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Review

The Role of the Circular Economy in Road Transport to Mitigate Climate Change and Reduce Resource Depletion

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Abstract: The transport sector is responsible for several environmental impacts, including contributions to climate change through greenhouse gas emissions and depleting natural resources. A strategy to reduce these issues goes towards the application of a circular economy, a concept that offers a response to increasing concerns about resource scarcity and the associated impacts from their use. Thus, this paper aims to fill a gap in the literature that consists of the scarcity of studies that consider the circular economy application on a micro, meso, and macro level in road transport, including all stages as well as the 7 Rs of the reverse cycle. Therefore, an approach is presented to meet road transport needs, highlighting best practices obtained through a literature review, to promote climate change mitigation and resource depletion. Qualitative data were presented for each circular economy stage with 46 best practices identified, providing invaluable guidance to transport decision-makers. Thus, public policies focusing on all of the CE stages should be taken into consideration, not only those responsible for closing the cycle, such as waste and recycling or disposal and treatment.

Keywords: circular economy; sustainable development; road transport; best practices; climate change mitigation; resource depletion

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1. Introduction

With climate change affecting all of world's regions and with resource scarcity exacerbated by global population, urbanization, and economic growth, a transition that prioritizes sustainability is recognized as critical and urgent [1,2]. In this context, the 2015 Paris Agreement "aims to strengthen the global response to climate change threat with efforts to limit global average temperature to below 2 °C, preferably to 1.5 °C above pre-industrial levels" [3], where greenhouse gas (GHG) emissions linked to anthropic causes must decrease 40–50% by 2050 to prevent warming exceeding 2 °C [4]. Recently, during the UN Climate Change Conference in Glasgow (COP26) in 2021, it was identified that although there is a collective political will to meet the goals of the Paris Agreement, the current climate plans implemented by member countries are still far from meeting the Nationally Determined Contributions (NDCs) [5,6]. The Glasgow Climate Pact calls for all countries to submit stronger national action plans by the year 2022, instead of 2025, which was the original schedule.

Thus, the GHG emissions from the transport sector is a relevant factor to be considered. While important for urban mobility, road transport is also a major user of carbon-based fuels [7]. Over 60% of all oil consumed in the world goes to the transport sector, of which 76% is consumed by road travel [8]. This is especially true in an urban context since 15% of the total energy worldwide is used for urban passenger and freight transport [9]. This reality may become even worse because it is estimated that the urban global population will reach 68% by 2050 [10].

In terms of direct CO_2 emissions from fuel combustion, transport is responsible for 24%, with road vehicles accounting for nearly three-quarters of this total [11]. The transport sector currently emits about 9.7 $GtCO_2eq$, and if no mitigation policies are implemented, transport emissions could reach around 10 to 18 $GtCO_2eq$ in 2050 [12]. Changes in transport, such as efficiency improvements versus maintaining the business-as-usual scenario, is a choice that will influence communities, regional economies, and other variables [7].

A response that should reduce the adverse impact on the natural environment is found in CE principles' employment, which can be a path to change in the contemporary system of production and consumption [13]. CE principles comprise means to support both economic growth and sustainable resource management and offer a positive opportunity for change [14], due to the increasing concern for sustainability [15] and linked environmental impacts, such as resource waste [16] and GHG emissions [13].

Acceptance by national and subnational governments of the Paris Agreement framework together with circular economy (CE) strategies are essential to understanding its potential effect on climate change mitigation [17]. In terms of the necessity of increasing ambition to reduce GHG emissions, some countries have announced phasing out sales of new internal combustion engine vehicles. As well, the number of countries announcing pledges to achieve net-zero emissions by 2050 is growing [18].

This study undertakes a literature review of the recent CE concept applied to transportation in view of providing consolidated information to support strategies that assist transport decision makers to adopt best practices and minimize the impacts of the road transport sector on sustainable development. In particular, the review focuses on GHG emissions, maintaining products and materials in use, regenerating natural systems, representing a systemic change that builds long-term resilience, and providing environmental and social benefits. Haddach et al. [19] conceptualize best practices as processes, techniques, technological innovations, equipment development, or resources capable of promoting the relevant enhancement of quality, cost, safety, performance, environment, and any other concept that impacts society.

It is worth noting that new technologies, such as electric or hydrogen-powered vehicles are used as best practices for promoting CE stages considering the road transport sector in a general context; however, a specific analysis for each of these vehicle types is not performed and this is a limitation of the study.

