Rethinking Cars for Sustainable Mobility – Shared-Autonomous Vehicles and Circularity

Stephan Jüngling[1], Gordana Kierans[2], Said Easa[3], Dominik Wörner[1]

[1] University of Applied Sciences and Arts Northwestern, Switzerland
[2] MGT OPEN, Croatia
[3]Toronto Metropolitan University, Canada
stephan.juengling@fhnw.ch, gordana.kierans@mgtopen.com,
seasa@torontomu.ca, dominik.woerner@fhnw.ch

Abstract

Autonomous driving cars, underpinned by advancements in artificial intelligence, sensor technology, and the enhanced communication capability of 5G, are now poised to revolutionize transportation, promising significant improvements in safety, efficiency, and accessibility. However, the time for such a transition towards fully autonomous vehicles (AV) should coincide with the transition to Society 5.0, where cars are zero-emission vehicles and fully embedded into a circular economy (CE). This requires a radical change not only for the car industry but also for the car users, who are in the early transition from being car owners to car-users with automobiles becoming a more sustainable public mobility service. In this paper, we conduct a literature review about the state-of-the-art of autonomous driving and circular economy, as both cannot be established without substantial infrastructure enhancements for vehicle-to-everything communication and for building up more sustainable business models for the circular economy. We divide this journey into three different states where we provide a vision of new stakeholders and new business process models via the current state of its infancy, the middle state of its coexistence, and the target state of fully established Shared Autonomous Electric Vehicles (SAEV) and CE services. Given that such a radical change will undoubtedly face resistance, this transition scenario is analyzed using different aspects of power dynamics to show potential benefits and new business opportunities for the different stakeholders involved. In the final section, we show examples of different car manufacturers and how they see their current focus on new energy vehicles (NEV) and aspects of CE in their respective strategies.

Keywords: Autonomous Vehicles (AV), New Energy Vehicles (NEV), Shared Autonomous Electric Vehicles (SAEV), Shared Autonomous Mobility (SAM), circular economy (CE), process redesign, sustainable mobility

---

Smuts, Hanlie & Hinkelmann, Knut (2024). Proceedings of the 4th Conference Society 5.0 - Innovation for Sustainable and Inclusive Social Good, Volume 2, Mauritius, 26-28 June 2024, DOI: 10.5281/zenodo.11612759

DOI: 10.5281/zenodo.11617425

1. Introduction

It is not an exaggeration to say that the automotive industry is being radically transformed. Routinely, there are articles in European newspapers indicating how the well-established European automotive market is facing a Chinese disruption (The Market, 2023). At the same time, European efforts toward a true transformational shift away from fossil fuels are dwarfed by the strong resistance from an industry that has to face valid accusations of complacency and underestimating the competition from abroad (Handelsblatt, 2023).

At the same time, as the World Economic Forum Report (WEF, 2020) states, a coalition of stakeholders from the automotive industry itself and beyond, compiled a report with several important key messages toward reaching a sustainable mobility system. They state that the automotive industry must reduce its carbon emissions and resource consumption by adopting circular economy principles, such as using renewable and recycled materials, extending vehicle lifetimes, improving vehicle utilization, and integrating with the energy grid. They estimate that circularity can reduce carbon emissions by up to 75% and resource consumption by up to 80% per passenger kilometers by 2030, compared to a standard 2020 internal combustion engine vehicle. However, they also mentioned that circularity requires a common framework and a systemic transformation to energy decarbonization, material circularity, lifetime optimization, and utilization improvement until reaching an optimized ecosystem by 2024.

However, the discussion, - and even the fears - of which country's cars will dominate European or even global streets is missing a fundamental point. Our new generation of drivers is very aware of car's contribution to global warming and is less and less interested in driving, let alone owning a vehicle that sits idle 90% of its time and costs money (The Guardian, 2023). Nonetheless, the reality is that this generation will also need to get from A to B. Hence, how do we design a mobility system that fits their wishes and needs and does not stretch the demand for virgin materials past the breaking point?

Moreover, as the world moves more to self-driving, autonomous vehicles on the road and in the air, there are questions we must ask. How do we design these vehicles to be fully modular and circular to avoid waste and increase their longevity? How do we ensure they provide mobility for as many people as possible in cities and rural areas? Autonomous Level 4 cars, meaning they are genuinely autonomous, are already circulating in cities like San Francisco, Austin or Shenzhen (Law, 2023) and the time to adjust our thinking about cars serving Society 5.0 has already started. Some of the key stakeholders involved in the transition to AV range from dedicated end-to-end software development platform providers such as NVIDIA to well-known pioneers of self-driving cars such as Tesla or Waymo from Google, up to the less recognized but the world's largest robotaxi service provider Apollo Go from Baidu, which operates in 30 cities with over 60 Mio km testing and more than 3 Mio commercial rides (Block, 2024).

However, can these companies also support material circularity and become part of reverse logistics, i.e., used materials are returned to the producer for a renewed sustainable mobility service? And if they are in movement all the time, as the human need for a break is eliminated, what kind of quality level must they fulfill to increase longevity? How can car manufacturers design vehicles that provide mobility for humans and goods and also continue to earn revenue in the process? What should be the global denominator that moves all infrastructure providers towards the same goal?

As these changes will affect all of society and its access to infrastructure, design change alone is not enough. Analysing the distribution of power is also crucial as it can significantly impact the outcome of projects. As described in Li et al. (2022), New Energy Vehicles (NEV), were put into China's National Key Science and Technology Industrialisation Projects in its 9th Five-Year Planning (FYP) period, lasting from 1996 to 2000. It was thus the power of government that understood the need for a solution that both served the growing middle-class' desire for mobility and at the same time did not create a suffocating blanket of smog over cities.

Thus, in this paper, we will start with a literature review of the current state of autonomous driving and the circular economy and the required infrastructure changes. We divide this transition process towards fully circular and autonomous mobility services into three scenarios: Scenario 1 is the short-term, representing current ***infancy*** of AV and CE, with linear economy; Scenario 2 is the mid-term, representing the ***coexistence*** of Human Driven Vehicles (HDV) and fully AD vehicles with the linear and circular economy and; Scenario 3 being the long-term, representing the ***established*** *AD, with circular economy,* including all supportive infrastructure and smart city operational facilities. After this journey, we will provide insights into the current state of thinking of the car manufacturing companies themselves, then consider insights from this study of rethinking cars for more circular, sustainable mobility and then finish with some compelling evidence that CE and AD combined can lead us to a more sustainable future.

