, this can also be seen as a way to shift responsibility out of their reach. The research would have been more complete if a niche-innovation level actor would have been part of the focusgroup, to identify their needs, and their view on circularity in their product. An actor operating solely on the niche-innovation level is Zepp Solutions, that will launch a commercial hydrogen fuel cell vehicle in late 2023. On the other hand, killing two birds with one stone as a start-up might be a challenge to take upon.

The conclusion and recommendation are also based on the outcomes of the focusgroup. There is a risk here that the reports reflect the agendas of the companies that created the report. During the focusgroup, the agenda of one of the organisations was quite obviously embedded in an opinion. By suggesting a different business model, a participant with a background in the dismantling sector expressed their fear of losing business. This showed also in the enablers proposed. Several of them came in handy for the business-as-usual from the proposing participant.

This is mitigated by the variety of backgrounds of the participants. The focusgroup implied openness and therefore gave space to debate proposed enablers and barriers that were not backed by others. This openness showed in the fact that stakeholders of other value chain phases were calling OEMs out on their business model, and linear strategies. Another way of mitigating this risk was by interviewing non-biased researchers. The outcomes of the focusgroup are validated by both the participants of the focusgroup, and a researcher from the research group of Michael Saidani, author of three leading papers on circularity in the HDV sector.

7.2.3. Focusgroup results

To identify which barrier had the highest likelihood and the highest impact on the transition to a circular HDV value chain, the focusgroup participants were asked to map the barriers on a matrix (see Figure 36). However, due to the limited time available during the focusgroup, the mapping of the barriers in the second round is incorrect and is not based on a common understanding. This is also underlined by the focusgroup reflection. This took away the chance to see how the perception of barriers would change in a future situation of the HDV value chain.

7.2.4. Data uncertainties

There is no general comprehensive summary of data on the material composition of the heavy vehicles, but only compositions of individual models in specific studies, like life cycle analysis (LCA). This does not allow drawing material-specific and weight-related conclusions (Baron & Loew, 2022). Furthermore, EoL management is member-state specific; reporting is not available on the EU level (Baron & Loew, 2022). On top of that, data on good practices for circularity is sporadically available but is not by means to draw general conclusions on the status of circularity.

The quantitative analysis provides a general idea of the stock and flows of HDVs in The Netherlands, but it does not provide information on specific flows of components, and impacts of circular strategies, such as remanufacturing or reusing. The only source for used goods trade are the IT statistics, and mainly for used cars and trucks. However, they do not provide any insights in the trade in (used) components, as this level of detail is too high (CBS, 2022, personal communication).

Also, data collection on the effects of the implementation of ECOWAS import regulation was limited, due to the recent implementation. New research of ILT is currently ongoing and building on the previous research of ILT (2020). This has the ability to point out any effects of the new import regulations.

An important limitation in obtaining comprehensive and transparent data is the lack of an EU Directive, which forces companies to register and deregister EoL vehicles, wrecks and dismantling. A consistent overview of data is important for evaluating the value chain on its circularity. These data inconsistencies make it harder to quantitatively evaluate the value chain properly, whether it is between organisations, or between organisations and reality.

Apart from that, the total amount of vehicles being dismantled in The Netherlands is larger than the amount of Dutch registered vehicles. In 2021, 255 vehicles have been dismantled in The Netherlands (CBS, 2023). However, a major dismantler reports a throughput of approximately 350 vehicles a year alone (Vos Truckparts, 2023). Also, salvaged cars are imported to be dismantled. More often than not, these are not declared at the Dutch customs. Therefore, the full market size of vehicle dismantling is larger than the outflow shows. This data gap is expected to be solved under the ELV directive extension because it mandates Certificates of Destruction (CoD).

The International Trade (IT) statistics have some limitations. Used to be stooled on monetary numbers, the quality of the IT volume statistics has noticeably increased in the past few years. However, it is not yet possible to check the IT statistics on the highest detail level.
Also, there is a threshold under which no declaration is mandatory. Per the 1st of January 2020, no declaration is needed for import from EU member states under a value of €800.000 and for export to member states under a value of €1.000.000 (CBS, 2020). For EoL vehicles this might be a problem

because the intrinsic rest value is considerably lower than that of new vehicles and therefore the trade in EoL vehicles stays often below the threshold value.
Another limitation is the estimation for gaps in the data and use of coefficients for certain IT statistics due to the conversion of units to kilogrammes (CBS, 2020)

8. Conclusions

Chapter 8. Concludes the research. First, to answer the main research question *"How to overcome the barriers to a circular value chain for Heavy-Duty Vehicles produced in The Netherlands?"* the sub-research questions are discussed in the three sections corresponding to the research design. These are the value chain analysis in section 8.1, the barrier identification and influence of developments in section 8.2 and the enablers to overcome these barriers in section 8.3. Section 8.4 concludes this chapter with recommendations for future research.

8.1. Value Chain Analysis

sRQ1: What does the current value chain of the Dutch heavy-duty vehicle look like?

The two OEMs producing in The Netherlands have a total share of 28% of the European Heavy-Duty Vehicle (HDV) market and contribute roughly 20% to the total annual European HDV production of roughly 500,00 vehicles. Some 80% or 80,000 new vehicles are then exported within Europe (~90%) and the remainder ~10% to other destinations. The Dutch export of new vehicles has a value of 6,4 billion euros. This underlines the importance of the Dutch HDV sector for both the Dutch economy and for the shift towards a circular HDV value chain as it is able to drive impactful change at the beginning of the value chain.

Each year, roughly 15.000 vehicles are newly registered in The Netherlands. The new vehicles are intensively used: New trailers have an average annual mileage of 100.000 kilometres, with outliers of 400,000 km. The average vehicle is designed for a lifetime of 8 years or a mileage of 1.2 million kilometres. However, 95% of the Dutch-registered vehicles are exported before the End-of-Life phase (EoL) is reached.

Dutch Authorized Treatment Facilities (ATF) are highly efficient in End-of-Life Vehicle (ELV) handling. They mostly handle salvaged vehicles, that still have a high intrinsic value. The true number being handled is higher than reported by Dutch statistics because they also handle imported ELVs. This process is labour-intensive but has high-quality output. The components and parts are then offered on the aftermarket, often with a warranty. This is a well-functioning example of a circular strategy. Dutch ATFs only handle ~3% of the outflow of Dutch HDVs. The majority of Dutch ELVs are handled down the value chain in other countries. Estimated is that 70% is dismantled in Europe, and 30% in other parts of the world. It is currently unknown how well-functioning this dismantling is.

The cascading of HDVs contributes to the lifetime elongation, which is a valuable circular strategy. This is also underlined by the statements in the focusgroup. Reuse, of both components and whole vehicles, is considered to have the most significant contribution to a more circular value chain.

sRQ2: What circularity strategies are currently prevalent in the heavy-duty vehicle sector and which other ones have the potential to contribute to the road towards a circular economy?