Subsided by the literature review, this paper presents the CE stages applied to transport, the life cycle stages of vehicle production and operation, as well as energy consumption and a framework of the best practices existent in literature to be applied at micro, meso, and macro levels in a transportation system. The paper also aligns all CE stages to the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs) [20], within which this study is mainly related to "affordable and clean energy" (Goal 7), "sustainable cities and communities" (Goal 11), "responsible consumption and production" (Goal 12), and "climate action" (Goal 13). The relevance of this study is in addressing a subject of global amplitude, which has been the subject of debate in reports such as the IPCC (2022), which still lacks related research, especially regarding the CE stages that, although not responsible for closing the cycle, are of great importance in reducing GHG emissions and the depletion of natural resources.

To fulfill our objectives, in addition to this introductory section: Section 2 presents a conceptualization of CE, highlighting its advances concerning linear economy; Section 3 shows how the methodological process was carried out to effectively conduct the literature review, pointing out the main gaps identified in knowledge; Section 4 presents a complete CE cycle proposed by authors and also highlights the best CE practices identified in the literature that can be implemented by transport decision makers, as well as the 7 Rs of reverse logistics; Section 5 describes in detail each of the best practices outlined in Section 4;

and finally, Section 6 presents the final considerations, which also contain proposals for future studies.

2. Theoretical Backgrounds

In this section, the main concepts of CE are presented utilizing a comparison with the linear economy. In addition, the basic CE stages considered in this study are also defined. Both scholars and practitioners claim that consideration of CE is useful for spurring sustainable development [21], thus "it is imperative to provide a comprehensive review of the CE concept" [1] which has been introduced as "an economic model for the transition from the linear to the circular system" [22]. For many years, the description of the linear economy (Figure 1) as "take, make, waste" has been broadly recognized, but nowadays, a new concept has emerged [23].

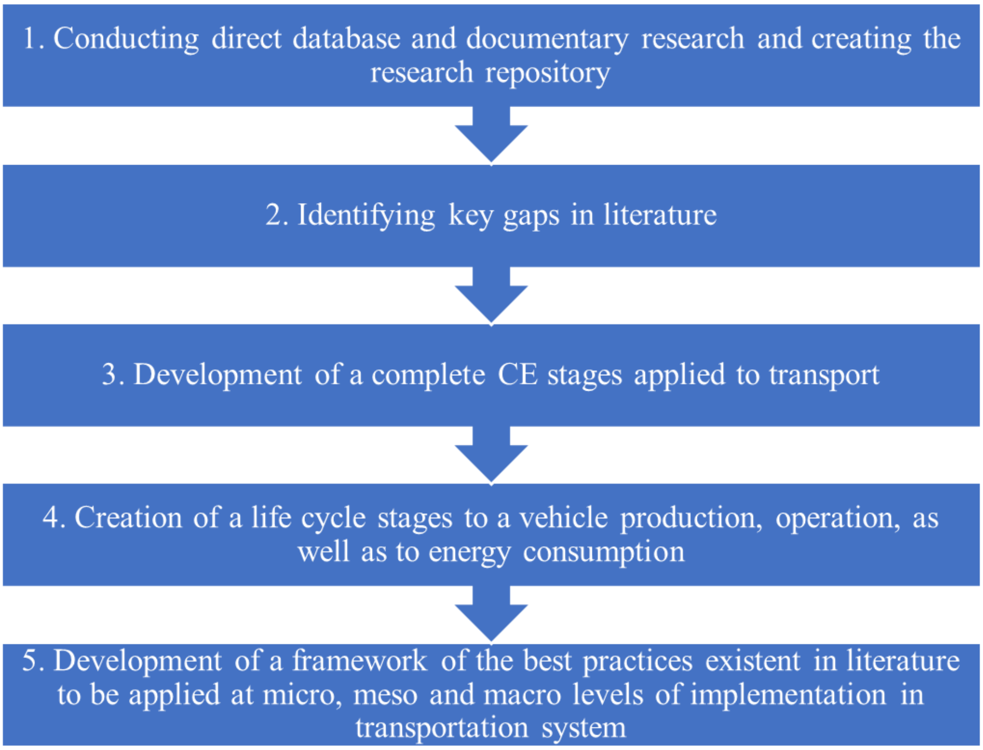

Figure 1. Steps of literature review.

In general, the linear economy's constraints are overcome by CE since it promotes cyclical flows of resources in the production-consumption system [24], thus moving towards sustainability [25]. The circular model is an economic system that promotes maintenance activities, sharing, leasing, reuse, remanufacturing, and recycling within closed loops to promote sustainability in management throughout the system's life cycle [26].