2. Literature Review

The literature review is divided into three topics that are necessary building blocks for the design and analysis of the different implementation steps of AV and CE namely: shared, electric AV; the circular economy, and; AV infrastructure.

2.1 Shared-Electric AV

Currently, there is justifiably a plethora of contemporary literature on AV as they are now seen as the future of mobility and thus have a potential consequential disruptive impact not only on the environment but also on society and the economy (Williams et. al. 2020). The positive impacts of AV range from safety improvements, increased accessibility by the elderly and disabled people, more effortless driving, with less congestion and environmental impact. On the other hand, AV may have adverse impacts, including loss of driving jobs leading to shifts in the labour force and behavioral uncertainties regarding how consumers will consider their willingness to travel (Onat et.al., 2023). AV will also have a considerable impact on the Original Equipment Manufacturers (OEMs) with the most important traditional key components such as the engine, transmission, and chassis being replaced by many new key components such as 5G communication and sensor technology. In addition, the required software engineering/machine learning processes for continuous updates and deployment of machine learning models will become key skills for New Energy Vehicles (NEV) and also Shared Autonomous Electric Vehicles (SAEV) manufacturers.

Moreover, SAEVs have the potential to play a vital role in terms of energy management. Iacobucci et. al. (2019) describe a scenario with SAEV used as a Virtual Power Plant (VPP) or a microgrid with intermittent renewable energy. The model simulates aggregate storage availability from vehicles based on transport patterns and optimizes charging. The case refers to a grid-connected VPP with rooftop solar and the case of an isolated microgrid with solar, wind, and dispatchable generation. The results show that SAEVs offer significantly lower costs compared to privately-owned vehicles. SAEV can also substantially decrease the total number of cars needed worldwide. They after all will be continuously operating on the road instead of standing still in a public or private garage which is the situation for more than 95% of the currently owned private cars. As Duarte (2018) points out, cars can and will be redesigned to be suitable for working, sleeping or socializing and be much enhanced in terms of comfort and functionality.

Implications of autonomous driving cars to the infrastructure are also quite diverse and raise challenges ranging from harmonization of traffic signs to a review of common design patterns addressing new ways of collaboration in a city (Mihalj et al., 2022). However, SAEV also has the potential to change life as we know it in urban areas and we would like to point out the following list of important facts which support our three transition scenarios in Chapter 4. SAEV will: (a) provide accessible mobility services to the home for all citizens; (b) require fewer parking spaces that can be reused for pedestrians or bikes; (c) serve as energy storage like hydroelectric power plants; (d) be much more complex with respect to software, sensors, ML models and; (e) allow for dramatic new designs.

2.2 Circular Economy and SA Vehicles

What is the Circular Economy? The circular economy is easily explained: it is simply a world without waste. According to Ellen MacArthur Foundation (2024), it aims to design out waste and pollution, keep products and materials in use for as long as possible, and regenerate natural systems. This definition avoids the confusion with the term "Recycling Economy" that many mistakenly still put on the same footing as the circular economy. Because waste management companies are actively affected by this transformational shift, Kirchherr et al. (2017), found 114 varying definitions of the circular economy. Despite this, there is consensus that continuing with the linear model of producing waste and hoping that better waste management and recycling will solve humanity's problems is not enough. As the definition states, the core concept of the circular economy is the requirement to design out waste. It is no surprise that certain industries are embracing circularity faster than others, as presently product and supply chain complexity creates numerous obstacles. As we will illustrate later, power structures can help the circular transition. To illustrate, Rentizelas (2022) states that regulatory initiatives propel car manufacturers toward a circular economy paradigm that incorporates reuse, remanufacturing, and recycling processes. And, Halia (2023) conducted a qualitative descriptive analysis of the top 10 automotive companies on the Global Fortune 500 List to assess their respective levels of circularity.

Why Do We Must Start with Design? As with all life in nature, design refers to eliminating the concept of waste all altogether by reusing everything where all waste becomes nutrients for subsequent growth (Baumgart & McDonough, 2009). As our world is buried in waste, a totally different approach to how we make, use and dispose of products and services is required. The primary responsibility lies primarily in the initial design phase because once a product specification is decided, it enters the production phase and then only minor changes become possible (Nasr, 2016). Decisions made at the design phase influences 75% of the products' economic cost and also 75% of its social and environmental impacts. It is not surprising then that design now plays an increasingly crucial role in the production process. However, this new imperative is not just to create products with extended life cycles, but also to revert to designs where parts can be repaired and materials brought back at the end of usage. This requires a radical shift in thinking about how our monolithic products can have a more modular design such as following a LEGO metaphor. As separate parts have different longevity levels, a modular design allows the repair and/or replacement of broken parts without discarding the whole product.

However, based on observations of NEV in China, they are not yet convincing all about their longevity. Yes, they could become LEGO bricks, which can be adapted for individual mobility needs and used as parts of a shared mobility infrastructure for individuals and organizations. AV in principle could fulfil this function since they can be dislocated and used, wherever needed. Hence, this idea begs a question: How should AV be designed to serve as a mobility infrastructure in urban and rural areas and also leave no waste behind at the end of their lifecycles? To design out waste, companies must close their own product loops and bring their end-of-lifecycle products back to be used as raw materials once again. The captivating question that has been occupying our minds is: can autonomous vehicles be designed to transport passengers and also serve as a reverse logistics infrastructure for companies? If yes, how do they need to be re-designed?

Why is Circularity Itself Not Enough? Thus far, we have addressed the issue of how consumers could be open to replacing their combustion engine vehicles with electric cars. However, as Figure 1 below shows, that mindset opens a pandora box of new challenges as NEVs actually require significantly more virgin resources. Hence, only a smaller total number of vehicles and a durable, modular (LEGO style) SAV can offer benefits of improved mobility and also reduce the pressure on virgin resources. In the design of SAVs, there are two elements to consider with completely different lifecycles: the vehicle body itself and also its battery. Both have to be designed for longevity and there are several reasons for this requirement: a) in an established system, companies can reuse these materials as raw materials, and; b) this reuse will help companies bridge their raw material needs as the current demand for certain metals is inevitably going to increase as the investment in new extraction sites might not meet the speed of demand and; c) the current pollution and landfill situation does not offer any space for more waste materials.