Circularity strategies can be applied on different levels. In essence, the ultimate goal of a Circular Economy is to reduce the raw material intake to zero. Four different strategies have been identified, categorised following the circular R-framework: A modal shift to other transportation methods or to refuse the use of the vehicle (narrowing the loop), better use of the vehicle (narrowing the loop), zero emission during the use phase (narrowing the loop), lifetime elongation of the vehicle and its component (slower the loop), the substitution of raw primary materials by recycling of materials (close the loop).

Road Freight transport is already very efficient, compared to the utilisation of for example passenger vehicles. Furthermore, WLO (Welfare scenario study) scenarios indicate that no modal shift to other transportation methods is foreseen. On the contrary, the use of road transport is expected to increase in the coming decades, even as far as doubling this mode of transport. Thus, the HDV sector will be prevalent in its current capacity and even expand.

In this research, the focus for reduction of fossil fuel use is on electrification of the vehicle. Even with the current Dutch electricity mix with an emission intensity of 424 g/KWh, a BEV will reach the GHG emission breakeven point within 63,000 km. The biggest win in terms of GHG emission is therefore in the Use phase. However, the electrification of HDVs will have a sizeable effect on primary material intake. Research shows that the extraction of Critical Raw Metals (CRMs) is not able to supply the increased demand for e.g. lithium. Furthermore, high-quality recycling practices are needed to supply the whole automotive sector with sufficient lithium. Therefore, from a circular, CRM and operational perspective more emphasis is needed on innovative, more juvenile technologies, such as hydrogen fuel cells or biobased fuels.

Lifetime elongation of both the vehicle and its components is crucial for lowering the primary material demand. Elongation of vehicle use, by maintenance and repairment, and later in the lifecycle by reuse and remanufacturing is considered to have the most impact on primary material demand. If the lifetime elongation is following the same historical line as the increasing age of Dutch passenger vehicles, the primary material demand can be reduced by 40%. A case study shows that primary material demand intake for several components can be reduced between 80-90% by remanufacturing components instead of producing new components. Business models like Caterpillar's Non-Road Mobile Machinery show that this is a viable and profitable business strategy.

Substitution of primary raw materials by recycling materials is the way to close the loop and prevent material loss. This is a common practice, with currently a large focus on ferrous metal recovery. Due to the high value of ferrous metals, these get often extracted. However, critical data on percentages of recycling is absent, especially in other countries. Also, the practices are unknown and to what extent they are polluting, e.g. with unsafe disposal of hazardous substances. For example, in LMICs it is reported that fluids are leaking into the ground and metal-containing components (e.g. chairs), are burned to retrieve the metal content. On top of that, a large potential lies in the better recovery of CRMs such as PGMs. For CRMs like lithium, it is even a necessity to focus on the use of secondary materials, due to expected shortages, foreseen as soon as 2025.

8.2. Barrier identification and influence of developments

sRQ3: What are the barriers and influential developments to the transition to a circular heavy vehicle value chain?

These barriers mainly hamper the reuse of components and vehicles. Reuse, with the aid of remanufacturing, refurbishment or repair are R-strategies that slow the loop. For the heavy-duty vehicle, these R-strategies are considered to have the most impact on making the value chain more circular. The heavy-duty vehicle will not be phased out in the foreseeable future. Hence, product refuse or rethink (narrowing the loop) is not very probable. Closing the loop by recycling is in the last stage also important, but should generally speaking be exercised as late as possible. The HDV is a highly valuable product, from which the value should be retained as long as possible.

The barriers are categorised as technological and infrastructural, supply-chain governance, economic, institutional and cultural barriers.

- The most pressing technological and infrastructural barriers are the trade-off between use performance and circularity, the lack of standardisation and the lack of knowledge and infrastructure in LMICs to safely, sustainably and circular handle ELVs and newer generation vehicles, with emission IV – VI standards. The trade-off between fuel efficiency and circularity hinders dismantling and high-grade recycling, due to the use of composites, and welded components. The lack of standardisation in combination with quick innovation and long-living vehicles results in components being quickly outdated, materials that age and are subject to wear and tear, and hard-to-achieve economies of scale. The lack of knowledge and infrastructure in LMICs to safely, sustainably and circularly handle ELVs is one of the most pressing issues because 95% of the Dutch vehicles do reach their EoL in these countries. Furthermore, these countries are not able to maintain newer generation vehicles and rebuilt them with more pollutant, older engines.
- The lack of traceability of the vehicle along the value chain is an important supply chain governance-related barrier. This is embedded in the overarching lack of data in the HDV sector. The lack of data on the whereabouts of vehicles results in missing vehicles, 'dumping' ELVs as used vehicles in LMICs and dismantling of ELVs in illegal ATFs, with unknown and potentially environmentally hazardous and for humans risky practices. This hampers designing policies for policymakers and adapting circular design for industry players. The lack of collaboration is also hampering the transition, because coordination on material use, circular design and ELV handling thrives by a multi-stakeholder approach.
- The price of the heavy vehicle currently does not reflect the true costs of production, resulting in a non-level playing field for circular practices. This economic barrier is the most pressing finding of the focusgroup. Virgin materials are relatively too cheap, and circular practices are labour-intensive. Labour is expensive and therefore circular practices remain the non-economic option. Apart from salvaged vehicles, with a high intrinsic rest value due to the components available for the aftermarket, an ELV, in the EoL phase due to old age, has not enough value to be dismantled in the Netherlands. Hence, investing and taking up responsibility for reverse logistics and ELV handling in The Netherlands is yet financially unattractive.
- Institutional barriers are mainly a lack of, or counter-productive regulation. The absence of the ELV directive for HDVs results in less traceability of the vehicle, export of ELVs as used vehicles and no Extended Producer Responsibility for ELVs. Regulation aiming at minimal recyclability rates can be seen as a way forward but require careful design as it can be counter-productive as it promotes downcycling or even backfilling, and as a result, creates new circular barriers.
- The cultural barriers have a significant impact on the system. Companies have a business model that promotes linear practices. Keeping business-as-usual means linear practices are staying incumbent. This is enhanced by the linear mindset present in the value chain and can be seen as one of the root causes for the stalling of the circularity transition. Circular practices have to be embedded in the business-as-usual. However, a systemic shift throughout the value chain is needed for the transition towards a circular value chain.

The current system of the HDV value chain is not operating in a vacuum. To analyse the factors that influence the transition of the HDV value chain to a circular economy, two types of developments are identified. The first are institutional developments: ELV directive extension, ECOWAS import regulation, ZE stadslogistiek (city logistics), and CO_2 emission standards. The second are technological innovations for the zero emission transition. The most promising and currently most prevalent innovation is electrification.

The following developments influence the HDV value chain in several ways.

Electrification
The first challenge of electrification is the increasing demand for CRMs. A shortage of lithium is expected as soon as 2025. Furthermore, the technology is rather juvenile, and innovations are quickly successive to one another. This means that current technology is quickly outdated, and in combination with the lack of standardisation in battery technology, this puts further strain on the demand.