CE aims to reproduce the circularity of ecosystems "by transforming wastes into resources, establishing a closed material cycle through minimization of dissipative emissions, dematerializing products and economic activities and decarbonizing energy" [24]. Ghisellini et al. [27] found in the literature that the CE concept root originated from ecological and environmental economics and industrial ecology. Different meanings have been used to describe CE with the concept of a cyclical closed-loop system as a common point [28].

In short, CE is a holistic system that serves a waste-free production-consumption system in such a way as to reduce the consumption of natural resources and energy. CE is a concept of creating value through the rational use of resources to minimize the adverse environmental impact of our societies at all phases of a product life cycle, which enables the used products to be collected and reused, recycled, or remanufactured [13].

The CE can be applied at different levels: (i) micro: single process; (ii) meso: eco-industrial parks; and (iii) macro: local, regional, and national economies [27,28]. The micro level is related to CE implementation by a company of cleaner production and industrial ecology [29] and ecodesign [27] practices. The meso level regards the network between companies leading to industrial symbiosis [28,29]. The application at the macro level regards legislation to promote zero waste programs, eco-cities, and collaborative consumption [27].

3. Methodology and Gap Analysis

This section describes the procedure used to conduct the literature review, focusing on relevant and current studies on the subject, as well as highlighting the main knowledge gaps that the study intends to address. A review of transport-related best practices for each CE stage was completed, prioritizing international studies and reports selected from the literature, as shown in Figure 1.

The literature search was performed in Web of Science and Scopus databases by using a search guided by topics "road transport*" and "circular economy". Additionally, documentary research was conducted as a complementary source for gathering best practices, wherein reports and guidelines were considered. It is worth noting that the choice of keywords and their combinations considered a brainstorming process to choose the most relevant keywords. Subsequently, a team composed of academics and professionals in the transport field refined these keywords to provide solid validity.

However, since initial research in databases provided a very limited number of relevant studies that were directly applicable to transport and that considered vehicle parts and components, operation, and emissions, one increased the research field by using other relevant terms to road transport such as "vehicle", "automotive industry" and "supply chain". Figure 2 illustrates the intersection between the main themes of the article and guided the authors to identify the keywords used and their combination using Boolean logic operators.

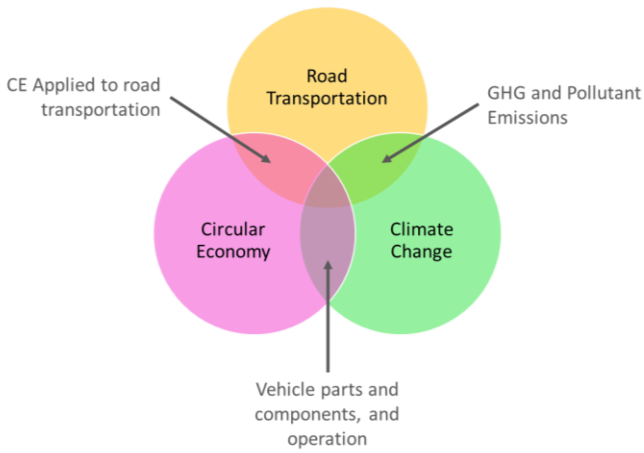

Figure 2. Keywords used in the queries for the literature search.

Thus, 42 studies were identified with the quality and applicability necessary to be incorporated in the research repository, consisting of 40 articles and 2 reports that address CE application or, at least, the closed-loop concept in road transport, which assists in mitigating climate change and reducing resource depletion. Although the focus of this paper is not to carry out bibliometric approaches to research repositories, it is worth noting that a gradual evolution of the topic was perceived, mainly from 2015 on, with a peak in the number of publications in 2019, which accounts for 26% of the studies; however, papers in 2022 are still being published. In addition, studies based on the closed-loop concept were widely used in the 90s.

The fact that 80% of studies were published in the last four years points to the relevance of the topic and indicates that it will be fruitful for new research. Additionally, these studies were published in important periodicals, such as the Journal of Cleaner Production, which accounts for 24% of publications considered here.

The bibliometric analysis also indicates investigations in several areas that seek to identify how to incorporate CE concepts in road transport (and are published in relevant periodicals) in topics such as waste management (Waste Management, Resources, Conservation & Recycling, and Journal of Material Cycles and Waste Management), energy (Energy, Journal of Energy Storage, and Energy Reports), and environmental science (Journal of Environmental Sciences, Sustainability, and Journal of Environmental Management).

Nonetheless, it was also found that transport as the main subject was considered by only around 62% of the studies. Most of the studies are concentrated mainly on the last CE stages: waste and its disposal and treatment, and recycling as the most considered of the 7 Rs, as shown in Figure 3.