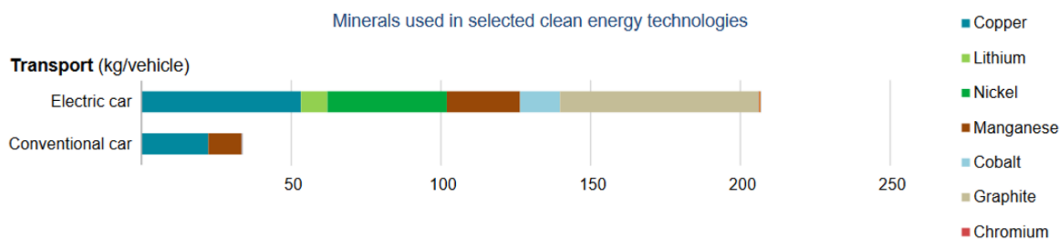

Fig. 1: Demand for Minerals, Source: International Energy Agency (IAE, 2021)

Without addressing these realities both the vehicle and the battery will otherwise become waste. Currently, different NEV producers are working on disparate battery solutions. However, these efforts rarely consider circularity in the design phase (Masiero et al., 2016). This will change radically in the upcoming years due to resource shortages as the NEV industry is competing in the renewables sector for the exact same resources.

Another social concern to consider is the commodity market. The production of crucial resources for NEV is geographically even more concentrated than oil and gas (International Energy Agency, 2021). For example, the world’s major exporter of cobalt is the Democratic Republic of Congo (DRC) with 70% of global reserves and 51% of world production (cobaltinstitute.org, 2023). Yet, details about human rights abuse and environmental issues in the DRC have been widely reported. Moreover, 98% of all the cobalt that is mined as a by-product as it does not have its own ore and depends on copper and nickel mining demand. Some countries like Indonesia are curbing their exports of mineral ores in order to spur job creations at home. These regulations will heavily influence the price of the commodity (The Straits Times, 2023).

2.3 AV Infrastructure

AV infrastructure has received little attention thus far since many stakeholders have initially focused their attention on issues related to AV (e.g. safety). More focus on AV infrastructure requirements to promote Shared Autonomous Mobility (SAM) will soon be needed. For example, there are no established guidelines regarding adequate road infrastructure to support AV operation in our diverse urban environments. However, it is envisioned that some infrastructure changes will inevitably be implemented during AV pilots, additional infrastructure to suit mixed traffic (AV and HDV), and finally, an infrastructure that can support a complete transition to automation.

For regular AV requirements, there are typically five levels of automation. We are focussing on level 4, where AVs are equipped with vehicle-to-everything (V2X) technologies that will enable genuinely autonomous driving. According to (Manivasakan et al., 2021) the required infrastructure includes the following: (1) digital infrastructure; (2) physical infrastructure; (3) usage, human-machine interface, accessibility, and vehicle aspects; and (4) cybersecurity, data management, and privacy. For electric AV, significant additional infrastructure will be needed, including:

Charging Stations. A robust network of public charging stations is required. These stations should be strategically placed in urban areas, on highways, and in other high-traffic locations to ensure convenient access for NEV owners. In addition, drivers will need to access overnight charging capabilities at their homes or apartments.

Clean Power Supply. Sufficient clean power generation to support these vehicles is also needed. Using renewable energy sources (e.g. solar and wind) is crucial in sustainably providing electricity for charging stations.

The NEV infrastructure demands include personal cars, utility vehicles, delivery trucks, public transit, and commercial fleets. In addition, municipalities must develop charging standards into their permitting processes, invest in the essential electrical infrastructure, and develop methods and regulations for retrofitting existing buildings and parking facilities.

2.4 Circular Economy Infrastructure

The above-mentioned infrastructure enables a smooth operation of NEV and, consequently, SAV, but does not address circularity. Current supply chains are highly efficient but operate only as one-way highways. Moving forward, existing infrastructure must be reconfigured, as well as, new ones constructed (Nogueira, et al., 2020), in order to reach the material circularity that the European car makers demand. The industry's resources are often mined in a faraway part of the world, processed somewhere else, formed into products elsewhere and then sold in yet another country. Hence, regaining materials from end users can pose a significant challenge for producers. For this reason, in this paper, we look at the circular economy infrastructure from two sides. Firstly, what kind of infrastructure is necessary for SAV producers to get their materials back at the end of the life cycle? And, secondly, can SAV include a designated transportation area that can support the circular infrastructure of other companies? To access secondary materials, companies will need to design their own reverse logistics, or they can access the so-called secondary markets. As Goovaerts & Verbeek (2018) rightfully argue, *"...competitiveness of a business today is not solely dependent on its own performance but on the value-creating systems within which it operates.*" However, the first approach might require a large upfront investment, which might not be welcomed by all stakeholders, especially investors and shareholders. Companies are prone to show a lukewarm investment interest and only comprehensive regulatory pressure can exhibit enough power and impact the companies' cost priorities in order to accelerate these investments. The second approach requires well-developed secondary markets where the value of used materials is well-established and traded. Companies can purchase these materials like any other resource and use them for their production. These markets can only be successful if ultimately the cost of secondary materials is lower than virgin materials. As a consequence, these markets can only thrive if their extraction and their path to the trading hub are not too costly. Under the assumption that these markets develop in major production hubs, which are likely be urban centres as they are linked with the smart city approach that aims to increase sustainability in urban areas, SAV can support these local markets by delivering secondary materials to assigned storage spaces. From there, it can reach trading spaces. However, this assumption depends entirely on municipal leadership, their commitment to circular economy and their willingness to co-finance the supporting infrastructure and the system dynamics within their constituencies.

3. System Dynamics and New Design Considerations

Considering the intricate nature of changes within each of these topics and their interconnectedness, any radical transformation required to achieve the objectives of the envisioned sustainable mobility scenario - one that challenges existing mindsets - will undoubtedly face considerable resistance. Avelino (2021) examines power dynamics within the context of social change and invites us to formulate empirical questions on the relationships between power and processes of social change and innovation. She offers seven prevailing points of contestation in academic debates on power, which we use to reveal important insights and potential solutions for paving the way for rethinking of cars for sustainable mobility.

Power 'over' versus power 'to': This refers to the ability of an actor to control, influence, or dominate *'over'* others versus an organization or individuals which also may also have the ability *'to'* act. While traditional car manufacturers have historically held significant power *over* the entire automotive value chain from production, distribution to pricing, new NEV startups such as Tesla have disrupted the industry by making changes *to* established norms. As mentioned earlier, in China, the success of NEV goes back to China's National Key Science and Technology Industrialisation Projects in its 9th Five-Year Planning (FYP) period, lasting from 1996 to 2000. In the West, governments and regulatory bodies exert power over the industry by setting emission standards, safety regulations, and taxation policies.