Nevertheless, the largest challenge is the impact on the global HDV value chain. LMICs have no infrastructure to adapt to zero emission technology. This can lead to a forced systemic shift for the full HDV lifecycle, from production to dismantling, to be within EU borders. Firstly, this should be anticipated by preparing the EU value chain stakeholders for a circular economy. Secondly, this might force LMICs to shift towards alternatives for the European used vehicles. Findings from the focusgroup state that these HDV alternatives, often from Asia, are significantly more pollutant, and have a lifespan of roughly 100,000-150,000 kilometres: 10% of a European HDV.

Institutional developments
The upcoming new regulations are in general accelerating the transition towards a circular HDV value chain. New ECOWAS import regulations should improve the quality of the imported vehicles. Up to 80% of the current fleet of used vehicles imported by the ECOWAS countries is not allowed to be imported under the new regulations. However, stricter policies on exporting vehicles are necessary from developed countries, such as The Netherlands. LMICs are to such an extent dependent on the import of low-cost vehicles, that even vehicles considered ELVs or without roadworthiness certificates will still be imported unless exporting countries will collectively ban these from being exported. The ELV directive can be an enabler to overcome this problem. Two challenges raise: The first is the definition of an ELV, which is different for The Netherlands than for an ECOWAS country, this should be addressed. The second is that these countries do not possess the infrastructure to maintain newer vehicles, for example with a EURO VI standard.

By following the Solution-focused Sustainability Assessment, these barriers, developments and their interactions were identified by authoritative stakeholders from the Dutch HDV industry. To ensure nuance, and a complete view, the results from the focusgroup were validated by the stakeholders, and reviewed by a researcher-expert in the field of circularity in the Heavy-Duty Off-Road sector.

8.3. Enablers to overcome barriers towards a circular heavy-duty vehicle chain

sRQ4: How can enablers help to overcome the barriers towards a circular heavy-duty vehicle chain?

The uptake of circular practices is not hindered by technological know-how, but more so by the diffusion of this knowledge, market barriers and by regulatory structure. The technological barriers are well documented and often mentioned. However, research shows that the technological barriers are often not the most pressing ones. These are nested in more overarching barriers, such as the market structure and its absence of reverse logistics, or perverse incentives of cheap virgin material prices. Institutional changes like augmented regulation could overcome this, and in the meantime be used to alter companies' hesitant attitudes towards new business models. The recommendations in paragraph 6.5. provide a guideline for actions to take and enablers to implement to make progress towards a circular heavy-duty vehicle chain.

One type of recommendations stand out: The recommendations that create a more level-playing field for circular practices. The market, its efficiency and its supply and demand balance are currently the strongest drivers in this industry. The quickest win is tax relief on repair and reuse. This is already a validated enabler due to its successful implementation in Sweden in 2017. Research on consumer products, like shoes and bikes, that the impact is rather small. This might be different because value retention is more sought after in the HDV sector, and practices are more labour-intensive. Another enabler is the circularity indicator. This would help create a basis for competition on circularity practices rather than on price. The indicator could hence accelerate and promote sustainable procurement. The most impactful enabler is the full attribution of external costs, such as environmental and social impacts, to the market price of a vehicle. If the use of raw materials, energy and transport is given a true price, these costs are likely to be passed on in all links of the chain. This will mean that practices will be measured evenly. This form of (true) pricing can induce a new market equilibrium in which secondary materials and circular practices are similarly valued as virgin materials and the production of new vehicles. This would also level the playing field between different R-strategies and naturally favour less resource-intensive strategies. It can result in more local reuse, because of energy-intensive transportation, or the application of 'higher' R-strategies, like reuse over recycling, due to less energy used to bring the product back on the market.

Every phase of the Dutch heavy-duty vehicle sector is operating efficiently – in a fairly linear way –. It is important to note that the production phase is by no means circular or sustainable. This is to be addressed by future policies as well. On top of that, this efficiency becomes less relevant when considering a larger geographical scale, because less than 5% of the HDVs end their lifecycle in The Netherlands. Therefore it is crucial for achieving circular ambitions globally, and in a just way, to consider vehicle use and ELV handling in less developed countries. Nevertheless, due to its efficient ELV handling, the Dutch HDV sector is able to act as a niche-space for experiments. With enhanced communication and collaboration between OEMs and dismantlers, the lines can be very short. Hence, circular design can be tested and lessons can be learned on improvements for dismantling and quality of recycling.

This research on the transition towards a circular HDV value chain contributes to the overall debate on circularity and a Circular Economy as well. It shows that the debate is far more nuanced than just designing top-down national or even European policies. Policies are definitely too short-sighted if the international context of a product is not taken into account. It is also important to consider the business context of the product and its lifecycle. Circularity and a Circular Economy are difficult concepts that due to their multi-faceted nature ask for a balanced trade-off rather than a silver bullet solution. For the HDV sector, this means that, business-as-usual needs to change to a fairer value chain that resolves the allocation of all costs, as well as environmental and social costs. Both in The Netherlands and Europe, as globally, even though this might make the heavy-duty vehicle significantly more expensive.

8.4. Recommendations for future research

This research shows that the current and future developments in the HDV sector have a strong international component. Future research could identify the international volume flows of heavy vehicles as the Dutch stakeholders operate in a global market. This is recommended by various articles because the lack of data on the location of ELVs and their handling is widely recognised. Because central registration of ELVs is not practised for HDVs, a bottom-up approach is advised. The case of the dismantled vehicle, shown in Figure 31, can be an example. By gathering data at ATFs in various countries, the bottom-up analysis can be extrapolated. This could build a proper basis for specific policies and enhanced circular design. The other recommendations for future research are bulletized below:

- The quick uptake of zero emission technology can lead to a forced systemic shift of the HDV value chain to be completely within EU borders. Because this is a huge shift, future research should look into the characteristics of this change. This can aid both policymakers and industry players to prepare appropriately for this shift.
- Furthermore, LMICs both love and hate the used truck. It is needed in their economy, but it imposes various health risks and emissions due to the low quality of the vehicle; often, it is considered an ELV in The Netherlands. More research is recommended to understand the effects of developments such as electrification and new import and export regulations on LMICs. Brink et al. qualitatively studied in 2021 the effects of Dutch CE strategies on the textile industry in LMICs. This could be applied to the HDV case, to determine the implications along the international value chain.
- The truck is a product, with a long lifetime, and value retention that will have many different owners in many different countries. A suggestion for future research would be to determine the optimal point between prolonging the life of the truck and dismantling it properly. Various indicators should be used, to make a well-informed balance. A strict emission approach would be too limited, as the environmental burden is just one aspect. A used truck has both positive (transport means) and negative externalities (safety hazards) in importing countries.
- Following the SfSA, future research can build upon this research by assessing the enablers on their impact on the value chain and eventually implementing the most impactful enablers.
- This thesis developed a conceptual framework to be able to understand the value chain, identify the current state of circularity, and enablers to overcome barriers that hamper the transition to a circular value chain. The framework should be applied to other product categories to test its robustness and applicability. It would be interesting to do this on products with the same characteristics (global value chain, with the EoL phase not within The Netherlands, a valuable and complicated product with a long lifetime), like wind turbines, and on products with a shorter lifecycle, such as WEEE products, or products that are less complicated and less tech-

savvy such as beverage packaging. This research used the niche-innovation level of the MLP to research the influence of zero emission technologies on the transition towards a circular HDV value chain. An interesting angle on the use of the MLP for researching circularity in value chains is to look into circularity as a niche-level innovation.