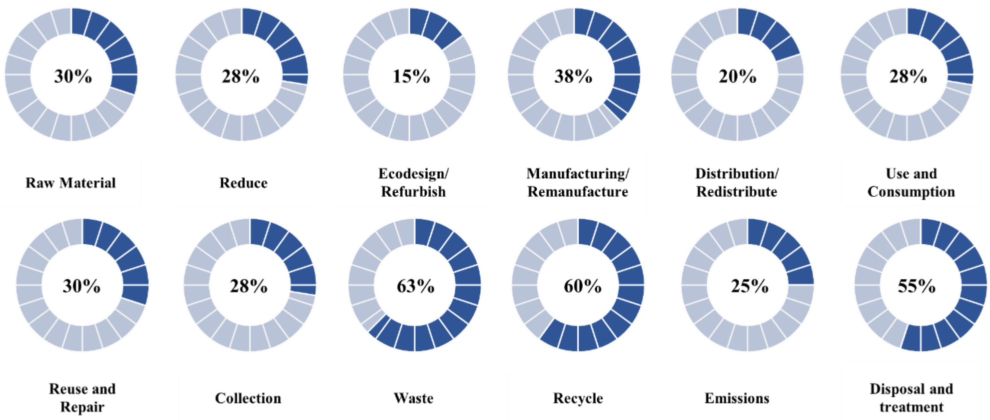

Figure 3. Percentage of studies by CE stage.

However, although the best practices to achieve a circularity in the last CE stages are relevant, others with the same purpose can be found in studies wherein other CE stages are considered, e.g., best practices applied to manufacturing can facilitate future remanufacturing. The application of best practices at each cycle stage can help mitigate the impacts of climate change and resource depletion in the entire life cycle of the vehicle. Although these actions have a more specific application, they focus on one or two cycle stages, promoting a systemic benefit.

In addition, with a view of the identification of best practices that serve one or more stages of the cycle, other studies were selected that, despite not specifically addressing the CE concept, at least consider the closed-loop concept. This strategy was adopted specifically to fulfill the objectives of our research, which, differently from current literature, seeks to include all CE stages applied to road transport.

However, reduction, reuse and repair, and emissions stages are subjects that need more investigation considering the CE for road transportation and how that impacts climate change. It is noteworthy that the non-consideration of all stages does not concern just one application stage but the lack of an overview of the whole life cycle for transport required to achieve circularity and the impact of each CE stage on climate change. In addition, only approximately 62% of studies consider transport as the main subject. Other publications identified in complementary research indicate neither the application of the CE concept specifically to the transport life cycle, nor to the vehicle, fuel, or energy. The analyses of these studies are mostly focused on waste management and reverse logistics, wherein transport is only being used as a tool to optimize this process. This approach does not consider energy use, which in the context of transport operations does not generate waste, but GHG emissions and pollutants.

Policies used to promote best practices related to CE stages are another issue that should be considered. Saidani et al. [30] identified a lack of regulatory frameworks in the U.S., wherein neither quantitative targets for recycling light or heavy vehicles nor national regulations were created. Meanwhile, in Europe, the legislation is more consolidated and seeks to encourage the reuse of automotive parts, as well as the remanufacturing and recycling market associated with them. Nevertheless, policies are a key action lever to facilitate the entry of end-of-life vehicle components into appropriate circular loops.

Another obstacle is the difficulty in accessing standardized data by actors involved in the circularity process of vehicle parts at their end of life. The access to information on the extraction of raw material, original vehicle parts, component production [30], and data transparency are essential to facilitating the replacement with recycled parts demanded by the automotive recycling market at appropriate prices [29,30]. Policies related to air quality and climate change have been used to reduce pollutants and GHG emissions through the imposition of limits on regulated emissions from fossil fuel combustion.

4. Results

According to the literature review, the CE concept for transport could be divided into a first and second life cycle and should consider the final disposal for residues that cannot be recycled, as expressed in Figure 4. The first cycle considers eight stages: (1) raw materials; (2) ecodesign; (3) manufacturing; (4) distribution; (5) using and consuming; (6) collection; (7) waste or emissions; and (8) disposal and treatment. The reverse cycle is divided into the 7 Rs, which can be considered at more than one cycle stage: (1) reduce; (2) refurbish; (3) remanufacture; (4) redistribute; (5) reuse; (6) repair; and (7) recycle.