Centered vs. Diffused Power: Concerning power there is also a significant difference in how China and the Western World see power. The Central Government in China makes decisions based on a single-minded strategy, while in Europe multiple stakeholders need to agree to a solution before new initiatives can be implemented. As consumers become more informed and more environmentally conscious, their growing demand for electric and sustainable vehicles will empower them to shape the industry. Shared mobility services (e.g., ride-hailing, car-sharing) also give individuals the *"power to"* access transportation without car ownership. In effect, these platforms democratize mobility.

Consensual vs. Conflictual*:* The sheer number (and also the size) of cars today clearly contributes to congestion, pollution, and resource depletion. However, car manufacturers are nonetheless maximizing production and sales to generate revenue and profits and thus may resist reducing production due to their short-term financial interests. After all, lower production could impact revenue, employment, and market share. This could then lead to conflicts related to environmental impact, urban planning, and infrastructure strain. However, as shared mobility, ride-hailing, and carpooling continue to become a valid alternative to private car ownership, car manufacturers could invest more in shared mobility platforms, creating win-win scenarios for themselves and their customers.

Constraining vs. Enabling*:* The development of NEV can be seen as an exercise of innovative power *'to'* new car manufacturers and consumers who are creating new resources and challenging the existing structures of our fossil fuel dependency. However, NEVs also depend on the availability of electricity, charging infrastructure, and especially battery materials, which can constrain their acceptance and impact. However, it is clear that autonomous driving can enhance efficiency and safety and their self-driving features can be used to optimize energy consumption, reduce traffic congestion, and improve overall transportation efficiency. Despite these assets, the development of a reliable SAV infrastructure is complex and resource-intensive. Potential safety concerns, regulatory hurdles, and ultimately public acceptance are constraining factors.

***Quantity vs. Quality*:** By designing cars that are more durable, modular, repairable, and recyclable, the car industry can extend the lifecycle of cars and reduce maintenance costs. The circular economy can change the way power is exercised and distributed in the car industry by creating new opportunities for collaboration, innovation, and transformation. As long as the car manufacturers remain the primary owners of their own cars within the Product-as-a-service business model, increasing the quality of cars will be in their own interest. And, as owners of the batteries, they can also harness the collective charging and recharging capacity of their entire vehicle fleet and be in a position to offer energy supply services akin to the vital role played by water reservoirs in a country.

Empowerment vs. disempowerment: Governments and regulations can either enable or constrain the innovation and transformation of any economic sector. Regulators can empower car manufacturers and consumers by providing incentives, subsidies, infrastructure, and information for the adoption of NEV. Insurance companies can be empowered by collaborating with AV mobility service providers to offer bundled insurance packages.

***Power = knowledge vs. power ≠ knowledge**:* Avelino (2021) also refers to the debate on whether power and knowledge are inseparable or distinct phenomena. As Society 5.0, we have access to a lot of information but often lack the ability, or especially the authority, to act on it appropriately. Humanity should favor both the common good CE principles and shared AV mobility services over the individual power prestige of car ownership with its less expensive but environmentally unfriendly products.

4. Scenarios for AV & CE Implementation

To better visualize the transition from the current state of car manufacturers and private and corporate car owners to the future state of fully autonomous vehicles and circular economy services, we suggest viewing snapshots of potential business processes that characterize the different stakeholders, their interactions, and the available infrastructure with the help of three business process models for short, mid, and long-term scenarios.

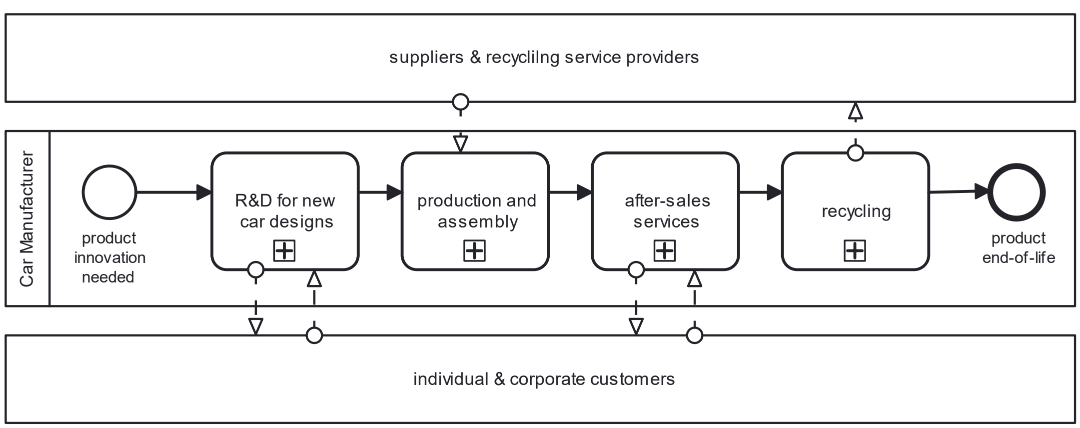

Fig. 2. Short-term scenario: current infancy of AV and CE

Short-Term Scenario: Current Infancy of AV and CE: The current life cycle thinking of cars is mainly centred around three stakeholders, which is visualized in Figure 2. R&D of the car manufacturers has been mainly designed with individual or corporate customers in mind who typically own their cars for up to a decade or more. And, in many countries and cultures, the purchase by these customers also serves as a status symbol with luxury brands and high-performance vehicles being associated with wealth, power, and prestige. Indeed, being able to drive one's own car is one of the important prerequisites for business life. |In addition, this status quo also provides a considerable market for driving instructors and plays a crucial role in traffic safety and therefore intrinsically involves the entire insurance business. Given the constant global trend of increasing vehicle production over the past two decades with 89.8 Mio produced in 2023 (S&P Global, 2024) and the total number of now about 1.4 billion cars worldwide (Hedges & Company, 2023), demands to improve environmental compliance are growing. Hence, due to this pressure coupled with rising fuel costs, the R&D of manufacturers is placing a growing emphasis on energy efficiency, leading to an overall increase in efficiency of around 6% since 2021. However, the new demand of customers towards more innovatively sustainable cars can be supported by new tools (Bauer, C., 2020) that can help meet not only CO_2 emissions but also other further relevant environmental indicators that are factored into car buying decisions. Collectively, this has the potential to steer the life cycle of cars towards greater sustainability. And as illustrated earlier, the increased materials need for NEV accentuate this urgency for even more sustainability.