- Lastly, this research underlines the need for an even more demarcated categorisation than intended by Hanemaaijer (2023) and the NPCE (2023). Apart from this giving direction for policymaking, it also puts extra strain on policymakers. Therefore, future research could be of substantial help to identify overlap between products that could reduce the complexity of making specific policies. The overlap should not only be looked for in technical characteristics. The cases of passenger vehicles or NRMM versus heavy-duty vehicles prove that this is not sufficient. Interesting would be to look for similarities in market dynamics, such as products that are produced and used in The Netherlands, but do end their (economic) life within the Dutch borders.

Appendix A.

SLR on Circularity in the heavy vehicle sector.

To identify barriers, opportunities and enablers for a CE in the HDV sector, an explorative review is used. First of all, this helps to get a better understanding of the current situation for a CE in the HDV sector and is a starting point for finding a more comprehensive set of barriers and enablers amongst stakeholders.

8.4.1. Search strategy and findings

Table 16. Shows the search strategy findings.

Table 16: Search strategy findings

Author (year)	**Title**	**Automotive/HDV**	**CE / Specific circular strategy**
De Abreu et al. (2022)	The role of CE in Road Transport to mitigate climate change and reduce resource depletion	Automotive	CE
Paradowska (2017)	Grounds and challenges for implementing CE in the EU road transport sector	Automotive	CE
Ronkko et al. (2021)	Remanufacturing in the HV industry – case study of a Finnish machine manufacturer	HDV	Specific circular strategy: remanufacturing
Saidani et al. (2020)	Dismantling, remanufacturing and recovering HV in a CE: lessons learnt from an industrial pilot study	HDV	Specific circular strategy: remanufacturing
Saidani et al. (2019)	EoL management of LVs and HVs in the US	HDV	CE
Saidani et al. (2018)	HV on the road towards CE: analysis and comparison with the automotive industry	HDV	CE
Zhu (2014)	Supply chain barriers for truck engine remanufacturing in China	HDV	Specific circular strategy: remanufacturing
Sopha et al. (2022)	Barriers and challenges for implementing EVBs	Automotive	CE; batteries

Articles have been reviewed with different links with CE: The first are looking into the HDV sector and CE as a whole (De Abreu, 2022; Paradowska, 2017; Saidani, 2018, 2019). The second type looks into a specific part, e.g. remanufacturing (Ronkko, 2017; Zhu, 2014). Lastly, one article looks into an industrial pilot study (Saidani, 2020).

The HDV sector is not entirely indifferent with the rest of the automotive sector. Therefore it is also beneficial to look into the barriers and challenges the general automotive sector is facing on the road towards a CE. The paper of Saidani (2018) gives an overview of challenges faced by the automotive sector, another paper that gives a comprehensive overview is ….

Almost every source underlines the lack of literature on CE in the HDV sector (Saidani, 2018, 2019, 2020) or on the limited number of relevant studies considering vehicle parts and components (De Abreu, 2022). Therefore, several sources originated from grey literature have been used to define the status of CE in the HDV sector.

The automotive sector encompasses motorised light road vehicles weighing less than 3,5 tonnes laden and is therefore subjected to the Directive 2000/53/EC. The heavy-duty sector consist of everything that is nominally defined as vehicles weighing more than 3.5 tonnes (laden), e.g. trucks, lorries, or buses. In this research, the focus will be on vehicles intended for transporting goods. Hence, Heavy Freight Vehicles are considered, whereas buses are not, and neither are Non-Road Mobile Machinery (NRMM) like excavators.

Currently, there is a lack of state-of-the-art literature regarding waste minimisation and end-of-life management of HDVs. (De Abreu, 2022). Most research is focused on the technical design and use phase of the HDVs, since over 95% of the total environmental impact, throughout its life cycle, is generated during the use phase (Hill et al., 2012; Scania, 2022). This also leads to a focus on GHG emission mitigating measures and indicators, rather than looking into other indicators such as raw material use, and value creation through reverse logistics.

On the other hand, the end-of-life management and circularity of passenger cars – i.e. the automotive sector as a whole, have been extensively studied throughout numerous studies. To illustrate the lack of circularity literature in the heavy-duty vehicle industry compared to the automotive sector, see Figure 2.

The following search queries have been used:

- (“Road Transport” OR “Heavy Vehicle” OR “Heavy-Duty Vehicle”) AND “Circular Economy”) for the heavy-duty vehicle industry
- “Automotive” AND “Circular Economy” for the automotive industry as a whole.

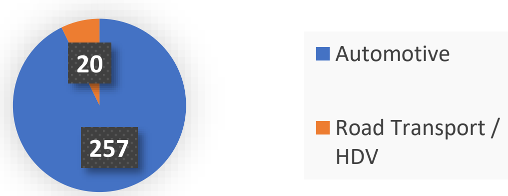
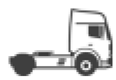
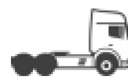


Figure 2. Literature appearance in affiliation with the Circular Economy (2017-2022)

Figure 2 shows the difference in literature depth on the various topics. In 2017, the first study on the combination of Road Transport / HDV / HDV and the Circular Economy appeared, with a total of 20 results until now (2022). In the same period, the whole automotive industry has been mentioned 257 times falongside the circular economy. The tonnage of end-of-life HDV vehicles represents the same order of magnitude as end-of-life vehicles in Europe. Therefore, the HDV industry could be seen as important as the automotive industry and is therefore a significant area of work for policymakers and industrial practitioners (Saidani, 2018).

Appendix B.

Detailed characteristics of heavy-duty vehicles.