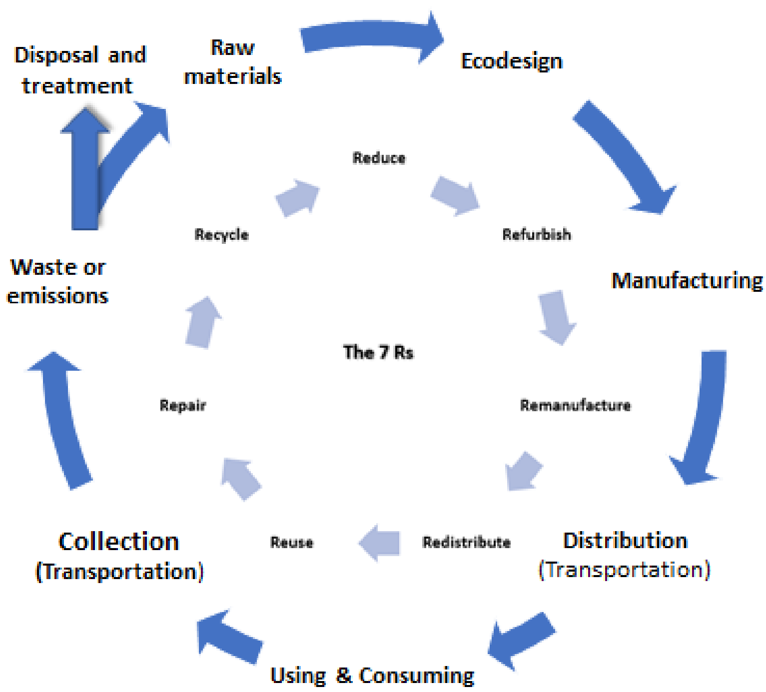

Figure 4. Circular economy stages applied to transport.

Table 1 provides an overview for each CE stage that will be further discussed in Section 4.

Table 1. Description of each CE stage considered in the research.

Stages	Description
Raw Materials	Raw materials are inputs usually extracted or produced from natural resources or obtained through the recovery or recycling of solid waste before final disposal [31], which allow activities such as transport to continue operating, mainly using energy [32].
Ecodesign	The first concept in ecodesign was established as the improvement of environmental aspects of the performance of the product throughout its life cycle, according to the Ecodesign Work Plan [33]. The product is thus designed to reduce the use of raw material and is created to last through its design life cycle and then be available for eventual reuse or recycling.
Manufacturing	Manufacturing is a process that can be sustainable if the concept of cleaner production is applied. This concept was defined by the United Nations Environment Programme (UNEP) as an integrated environmental strategy applied to the production process to increase ecoefficiency and reduce environmental impact [34].
Distribution	The distribution segment of the chain is positioned between the main manufacturer and final consumer, where it is more common to transport finished or partially finished goods in transfers between factory warehouses and their distribution centers or wholesalers' warehouses, which will distribute them to end customers [35].
Using and Consuming	The consumption process, together with production/distribution and vehicle use, supplement the concept of "end of life" by reducing, redefining, recycling, and recovering materials [36].
Collection	Collection and transport is a critical process of waste management [23], especially when considered together with concerns about social and environmental impacts related to emissions of pollutants and implications for the worsening of urban air quality due to fossil fuel consumption [9].
Disposal and Treatment	The treatments of a product are mechanisms that can help reduce the volume and toxicity of waste before disposal, and can be classified as biological, physical, and chemical [37]

Complementarily, a brief description of each of the 7 Rs of the reverse cycle is presented in Table 2.

Table 2. Description of each 7 Rs of the reverse cycle considered in the research.

Reverse Cycle	Description
Reduce	Reduction is the process of decreasing the exploitation of natural resources and energy consumption [13].
Refurbish	Refurbishing is the process of returning a product to good working condition, replacing or repairing major components that are defective or close to failure [38].
Remanufacture	Remanufacturing comprises activities to extend the life of the product through repairs, restoration, and upgrading [25].
Redistribute	Redistribution comprises the reverse logistics [39].
Reuse	"Any operation by which products or components that are not waste are used again for the same purpose for which were conceived" [40]
Repair	Repair consists of restoring existing items [38].
Recycle	Recycling is defined by product reprocessing and secondary material recovery activities used to manufacture new products [25].

The proposed overview of all CE stages aim to consider more than the closed loop stages' recycling strategy of the waste generated in the product's closed life cycle flux (cradle-to-cradle), that is, further studies should also give special attention to the application of best CE practices in other life cycle stages that are poorly investigated in the scientific literature, such as raw materials, ecodesign, and using and consuming, as already discussed in Section 3, especially when it comes to transport, which considers both energy consumption and the vehicle's life cycle.