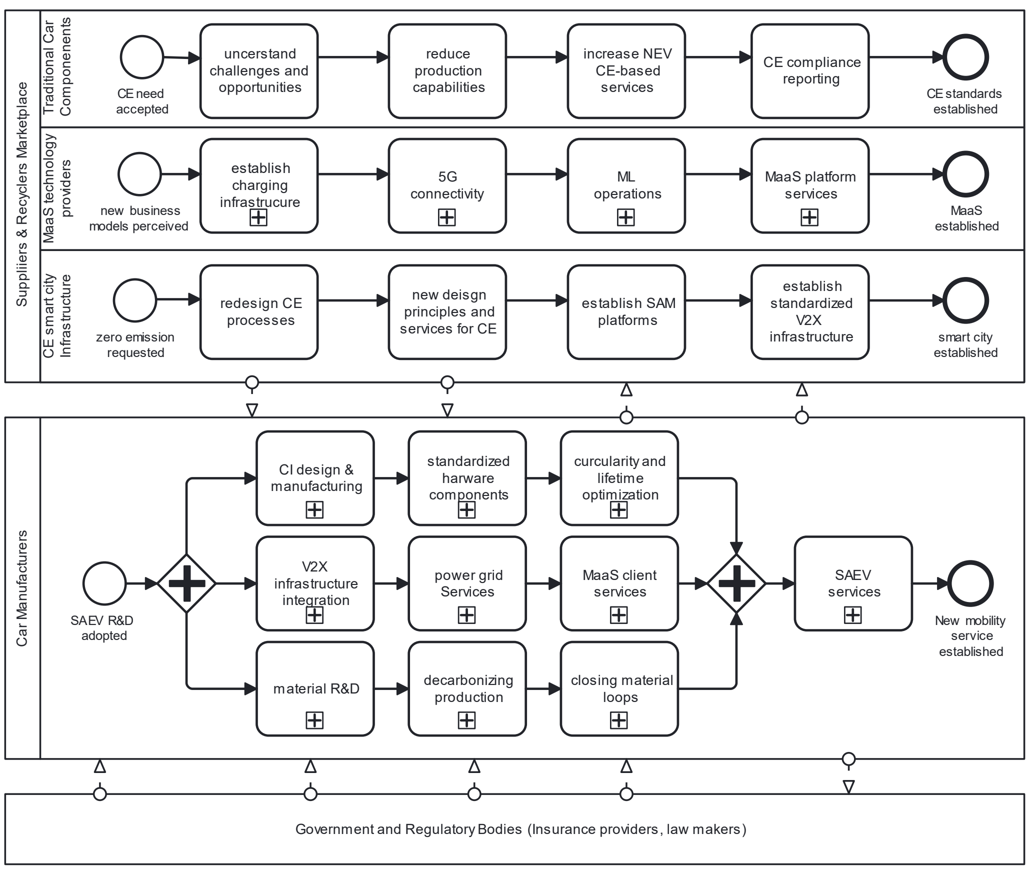

Fig. 3. Mid-term Scenario: Coexistence of AV and HDV

Mid-Term Scenario: Coexistence of AV and HDV: This scenario is characterized by having around 50% of the market by Shared Autonomous Electric Vehicles (SAEV) in Level 4 with the remaining 50% being Human Driven Vehicles (HDV). Many highways now have dedicated lanes for AV, which all move at the same constant speed, with less fuel consumption and almost no congestion. Most car manufacturers have adopted to new SAEV Research and Development (R&D) approaches, which are represented in Figure 3. As the majority of the key components of modern vehicles are using highly sophisticated software, increasingly communications such as Machine Learning models and contemporary software engineering best practices will have to be incorporated into new car designs.

Long-term Scenario: fully established SAEV and CE: This long-term scenario (see Figure 4 below) shows the potential for establishing new services and new business processes between some of the new, emerging stakeholders.