Segment:	Vrachtauto Klein (2-assen)	Vrachtauto Middel (2-assen)	Vrachtauto Groot (2-assen)	Trekker (2-assen)	Trekker (≥3 assen)	Zwaar-speciaal (≥3 assen)
Toegestane maximum massa [gem]	3,5-7,5t [4,5]	7,5-16t [12,5]	16-23t [19,5t]	16-23t [19,5]	>23t [27]	>23t [33]
						
Leeggewicht (t) [gem]	2,3-4,8 [3,0]	6-10 [7,5]	8-13 [10,5]	7-9 [8,0]	8-12,5 [9,0]	11-36 [18,0]
Laadvermogen (t) [gem]*	0,5-3 [2]	3-8 [5]	7-11 [9]	30-33 [31,5]	30-33 [31,5]	0-85 [15/30]
Max vermogen (kW)	[115]	[149]	[221]	[322]	[352]	[303]
Wielbasis (m)	4,0	4,5	5,3	3,8	4,3	6,3
Voorbeelden:						
Volvo	-	FL	FM, FE	FH	FH	FM/FH
Mercedes	Sprinter	Atego	Actros	Actros	Actros	Actros
MAN	TGE	TGL	TGS	TGS	TGX	TGS
DAF	LF 180 FA	LF 210 FA	CF 260 FA	XF 480 FT	XF 480 FTG	CF 300 FAG
Scania	-	P220	P250	S450	R450	P320
IVECO	Daily 40C18, 50C18	120E	AS260SY/PS	AS440ST/P	AS440S57TX/FP	AD260SY/PS
FUSO	Canter	Canter				
Renault	Master	D	D (wide)	T	T	C

* De gemiddelde toegestane maximum massa is de optelsom van het gemiddelde leeggewicht en het gemiddelde toegestane laadvermogen. Voor trekker-oplegger combinaties geldt het maximum gewicht samenstel (treingewicht of GTW) en de maximum massa oplegger (trekgewicht), waarbij de toegestane maximum massa van de oplegger en het leeggewicht van de oplegger bepalend zijn voor het maximum laadvermogen. Vrijwel alle trekkers hebben een maximum gewicht samenstel van 50 ton en een maximum trekgewicht van circa 41 ton (=50 ton minus leeggewicht trekker). De meeste zware opleggers (>3,5 ton) hebben een toegestane maximum massa van 38-41 ton en een leeggewicht van 7-8 ton. Dit geeft een typisch maximum laadvermogen van 30-33 ton.

In het segment zwaar-speciaal zitten ook de mobiele kranen met een maximum toegestane massa tussen 50 en 100 ton (tot 85 ton laadvermogen). Daarnaast heeft ongeveer de helft van dit segment de mogelijkheid een aanhanger te trekken, waarbij een maximum gewicht samenstel van 50 ton geldt. De maximum massa aanhanger geremd (maximum trekgewicht) ligt voornamelijk tussen 20 en 40 ton. Dit kunnen combinaties zijn van een voertuig met relatief laag leeggewicht van 10-15t met een zware aanhanger van 35-40t tot aan een voertuig met een hoger leeggewicht van circa 20t met een lichtere aanhanger van circa 30t. De resulteert in gemiddelde laadvermogens van 15t zonder aanhanger tot 30t met aanhanger.

Figure 35: Main characteristics of HDVs. (RVO, 2022)

Appendix C.

Focusgroup “circularity in the heavy vehicle sector” report.

Participants:

- Ecodesign / production
- Large user (1200 vehicles for waste transport)
- OEM affiliated dismantling facility
- Non-OEM affiliated dismantling facility
- Branch organisation for automotive dismantling
- Branch organisation for automotive recycling
- Recycler / waste upcycling
- Inspection on used vehicle export
- Policy researcher on climate, air and energy
- Policy researcher on climate, air and energy

This focusgroup is organised to gain insights in CE strategies, enablers to overcome barriers that hamper the implementation of these strategies and influence of technical developments such as electrification and institutional developments like ECOWAS import regulation. To gain these insights, experts from along the HDV value chain are consulted together by means of a focusgroup. This method is following the Solution-focused Sustainability Assessment (SfSA) method(van Bruggen et al., 2022; Zijp et al., 2016).

The insights will be used to 1. Validate barriers from literature, 2. Gain novel insights, expanding knowledge beyond the literature, 3. Explore the solution space for overcoming these issues 4. Qualitatively investigate effects of various technical/institutional developments.

A disclaimer is that the results of the focus group are not comprehensive and exhaustive. The focus group was organised in way to prevent tunnel vision and anchoring as much as possible. However, due to a limited time, limited topics and pathways have been explored.

Technical and infrastructural barriers

The Dutch dismantling facilities are frontrunners. Their operation is highly efficient, little components or materials are regarded as waste.

A significant trade-off remains between circularity practices, such as dismantling for reuse and high-grade recycling, and emissions during the Use phase. For instance, elongating the lifetime of an HDV may mean that a less efficient vehicle is used for a longer period. In the case of combustion engines, 95% of the emissions during the vehicle's life cycle occur during usage(Scania, 2021a). Therefore, small improvements in this phase can result in significant reductions in fuel consumption and emissions. To achieve these goals, the industry has made considerable strides in fuel efficiency and emission reduction, leading to increased complexity in vehicle components. Modern components are more electrified and smart, and mono-materials have been replaced with lightweight composites. Additionally, various materials are often joined together using glues or welding techniques, making disassembly more challenging and reducing the overall rate of high-grade recyclability.

Insufficient emphasis on design for circularity to facilitate dismantling increases the time and complexity of the dismantling process, and reduces the rate of high-grade recyclability. Recyclers' sorting categories are often challenging for mechanics to follow, exacerbating this problem. Consequently, composite and mixed materials are frequently rejected and ultimately incinerated, further reducing the recyclability rate.

Another significant challenge is the lack of standardization, with only a few items such as dynamos, brakes, or stabilizers being standardized among brands and models. Innovations are fast, but the lifecycle of an HDV is long. Reliability lines of OEMs require a lifetime of at least 8 years or roughly 1M-1.5M km in distance on the road. But reality is that the vehicle is often used for 20 years. It is difficult for OEMs to anticipate for proper dismantling by designing something that will end its lifecycle after 20 years. Except from a couple wear parts, components are designed to last the full lifetime. In the meantime, innovations are quick. Therefore, vehicles and their components are quickly outdated. Emission standards going from EURO I to EURO VI in 20 years, show older ICEVs being outdated rather rapidly. Zero emission technologies are still in their early stages, resulting in fast innovation that exacerbates this effect.

Even considering all issues mentioned above, the Dutch facilities responsible for dismantling (HDVs) are considered to be at the forefront of the industry. They operate with high levels of efficiency, minimizing waste by repurposing components and materials. However, 95% of all Dutch registered vehicles don’t end their life within the borders of the Netherlands (RVO, 2022),. The vehicle has a high chance to end up in a non-authorized facility, that doesn’t have the infrastructure, or knowledge to dismantle the vehicle properly. This can significantly affect the circularity in the HDV value chain. On top of that, Low and Middle Income Countries (LMICs), do not have the infrastructure to use and maintain newer vehicles. Consequently, newer vehicles, like EURO IV or EURO V, are imported, but then completely stripped from any advanced technology, and are equipped with old, more pollutant motors, as old as EURO I.

Supply chain governance and information

Collaboration within the supply chain, both horizontally (between organizations in the same value chain phase) and vertically (between organizations of different value chain phases), can be improved to enhance circularity. For instance, data lacks on the composition of components, and it is hard for non-OEM affiliated dismantling facilities to get full legal information on the right replacement of malfunctioning equipment. The lack of collaboration between dismantlers and designers, results in a design less suitable for reuse and recycling. Apart from that, reuse and recyclability is hampered due to the lack of knowledge on reusability of components. The exact rate of wear is hard to predict and due to the absent standardisation, it is unsure which component can be used where.