The vehicle as a product entirely fits into the concepts of CE. On the other hand, the energy consumed by a vehicle, whether through fuel combustion or electricity, emits GHG and pollutants into the atmosphere that fit into the concept of CE, which also considers energy loop and emissions [27–30,41–43]. The CE concept has gained force due its connection to other strategies such as cradle-to-cradle design [29] and the life cycle approach. Figure 5 shows the life cycle stages of a vehicle's production and operation, as well as energy consumption, and a framework is presented that considers interactions between the well-to-wheel, cradle-to-gate, and the complete life cycle (cradle-to-cradle).

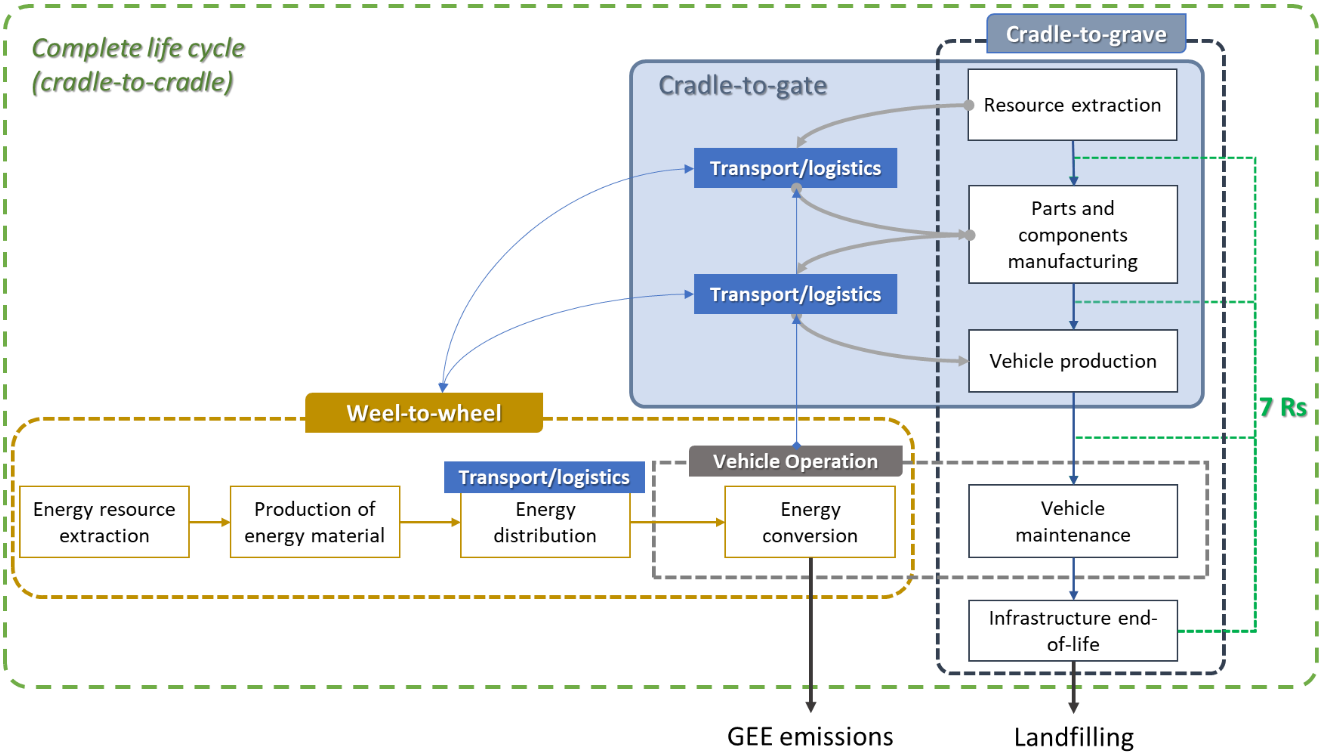

Figure 5. Life cycle stages of the transportation system, considering the flow for the production, operation, and EoL, as well as the energy consumption. Source: Bauer et al. [44].

The well-to-wheel LCA approach refers to the entire flow of energy consumed by vehicle operation and emitted to the environment in the form of GHG, from extraction and transportation to consumption in the vehicle operation stage. The cradle-to-gate approach refers to the production stage of the vehicle, considering the extraction of raw materials, production parts, and vehicle manufacturing, as well as the transportation of resources, parts, and components, until reaching the gate of the industry.

The cradle-to-grave approach is a wider concept, comprising the cradle-to-gate approach together with the distribution of the vehicle to consumers, the maintenance while it is in operation, and the EoL, then contemplating the waste management, and when necessary, their treatment and correct final disposal in landfills. It is worth noting that the 7 Rs are applied, in majority, at the EoL to ensure circularity.