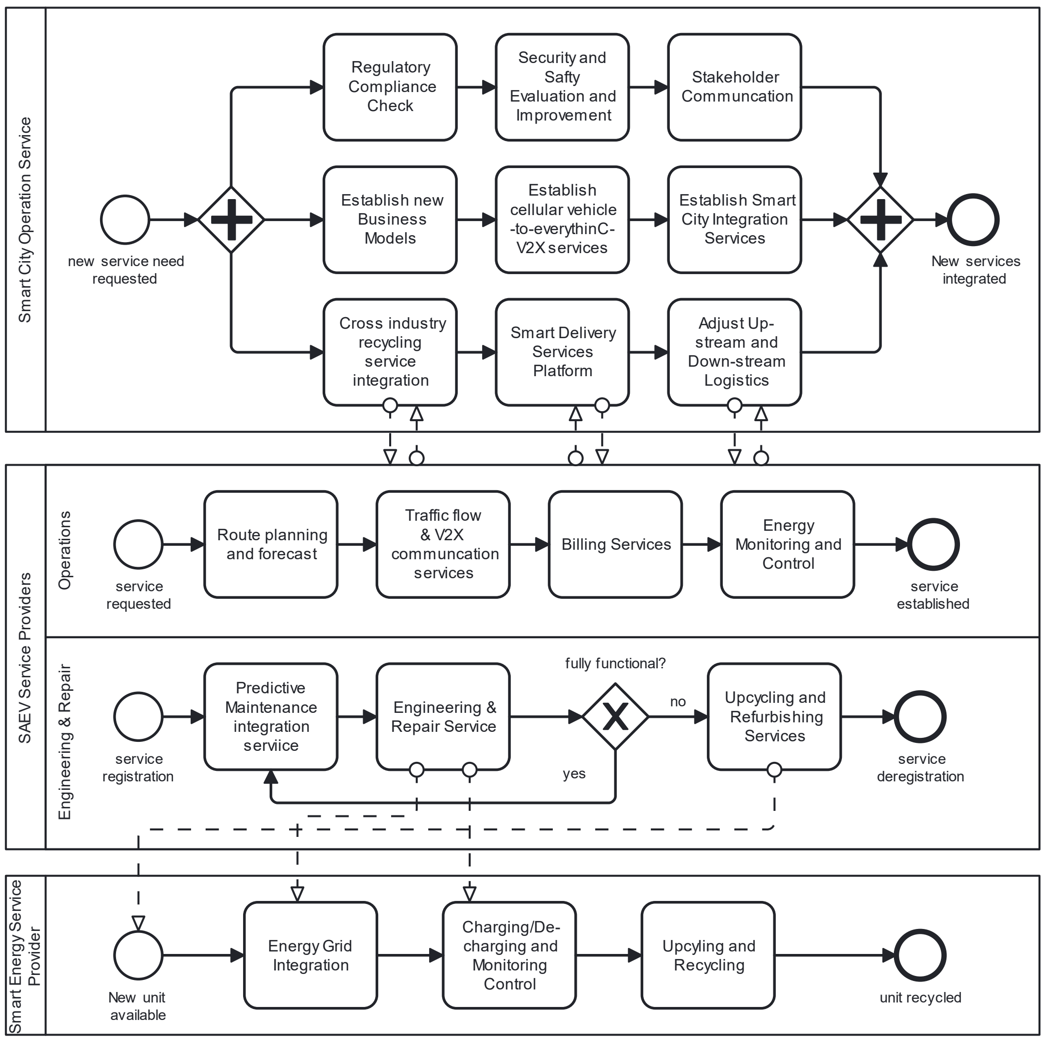

Fig. 4. Long-term Scenario: fully established SAEV and CE

Envisioning the scenario of fully-established AV and CE services, such as addressed by Quentin et. al (2023), who explore how AV can contribute to the transition towards the CE in the Rhine-Main Region in Germany has started already. From their albeit local perspective, they point out the important role of transport planning practices, including shared mobility services and the redistribution of road space and a broader view on transport development and demand management. On the other hand, there are many articles, that envision the role of AV in the CE, and they often discuss their potential to reduce waste and resource consumption by reusing, repairing, and recycling materials and products (Willams et.al, 2020).

Discussing further the long-term scenario of SAEV and CE, cities are establishing their Smart City Operation Services which include new governance aspects, new business models around the V2X and new cross-industry up and down-stream logistics which are necessary for the local support of the CE. These three different kinds of activities are visualized as three parallel lines and allocated to the Smart City Operation Services pool as can be seen in Figure 4. Car manufacturers have undeniably implemented their transition to smart SAEV mobility service providers. They not only drive the operation of the transportation services, which needs to be integrated with the Smart City Operation Services, but have also established CE principles, which are in part inspired by the aforementioned LEGO metaphor. Their entire fleet is under AI-based predictive maintenance observation where each of the parts can be repaired or upgraded on demand to the new requirements of the Smart City Operation Service. All cars and therefore all components need to be designed for much more robustness and thus longer operational lifetimes.

This scenario also models the dependency of the SAEV mobility service providers to other potential independent service providers such as battery manufacturers, who now also offer their batteries as services. As mentioned in the beginning, cars are increasingly complex ultimately and all LEGO-type components will also be provided as a service. In case the of batteries, they are also constantly monitored, charged, recharged and thus integrated into the energy grid of the city. Once the end of life for a car has been reached, its batteries could still be upcycled as energy storage for different purposes where the degradation of their function could still be tolerated.

5. Examples from Car Manufacturers

As mentioned previously, the transition towards electrification, autonomous driving, and circular economy as part of the sustainability strategy to rethink cars for greater sustainable mobility has become a focal point for global car manufacturers. They are strategically and increasingly aligning their product portfolios to realize this paradigm shift towards sustainable and technologically advanced practices, mainly to achieve carbon reduction targets but also not to lose market shares to innovative competition, especially from China.

It must be understood that electrification now stands as a cornerstone for reducing carbon emissions and our dependence on fossil fuels. Car manufacturers such as BYD and Tesla already offer an electric-only product portfolio. Other car manufacturers such as the BMW Group, the Mercedes-Benz Group, Volkswagen, or the Volvo Car Corporation are transforming their product portfolio into an electrified assortment, with each of them defining their individual targets. For instance, the Volvo Car Corporation wants to transform into a fully electric car company by 2030 by offering electronic cars only (Volvo Fully Electric, 2024). The Mercedes-Benz Group is preparing to offer electric-only cars by the end of this decade if market conditions allow (Mercedes-Benz, 2021). Table 1 provides more comprehensive targets and statements by car manufacturers regarding electrification. Whereas electrification is quite concrete, and this realization is already (at least partly) in place, the integration of autonomous driving

Table 1. Targets and statements regarding electrification and circular economy by global car manufacturers

Car manufacturer	Electrification	Circular Economy	Sources
BMW Group	"Electric mobility is among the major topics driving the ongoing transformation in the automotive industry. […] Our electrified vehicles are playing a major role in reducing fleet emissions and thus achieving our ambitious strategic carbon reduction targets."	"[…] the BMW Group has defined circularity as a strategic focus area. Our aim is to gradually bring the company closer to the ideal of the circular economy. From raw materials to recycling, we have the entire value chain in our sights"	BMW Group Electromobility, 2024; BMW Group Circular Economy and Circularity, 2024
BYD	BYD is the world's first carmaker to stop the production of fossil-fueled vehicles.	"BYD advocates the development of a circular economy, actively explores ways to improve the resource utilization and reduces the total use of packaging materials."	Times, 2022; BYD, 2022
Mercedes-Benz Group	"Mercedes-Benz is getting ready to go all-electric by the end of the decade, where market conditions allow."	"The overarching goal of the so-called circular economy is to keep as much as possible of the raw materials used in circulation."	Mercedes-Benz, 2021; Mercedes-Benz, 2024b
Volkswagen	"The battery is a key component in an electric vehicle, and an important cost factor. […] At the heart of this strategy is the new unified cell, which […] will be used in up to 80% of Group models by 2030"	"Volkswagen has anchored circular economy as a focus topic […]. Cross-divisional and cross-brand working structures have been developed at the Group level for managing the topics to be developed."	Volkswagen Group Strategy, 2024; Volkswagen Group Sustainability Report, 2023
Volvo Car Corporation	"Fully electric by 2030. […] by then we want all our new cars to be pure electric."	"…we're aiming towards becoming a circular business by 2040 – minimizing our use of primary resources"	Volvo Fully Electric, 2024; Volvo Sustainability, 2024

technology is currently being tested and is seen to be revolutionizing the automotive landscape, including all the underlying business models and the customer's mobility experience (e.g. Mercedes-Benz, 2024a, Volkswagen Group Strategy, 2024).