Outside of the Netherlands, the whereabouts of end-of-life vehicles (ELVs) and used trucks are often unknown to both authorities and OEMs, making the transition towards more circular practices difficult. The first consequence is that the current state of circularity within the value chain is unknown. Non-authorized facilities do not need to comply to safety, recycling and health guidelines and are therefore opposing circularity. This represents an environmental risk. However, there is not even an estimation of the quality of dismantling in other countries. Secondly, OEMs do not know how the large volumes of materials and vehicles flow. Hence, it is hard to adapt design practices to the main standards of dismantling. The lack of cooperation between member states and there vehicle registration systems amplifies this problem. The problem of 'missing vehicles' represents significant materials losses from the European system and it needs to be avoided that ELVs are exported as used (and therefore usable) vehicles outside of the EU.

Apart from that, the environmental and material impact is unknown of certain strategies like remanufacture, reuse or recycle. A trade-off exists between the benefits of a CE strategy, like remanufacture, and the increased footprint of component transport to a remanufacturing facility. Other, 'lower' CE strategies, like recycling, can turn out to be the environmental more preferred option. This issue is embedded in a larger problem. The whole value chain has issues with the vagueness of circularity. Currently, the transition towards a CE sets an ill-defined goal, and the lack of Key Performance Indicators hampers this transition.

Market / economic barriers

Utilisation of the HDV can always be improved, empty freight transport is still a loss of resources. However, HDVs have a higher utilisation rate than passenger cars, which are non-idle for over 98% of their lifetime. Consequently, this means that downtime, for example due to malfunctioning, or maintenance, is extra costly. Therefore, reliability of the vehicle and its components is of utmost importance and it is often the more economic option to replace and to be on the road again as quickly as possible.

To reduce downtime is not the only reason why CE strategies are often not economically preferable. The price of secondary materials and used components usually cannot compete with their virgin and new counterparts. The price of virgin material is too cheap, and does not reflect the true costs of production. On top of that, labour is expensive. Most CE strategies, like dismantling of complex components are labour intensive and time-consuming, which makes the business case worse. Furthermore, economies of scale and scope are difficult to achieve. The volume of annual ELV vehicles is relatively low, and heterogeneous, both in type, and in location where the vehicle reaches the end of its life.

It is also challenging to determine the right time to invest in new zero emission technologies as innovations are rapid and market developments can render technologies quickly outdated. For example, LNG was considered a relatively emission-friendly substitute for ICEVs. However, the volatility of gas prices due to the Ukraine crisis has made this fuel type too expensive and uncertain. This lead to a mass amortisation of this fuel type.

Institutional barriers

Various institutional barriers hinder the transition to a circular economy, taking on different forms. The first barrier is a lack of proper regulation. At present, there is no legislation governing the end-of-life treatment of HDVs, which retain their value for a long time. Consequently, no proper incentives apart from a certain degree of cost optimisation exist to promote circular practices for end-of-life vehicles (ELVs) and reduce emissions across the borders of the Netherlands and the European Union. Although some regulations such as the ECOWAS import regulation on vehicles older than ten years or less than the EURO V standard have been implemented(ILT, 2020), there is no component import/export regulation. This encourages the replacement of cleaner technologies such as EURO VI engines with more pollutant older types.

In addition to a lack of regulation, poorly designed regulations can be ineffective. For instance, the Extended Producer Responsibility (EPR) in the current ELV directive for passenger vehicles does not incentivize original equipment manufacturers (OEMs) to improve dismantling. The EPR imposes a standard recycling fee to be paid by OEMs, but because it is not a progressive scale, and ELV handling is not their responsibility, no incentive exists to design vehicles for better dismantling and recycling. Cross-border EPR is also currently not enforced. To start of the right foot, this ineffectiveness should be addressed when the directive is extended towards HDVs.

Regulations can also (in hindsight) create perverse incentives, such as weight-based requirements that do not consider the volume or value that may not be recycled due to the large weight share of ferrous metals in a vehicle. Regulation can also cause greenwashing, which can be misleading. For example, the current ELV demands a recyclability rate of 85%. However, the directive regards downcycling materials to inferior second lives – such as roadside posts – , and even backfilling as a "recycling practice" (EC, 2021).

Furthermore, regulation can be too stringent, impeding communication and cooperation in the value chain both horizontally and vertically. For instance, some participants of this focus group had to approve their participation on several levels within their organization to minimize the risk of violating competition law. Consumption tax (VAT) also acts as a barrier to the circular economy, leading to stacked taxes collected on the new product, again on the used product, and once more on labour, such as repair or maintenance. Export bans can also be too stringent. Banning export of old vehicles or components can hamper the transition towards a circular economy. Old types might be outdated in our developed economy. But, replacing pollutant vehicles with a less pollutant one is still an improvement and contributes to lifetime elongation.

Cultural

The transition to a circular economy in the HDV sector faces several cultural barriers. The foremost of these is the linear system and associated company culture. Although there are existing circular economy (CE) practices in place, they are based on cost efficiency rather than on a circular mindset. Producers of components and vehicles tend to have linear business models that oppose lifetime elongation by reuse or another strategy to slow the loop. Therefore, by facilitating more circular business models, there is a risk that the business-as-usual might be cannibalised. This emphasizes the need for a shift in mindset towards a circular economy.

Another cultural barrier to the transition is the lack of consumer interest in sustainable HDVs, as the willingness to pay a premium for sustainability is marginal. This lack of willingness can be attributed to several factors, including a lack of financial resources and a lack of understanding of the environmental benefits of circular practices.

A barrier that is understandable, but nevertheless significant, is the focus on scope 3 emissions by HDVs, which account for 95% of the environmental impact during the Use phase(Scania, 2021a). Nevertheless, the production of materials, component production and assembly and logistics are still highly polluting, both in GHG emissions, as eutrophication and biodiversity loss. This contribute to the overall environmental impact of the sector.

Hesitance towards innovation is another barrier to the transition, especially if it does not seem to have an immediate effect. For example, it can be challenging to persuade OEMs to invest in circular design when there is a consensus that the vehicle will end up as anonymous car fluff regardless. Furthermore, thinking in problems rather than in enablers hampers the transition towards a circular value chain. Overcoming these barriers will require a collective effort from stakeholders, policymakers, and consumers alike.

Best practices

Compared to other value chains, the HDV sector has a variety of best practices and acts to an extent circular.

The vehicle is designed, following reliability guidelines, for a lifetime of roughly 8 years. However, most of the vehicles drive way past that due date. Reparation and lifetime elongation are a vast part of the lifecycle, that doesn't end when the vehicle is amortised.