The best practices found in the literature for each stage and the implementation level, as described in Section 2, are highlighted in Table 3 to assist decision makers in developing strategies that apply to all stages of the life cycle of road transportation and minimize

GHG emissions. The results of the application of the LCA tool allowed us to identify opportunities to improve environmental performance [45] in each stage, wherein CE best practices could be implemented to achieve circularity.

Table 3. CE-related best practices and their implementation level.

CE Stages	Best Practices	Implementation Level	Life Cycle
Raw Materials/Reduce	Utilization of secondary resource	micro	cradle-to-cradle (7 Rs)
	Investing in recycling technologies	micro	cradle-to-cradle (7 Rs)
	Increasing the use of recycled material	micro	cradle-to-cradle (7 Rs)
	Re-use of product such as second life of vehicle batteries in residential sector	macro	cradle-to-cradle (7 Rs)
	Look for new technologies for use of waste or coproducts as raw material	meso	cradle-to-cradle (7 Rs)
Ecodesign/Refurbish	Develop low aerodynamic resistance vehicle	micro	cradle-to-gate
	Use less raw material by rethinking the vehicle design	micro	cradle-to-gate
	Rethink propulsion system toward renewable and alternative energy use	micro	cradle-to-gate
	Choose materials that require energy efficiency in manufacturing processes	micro	cradle-to-gate
	Think more durable and better-functioning products	micro	cradle-to-gate
	Modularity that allows interchangeable parts	micro	cradle-to-gate
	Refurbish products to reincorporate them to the economic system, turning more attractive by updating it appearance	micro	cradle-to-cradle (7 Rs)
Manufacturing/ Remanufacture	Rethink the vehicle to use lighter material in manufacturing the vehicle to reduce fuel consumption in the operation	micro	cradle-to-gate
	Less energy and material consumption in production process	micro	cradle-to-gate
	Improve energy-efficiency in manufacturing	micro	cradle-to-gate
	Vehicles with materials that will facilitate reusing, recycling and dismantling	micro/macro	cradle-to-gate
	Policies to promote remanufactures	macro	cradle-to-cradle (7 Rs)
Distribution Transportation/ Redistribute	Implementation of distribution and freight consolidation centers	meso	cradle-to-gate and well-to-wheel
	Night-time collection and distribution and route optimization	micro	Operation (end use)
	Use of cleaner mode of transport and energy efficient logistics	micro	Operation (end use)
	Reduce necessity of delivery services by using new technologies, e.g., 3D printers	micro	cradle-to-gate
	Routing of a local delivery system configuration and use of information systems	micro	Operation (end use)
Use and consumption/ Reuse	Adoption of low Emission Zones in urban areas	macro	Operation (end use)
	Toll to fight traffic congestion	macro	Operation (end use)
	Sharing economy and collaborative consumption	meso	Operation (end use)
	Vehicle occupancy optimization	micro	Operation (end use)
	Use of different types of vehicles	micro	Operation (end use)

Table 3. *Cont.*

CE Stages	Best Practices	Implementation Level	Life Cycle
Collection Transportation/ Recollect	Optimization of the number of vehicles and containers	micro	Operation (end use)
	Route selection and optimization	micro	Operation (end use)
	Limited disposal in landfill	micro	Operation (end use)
	Techniques for computational optimization of transfer station	micro	Operation (end use)
	Digital connection mechanism with consumers	micro	Operation (end use)
Waste/Recycling and Emission	Increased recycling of vehicle components	micro/macro	cradle-to-cradle (7 Rs)
	Promoting emerging technologies for propulsion of vehicles with zero emission	Micro/macro	Cradle-to-gate
	Use of electric vehicles with fewer parts and components unlike the combustion engine	micro/macro	cradle-to-cradle (7 Rs)
	Establish policies and regulation for end-of-life vehicles (ELVs) and generating energy	macro	Cradle-to-grave
	Method to optimization of municipal solid waste treatment	micro/macro	Operation (end use)
	Renewable Transport Fuel Obligation (RTFO) alike laws	macro	Well-to-wheel
Disposal and Treatment	Guidelines and regulations for the disposal of EVLs and oil residues	macro	cradle-to-cradle (7 Rs)
	Standardization in procedure of dismantling and technologies	macro	cradle-to-cradle (7 Rs)
	ASR must be properly characterized before recovered	micro/meso	cradle-to-cradle (7 Rs)
	Energy recovery from the heat created at the incineration of combustible waste	micro	cradle-to-cradle (7 Rs)
	Techniques to minimize the costs of waste treatment, e.g., the use of computational optimization	micro	Operation (end use)
	Targets for reuse, recycling and recovery of EVLs	micro/meso/macro	cradle-to-cradle (7 Rs)
	Encouraging new vehicle design without heavy metals	macro	Cradle-to-gate
	Incineration as an alternative to reduce the volume of waste	macro/macro	cradle-to-cradle (7 Rs)