With respect to CE, targets and ambitions are, to a certain extent, already incorporated into corporate strategies and budgets and mostly reported in corporate, social responsibility (CSR) reports. However, huge differences among the car manufacturers concerning the extent of their ambitions and their commitment to these measures can be observed. Also, some car manufacturers limit their circular economy practices to only selected vehicle components or focus only on some minor aspects, e.g. on packaging materials. To illustrate, the BMW Group distinguishes the circular economy into four different aspects. Firstly there is the design and development-enabling recycling at the end-of-life of the vehicle. Secondly, the supply chain and production approaches aim to increase the usage of secondary materials. Thirdly, there is a vehicle use phase focussing on the usage of recycled paper as a kind of resource-efficient packaging in the aftermarket business, as well as, on bringing components back into the re-use cycle. Fourthly, and finally, the end-of-life phase considers remanufacturing and recycling as a source of secondary raw materials (BMW Group Circular Economy and Circularity, 2024). The following table provides greater insights into the respective electrification and circular economy ambitions of five major global car manufacturers. The Volvo Car Corporation adds even more concrete measures and key performance indicators to its ambitions. Currently, 36 different component groups (such as engines, gearboxes, or clutches) are remanufactured, aiming at 35% recycled content in new car models by 2030 (Volvo Sustainability, 2024). On the other hand, the BYD CSR Report 2022 informs us that, under the section of green procurement and circular development, BYD is actively exploring ways to reduce resource utilization, focusing on the total use of packaging materials (BYD, 2022). Observing these declarations in Table 1, it is fair to conclude that car manufacturers are currently in the infancy phase of AV and CE and there is a long way to go to realize full integration of SAEV and CE.

6. Conclusions and Outlook

This paper addressing the subject of rethinking cars for more sustainable mobility has presented a literature review of the current state of autonomous driving and circular economy and their necessary infrastructure, presented three scenarios (short, mid, and long term) regarding the transition process towards fully-circular and autonomous mobility services, and provided insights into the global car manufacturers' targets for electrification and the circular economy. Based on this study, the following comments are offered:

Redesign*:* The motivation for this article arose from the fact that CE should be incorporated in all the lifecycle stages of AV, including planning, design, operation, maintenance, and disposal. In particular, great opportunities exist to incorporate CE in AV design. Thus, the new imperative is not only to create products with extended life cycles but also to rely on designs where parts can be repaired and brought back to the manufacturer at the end of usage.

OEM and the Circular Economy*:* A concise analysis of industry practices among global car Original Equipment Manufacturers (OEM) has been presented. It is evident that the CE concept is not yet nor nearly fully realized within current business frameworks. The explicit and mere mention of packaging material reduction in OEMs' CSR reports as a means to achieve CE goals highlights the urgent need for increased attention from researchers, industry practitioners, regulators and ultimately consumers. This will present opportunities for integrating CE practices into evolving business models and the transformation within the automotive industry. However, the current literature review is based on only a few OEMs and does not include other stakeholders from the automotive ecosystem. This should be investigated in depth in further studies.

Infrastructure*:* The literature review presented some deeper insights into different aspects of autonomous driving, specific thoughts about the circular economy, and the related AD and CE infrastructures aspects for both. This review also showed that AD and CE are not isolated topics as both require substantial additional infrastructure to be built.

Scenarios*:* The presented scenarios on the transition from the current state to fully autonomous vehicles with a circular economy reflect the experience of the authors - Western researchers based in Europe and

Canada - who have also had extensive experience working for Chinese organizations and/or living in China. We are aware that the elements of the presented scenarios may appear simplistic, given the complexity of the two systems involved (AD and CE) and the related technological, economic, and social considerations. Nonetheless, we believe the presented relationships between these two emerging systems are reasonable and provide evidence that CE and AD can lead us to rethink how we make cars to achieve a more sustainable mobility future.

Limitations: As most AVs are electric and, as such, require energy for not only charging but also for building the associated extensive IT infrastructure, future research should assess and evaluate whether the increased levels of energy consumption will offset environmental benefits. In addition, this paper does not factor in the time element or the possible adoption of Product-as-a-Service practices. That is, even if car producers design and produce truly circular AVs now, it will take at least ten years until that vehicle is possibly returned to be used as a secondary raw material.

References

(AS-WEF), A. S. and the W. E. F. (2020). Raising Ambitions: A new roadmap for the automotive circular economy. World Econonomic Forum. http://www3.weforum.org/docs/WEF_Raising_Ambitions_2020.pdf

Avelino, F. (2021). Theories of power and social change. Power contestations and their implications for research on social change and innovation. Journal of Political Power, 14:3, 425-448, https://doi.org/10.1080/2158379X.2021.1875307

Bauer, C. (2020). Life cycle assessment of cars: New web tool helps consumers and researchers. Paul Scherrer Institute. https://www.psi.ch/en/media/our-research/life-cycle-assessment-of-cars-new-web-tool-helps-consumers-and-researchers

Block, L., Herrmann, F., Wizl, J., Borrmann, D., Bratzel, S., & Böbber, F. (2024). Deutschland zum Innovationsstandort für das automatisierte und vernetzte Fahren machen: Herausforderungen und Maßnahmen zur Skalierbarkeit von automatisierten und vernetzten Fahrsystemen (AVF). Fraunhofer-Institut für Arbeitswirtschaft und Organisation IAO und Center of Automotive Management (CAM)

BMW Group (2024). Circular Economy and Circularity. https://www.bmwgroup.com/en/sustainability/circular-economy.html, accessed on 28 February 2024.

BMW Group (2024). Electromobility. https://www.bmwgroup.com/en/sustainability/electromobility.html, accessed on 28 February 2024

Braungart, M., McDonough, W. (2002). Cradle to Cradle. Remaking the way we make things. New York: North Point Press

BYD. (2022). BYD CSR report. https://www1.hkexnews.hk/listedco/listconews/sehk/2023/0328/2023032801987.pdf, accessed on 28 February 2024

Cobalt Institute. (2023). Retrieved from www.cobaltinstitue.org

Circular Flanders. (2024). Together towards a circular economy in Flanders. Retrieved from Circular Flanders - Hub of the Flemish Circular Economy (vlaanderen-circulair.be)

Duarte, F., & Ratt, C. (2018). The impact of autonomous vehicles on cities: A review. *Journal of Urban Technology*, 25(4), 3–18. https://doi.org/10.1080/10630732.2018.1493883