The Dutch ATFs are considered to be at the forefront of the industry. They operate with high levels of efficiency, minimizing waste by repurposing components and materials. The ATFs provide warranties for the components, certified by a certification authority such as Kwaliteitszorg Demontage (KZD, 2013). On top of that, recyclers have proven to produce secondary materials meeting virgin-grade standards. For example, secondary plastic produced from recycling can be used for safe children's toys.

Various bottom-up deposit schemes are currently in place to maintain the intrinsic value of components for as long as possible. For instance, deposit fees are imposed by engine and transmission producers on their products, while dismantlers charge a deposit fee for old electronic equipment.

If an indicator is proven to be reliable, its application can be used for new regulation. For example, the Vehicle Energy Consumption calculation TOol (VECTO) is a tool used for determining CO_2 emissions and fuel consumption form HDVs (EC, 2019c). Since 2019, this tool is mandatory for type approval of new trucks. A new proposition for CO_2 reduction standards, is based on the VECTO output. These new standards require a reduction in CO_2 emissions compared to 2019 levels by 45% in 2030, 65% in 2035 and 90% in 2040(EC, 2023b). This creates a level-playing field.

Another aspect of creating a level playing field is to consider the true cost of ownership (TCO). One organization has made a business case for more sustainable company apparel, which despite its higher initial cost, has a considerably lower TCO than conventional clothing due to its extended lifespan.

The utilisation of HDVs is constantly optimised. Fleet management systems register driver performance, and calculate the most efficient routes. Regulation encourages further optimalisation. For example, cities are reducing the transport movements in their centres. Therefore, waste transport companies started collaborating in a green collective. Members of these collectives are sharing their trucks and routes to optimise routes and reduce traffic in cities.

The green collective (RENEWI, 2022a) also shows a promising increase in stakeholder and user awareness. This shift is also underlined by an increasing interest of companies in sustainable procurement. Sustainability requirements are increasingly more often embedded in large tenders. This way, the markets dictates the OEMs into improving on their sustainability proposition.

Focusgroups such as this focusgroup "circularity in the heavy vehicle sector" can be considered a best practice as well. As previously noted, collaboration among stakeholders in the HDV value chain is often limited. However, the focus group provided a forum for stakeholders to openly share experiences and strengthen their networks.

Enabler

Different types of barriers have been identified and throughout the focus group, enablers have been explored to overcome different barriers.

The consensus during the focus group was that **True Pricing** is the most impactful enabler. The current market price for a vehicle does not reflect the true costs made along the value chain, because environmental and social costs are not accounted for. True Pricing refers to the market price and unpaid external costs, such as underpayment, loss of biodiversity and carbon emissions (True Price, 2019). True Pricing could significantly change the linear business case. It is suggested that the impact of reverse logistics for e.g. remanufacturing are able to nullify the benefits of keeping products in the loop. By calculation of the (external) costs of circular practices, a full valuation can be done on their impact. This would strengthen the level-playing field.

The quality of the output at the End-of-Life phase is dependent on the design of the vehicle. Therefore circular design is vital to achieve circularity.
A **circular design** facilitates the reuse, remanufacturing, and recycling of components and materials. Three aspects of circular design stand out: Lifetime elongation, modularity and design for recycling.
Lifetime elongation has a large potential to reduce the material impact of the HDV. By remanufacturing, repairing, and remanufacturing, both vehicle and components should reside in the loop as long as possible. One way is to improve the durability of the components.
Another way, is by increasing the **modularity** of the vehicle. Innovations are quick and components are also subject to a heavy use. Most of this innovation has historically been in the powertrain. The transition towards zero emission transport emphasises even more on drivetrain innovation. Most likely, innovations will follow-up rapidly, causing technology to be quickly outdated. It would be unnecessary to buy a whole new vehicle, if just the drivetrain has been improved. A more modular design would reduce the impact of quickly outdated drivetrains, will keeping the rest of the vehicle intact. Modularity can also make the dismantling less time consuming because the vehicle will be easier to disassemble.
Design for recycling will increase high-grade recycling by using more mono-materials, or by using materials that have a proven high recyclability. There is often a trade-off between the need to improve performance during the Use phase, e.g. by replacing mono-materials with lighter materials, such as composites or polymers, and design for recycling.

To facilitate and encourage circular practices, both in the beginning (e.g. Circular Design) and in the end (dismantling and recycling), improved knowledge and information is essential.
Data on the end-of-life phase of the HDV could greatly improve circular practices. One obstacle for practical circular design improvements is the lack of data on the large flows of ELVs. It is unknown to where, how and to what extent HDVs are dismantled in the EU. It is hard for both policymakers and OEMs to act if the current state of circularity in the value chain is unknown.
Insight in the performance of CE strategies is necessary to steer towards the right strategies. The impact of secondary materials and components and preparing them for use compared to their new counterparts is necessary to look into.
For further optimisation of dismantling and recycling processes, **identification such as a QR code** on components is suggested. For (dismantling) mechanics this is easier and quicker in use than a dismantling manual. This allows a reduction in labour intensity and a better sorting of materials by quick identification of the component, its material composition and reuse opportunities.
A Circular Transition Indicator is a key element in the transition to a circular economy. It helps to

measure circular performance of organisations and is able to set clear goals(WBCSD, 2022). Until now, most competition is on vehicle reliability, driver comfort and fuel efficiency. Reporting on ESG goals shows already that non-economic indicators can create competition as well. This renders organisations that fall behind to become quickly obsolete. The European Commission has currently 17 circularity indicators under revision. Choosing an overarching indicator is a delicate process, as a (in hindsight) wrong indicator could steer the transition into the wrong direction and/or be susceptible for greenwashing.

Sustainable procurement is an important tool, especially if it is exercised by parties with market power, like the government or large corporates with a substantial intern logistics component. Procurement criteria can include several ESG or circularity indicators besides the market price of a vehicle.

A systemic shift is needed for the circularity transition. **New Business Models** (BM) have the potential to cause a systemic shift. Other BMs force the OEMs to think differently about their product. For instance, Caterpillar's non-road mobile machinery Business Model includes a take-back programme with a **deposit scheme and voluntary product take-back** (Ellen MacArthur Foundation, 2017). A key component of Caterpillar's successful BM is its incorporation of the entire lifecycle of the product in the design process to ensure sound financial processes throughout all stages. This exemplifies that new BMs that hold the OEM responsible for the end-of-life phase can improve circularity across the entire value chain.
Another compelling new BM is **Product-as-a-Service (PaaS)**. Logistics companies are primarily interested in the use of Heavy-Duty Vehicles (HDV) to provide their services, rather than owning them. The shift of OEMs from vehicle suppliers to service providers would necessitate a rethinking of the vehicle's lifecycle, as they would retain ownership. Consequently, designing for dismantling would become routine to optimize End-of-Life Vehicle (ELV) handling.