Ellen MacArthur Foundation. (2024). The circular economy in detail. https://www.ellenmacarthurfoundation.org/the-circular-economy-in-detail-deep-dive, 14 March 2024.
Goovaerts, L., & Verbeek, A. (2018). *Sustainable banking: Finance in the circular economy.* In F. Flachenecker, & J. Rentschler, Investing in Resource Efficiency: The Economics and Politics of Financing the Resource Transition (S. 191-209). Heidelberg: Springer.
Handelsblatt. (2023). Die E-Auto-Krise ist ein Armutszeugnis der deutschen Autoindustrie. https://www.handelsblatt.com/meinung/kommentare/kommentar-die-e-auto-krise-ist-ein-armutszeugnis-der-deutschen-autoindustrie/29264280.html. Accessed on 21 December.
Hedges & Company. (2023). How many cars are there in the world in 2024?. Retrieved from https://hedgescompany.com/blog/2023/01/how-many-cars-are-there-in-the-world/
Iacobucci, R., McLellan, B., & Tezuka, T. (2019). Costs and carbon emissions of shared autonomous electric vehicles in a Virtual Power Plant and Microgrid with renewable energy. *Energy Procedia,* 156(September 2018), 401–405. https://doi.org/10.1016/j.egypro.2018.11.104
International Energy Agency (2021). The Role of Critical Minerals in Clean Energy Transitions, Report. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions
Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221-232. https://doi.org/10.1016/j.resconrec.2017.09.005
Law, M. (2023). Top-10-autonomous-vehicle-companies @ technologymagazine.com. Technology Magazine. https://technologymagazine.com/top10/top-10-autonomous-vehicle-companies
Li, Y., Zhan, C., de Jong, M., Lukszo, Z. (2015). Business innovation and government regulation for the promotion of electric vehicle use: lessons from Shenzhen. *China. Journal of Cleaner Production*, 134: 371-383. https://doi.org/10.1016/j.jclepro.2015.10.013
Makantasis, K., Kontorinaki, M. and Nikolos, I. (2020), Deep reinforcement-learning-based driving policy for autonomous road vehicles. I*ET* Intell. Transp. Syst., 14: 13-24. https://doi.org/10.1049/iet-its.2019.0249.
Manivasakan H, Kalra, R., O'Hern, S., Fang, Y., Xi, Y., and Zheng, N. (2021). Infrastructure requirement for autonomous vehicle integration for future urban and suburban roads – Current practice and a case study of Melbourne, Australia. Transportation Research Part A: Policy and Practice, 152, October 2021, 36-53.
Masiero, G., Ogasavara, M.H., Jussani, A.C., Risso, M. L. (2016). Electric vehicles in China: BYD strategies and government subsidies. RAI Revista de Administração e Inovação 13, 3–11. https://doi.org/10.1016/j.rai.2016.01.001
Mercedes-Benz. (2021). Mercedes-Benz electric drive. Mercedes-Benz Group. https://group.mercedes-benz.com/company/strategy/mercedes-benz-strategy-update-electric-drive.html, accessed on 28 February 2024
Mercedes-Benz. (2024a). Mercedes-Benz Autonomous. https://www.mercedes-benz.com/en/innovation/autonomous/, accessed on 28 February 2024
Mercedes-Benz. (2024b). Mercedes-Benz circular economy. Mercedes-Benz Group. https://group.mercedes-benz.com/responsibility/sustainability/resources/circular-economy.html, accessed on 28 February 2024
Mihalj, T., Li, H., Babić, D., Lex, C., Jeudy, M., Zovak, G., Babić, D., & Eichberger, A. (2022). Road Infrastructure Challenges Faced by Automated Driving: A Review. Applied Sciences (Switzerland), 12(7). https://doi.org/10.3390/app12073477

Nasr, N. (2016). A New Dynamic 2: Effective Systems in a Circular Economy. In Remanufacturing and the circular economy. 107–128. Retrieved from https://www.ellenmacarthurfoundation.org/publications/a-new-dynamic-2

Nogueira, A., Ashton, W., Teixeira, C., Lyon, E., Pereira, J. (2020). Infrastructuring the Circular Economy. Energies 2020, 13, 1805. https://doi:10.3390/en13071805

Onat, N. C., Mandouri, J., Kucukvar, M., & et al. (2023)1. Rebound effects undermine carbon footprint reduction potential of autonomous electric vehicles. Nature Communications, 14, 62583. DOI: 10.1038/s41467-023-41992-2

Quentin, P., Buscher, J., & Eltner, T. (2023). Transport planning beyond infrastructural change: An empirical analysis of transport planning practices in the Rhine-Main region in Germany. Sustainability, 15(13), 10025. https://doi.org/10.3390/su151310025Times, G. (2022). BYD becomes first carmaker to suspend output of fossil-fueled models—Global Times. https://www.globaltimes.cn/page/202204/1257571.shtml?id=11, accessed on 28 February 2024

S&P Global. (2023). S&P Global Mobility forecasts 88.3M auto sales in 2024. Retrieved from https://press.spglobal.com/2023-12-14-S-P-Global-Mobility-forecasts-88-3M-auto-sales-in-2024, accessed on 15 March 2024.

The Guardian. (2023). Young Europeans more likely to quit driving and have fewer children to save planet. https://www.theguardian.com/world/2023/oct/25/young-europeans-quit-driving-fewer-children-save-planet-climate-crisis. Accessed on 21 December 2023

The Market. (2023). Wir werden einen Auto-Tsunami aus China erleben. https://themarket.ch/interview/joerg-wuttke-wir-werden-einen-auto-tsunami-aus-china-erleben-ld.10037. Accessed on 21 December 2023

The Straits Times. (2023). Indonesia defends its curbs on nickel ore exports amid EU claim of breach in international trade. https://www.straitstimes.com/asia/se-asia/indonesia-defends-its-curbs-on-nickel-ore-exports-amid-eu-claim-of-breach-in-international-trade. Accessed on 20 December 2023.

Valadares Montemayor, H.M, Chanda, R.H. (2023). Automotive industry's circularity applications and industry 4.0. Environmental Challenges 12 (2023) 100725. https://doi.org/10.1016/j.envc.2023.100725

Volkswagen Group (2024). Autonomous Driving. (2024). https://www.volkswagen-group.com/en/strategy-15955, accessed on 28 February 2024

Volkswagen Group (2023). Sustainability report. https://www.volkswagen-group.com/en/publications/more/group-sustainability-report-2022-1644, accessed on 28 February 2024

Volvo Cars (2024). Fully electric. https://www.volvocars.com/intl/v/sustainability/highlights, accessed on 28 February 2024

Volvo Cars (2024). Volvo Sustainability. (2024). https://www.volvocars.com/intl/v/sustainability/circular-economy, accessed on 28 February 2024

Williams, E., Das, V., & Fisher, A. (2020). Assessing the sustainability implications of autonomous vehicles: Recommendations for research community practice. Sustainability, 12(5), 1902. https://doi.org/10.3390/su12051902

World Economic Forum (2020). Raising Ambitions: A new roadmap for the automotive circular economy. Circular cars initiative business model cluster.