Regulations play a critical role in steering the transition towards a Circular Economy. At the beginning of the value chain, **mandatory recycled content and biobased targets** are necessary to incentivize the use of secondary and biobased materials and reinforce eco-design measures. At the end of the value chain, promoting reuse and recycling is key.
The End-of-Life Vehicle (ELV) Directive serves as an example of such regulations, and is currently undergoing revision to potentially encompass heavy-duty vehicles. Within the ELV-Directive, **Extended Producer Responsibility (EPR)** mandates a removal fee that OEMs must pay for each vehicle they introduce to the market. However, this standard fee must be re-evaluated, and a differentiated fee based on the level of design-for-dismantling implemented could incentivize proper dismantling. The European Commission aims to merge the ELV and type approval (3R) directives, which would support the implementation of CE from manufacturing to ELV treatment (EuRIC, 2021).
Furthermore, **better and clear definitions of circular practices** are critical. The definition in the ELV directive should align with the definition of recycling with the Waste Framework Directive's definition, which excludes backfilling as a circular practice(EC, 2021). Additionally, distinctions should be made between various levels of high grade and low grade recycling (downgrading).
A revision of the **Taxation framework** is also necessary to encourage circular practices, potentially through a raw material resource tax or a reuse-repair tax relief. Sweden has already implemented the reuse/repair tax relief since 2017 (Milios, 2021).

A Circular Economy requires **more collaboration along the value chain**. OEMs need to have better knowledge on dismantling and recycling practices to improve their circular product design. Meanwhile, ELV stakeholders need more information from OEMs to improve their activities. Therefore, information exchange and a tighter value chain should be facilitated. However, companies are hesitant for tighter collaboration due to the potential threat of violating competition regulation. Governmental bodies should provide controlled space to collaborate without violating competition regulation.

Further remarks

It is important to keep in mind that LMCIs are heavily reliant on older European vehicles. As mentioned before, imported vehicles are rebuild to actually decrease the emission standard – e.g. from EURO V to EURO I – in order to be repairable in common maintenance facilities.

This emphasises, LMCIs are not able to utilise newer vehicles in an appropriate way, let alone that they will be able to use used BEVs in the foreseeable future.

New research, carried on from the 2020 report of the ILT on used vehicle export to Africa, will look into effects of new import regulation.

Both developments can have the effect that LMICs will have to shift towards other suppliers of (used) trucks, for example from Asia. This shift will hamper both the decarbonisation as the transition to a circular economy. First, the vehicles imported from Asia are mostly compliant to EURO III or EURO IV standards, which is considerably more pollutant than used vehicles from the EU. Second, these Asian types will not be awarded a EU type approval: the lifespan of Asian vehicles is roughly 100.000 km, which is only 10% of the lifetime of a vehicle approved by the European 3R Directive. This results in more vehicles produced and therefore more material demand.

It is evident that the European HDV value chain by all means is not yet circular. But a large potential to contribute to a cleaner and more sustainable world also lays outside the European borders.

Furthermore, it is important to state that electrification alone is not regarded to be adequate for the transport sector to become fully zero emission. Lithium resources cannot keep up with demand, and neither do the grid reinforcements. Hydrogen will be important as well. Phasing out ICEVs will still take a long time. However, the legacy fleet can use synthetic Fuels to be at least carbon neutral.

Mapping of the identified barriers

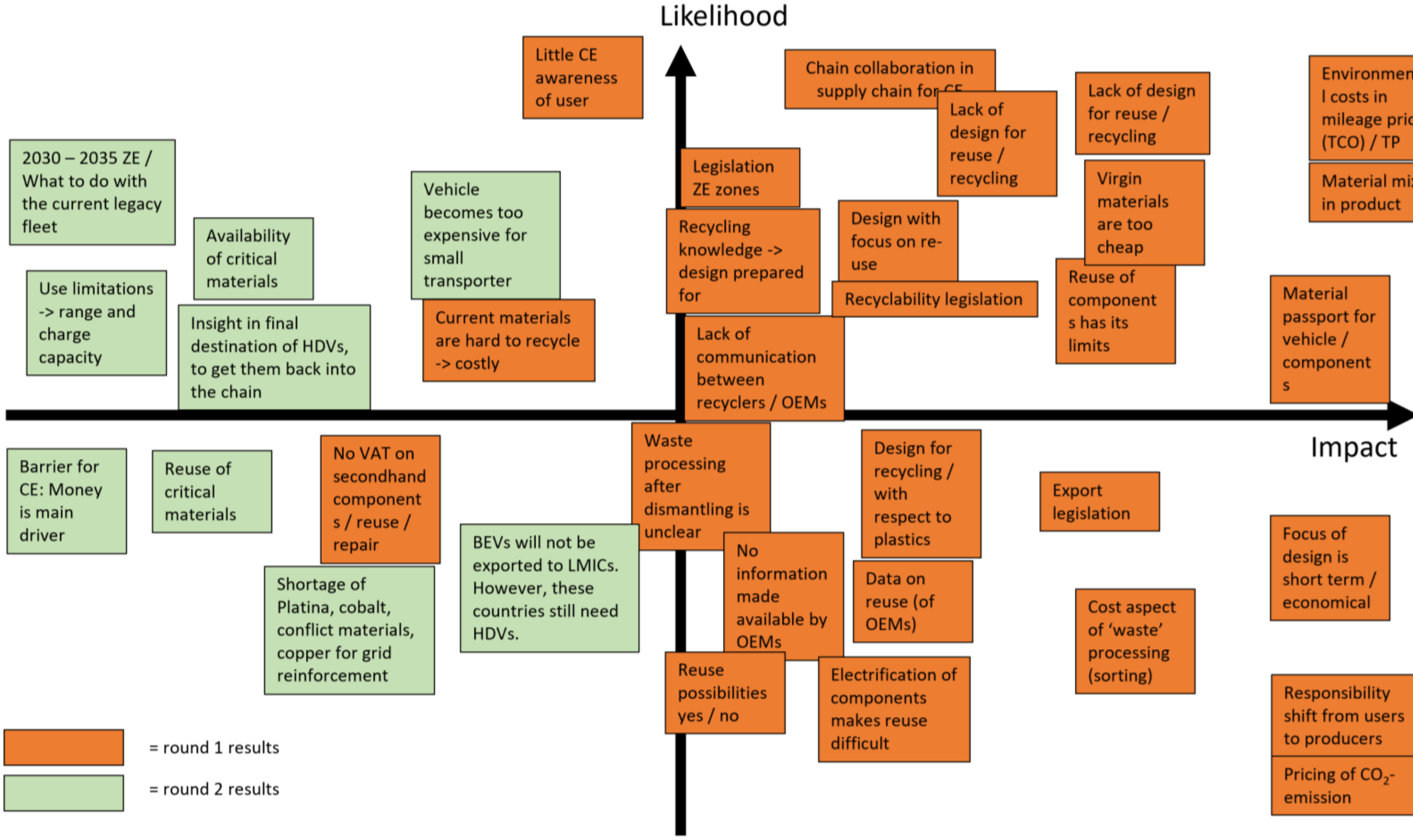


Figure 36: mapping of the identified barriers

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