5. Discussion

It worth noting that some best practices adopted in one stage of CE can impact another, especially when it concerns the reverse flux, e.g., recycling batteries can reduce the need for raw materials extraction. Therefore, the CE framework proposed for the road transport system and the concept and *status quo* of each step are discussed considering the direct and inverse related flux.

5.1. Application of Circular Economy Stages to Transport

This section discusses the best practices identified in the literature that can be applied at each CE stage as well as the 7 Rs that reduce the impacts of the road transport sector on climate change and natural resource depletion.

5.1.1. Ecodesign and Refurbish

The concept of ecodesign can be extended from product development to design environments, logistic chains, or services [46]. Therefore, ecodesign itself can be considered a best practice. Ecodesign reduces resource consumption, promotes the use of recyclable materials, and avoids the use of hazardous materials, being a best practice of sustainable supply chain management [47].

To Al-Sheyadi et al. [46], ecodesign consists of generating more durable products or products and production processes less intensive in energy use, considering it as a best practice of green supply chain management. The changes in product design can be oriented toward the use of less raw material, or of energy sources that minimize emissions [48] and pollutants by designing the product to be easily disassembled, remanufactured, or recycled [46].

In that way, ecodesign considers the choice of materials that require energy efficiency in manufacturing processes; more durable and better-functioning products generate less waste, regulating the emissions of waste of the process system, and modularity allows the use of interchangeable parts that can be replaced in case of a defect, thus avoiding the exchange of the entire product, which also generates less waste. It also includes the design of products that are able to survive their life cycle and be reused for other functions after their first use.

Another best practice is refurbishing products and returning them to market in good condition, extending their life by replacing or repairing their faulty components. It is also recommended that their appearance be updated [38]. An example of best practices for transport considering ecodesign is to structure the vehicle to provide low aerodynamic resistance to decrease fuel consumption, or to rethink the vehicle propulsion system with a view of renewable and alternative energy use [49].

5.1.2. Raw Materials and Reduce

Urban sustainability is a model that contributes to improving people's quality of life, which is causally related to the needs and limits of natural resources [50]. The main challenges of this stage are minimizing the use of materials and increasing the reuse of natural resources [51].

The main raw materials required for vehicle production are: (i) metals, such as steel, aluminum, and copper, mainly responsible for composition of the body, chassis, and engine parts; (ii) glass; (iii) rubber, found mainly in tires; (iv) special fibers; and (vii) materials comprising other parts, such as batteries [52]. In the case of energy resources, the main sources of fossil energy are diesel and gasoline, and the main alternative and transition energy sources are electricity, gaseous fuels (natural gas, hydrogen, and liquefied petroleum gas), biofuels, such as alcohols (methanol and ethanol) and biodiesel, and others [53].

Important sources of secondary raw materials can be found in ELVs [54]. The use of this secondary resource, when aligned with the investment in recycling technologies and the increased use of recycled material, provides a promising prospect [55] and follows the SDG, which promotes flexible and resistant infrastructure, inclusive and sustainable industrialization, and the nurturing of innovation.

However, concerning the economic aspect, the costs of end-of-life operations—applying best available techniques to preserve high-quality recycling—are expected to become higher over the coming years, especially due to new materials and equipment required in vehicles and the vast expansion of the electric vehicle (EV) market [26].

According to Cusenza et al. [56], new ideas are being inspired by the construction and transport sectors for the reuse of EV batteries in residential areas, along with renewable energy generation technologies to match the highly renewable forms of electricity generation with demand.

In view of respecting the biogeochemical cycles concept that should be implicit in the CE [28], the rate of the removal flux of resources and their release into the environment should be minimized to become closer to the natural levels. In this line of thought, distinguishing renewable and non-renewable sources allows for the determination of the rate of extraction and emission toward the capacity for environment regeneration [29]. In the case of renewable energy, the rate of extraction must be lower than the capacity of absorption by nature. On the other hand, non-renewable energy exploitation should be lower than the rate of creation of new sources of clean and renewable sources [29].

Regarding energy use by vehicle operation, zero emission by energy transition goals aim to reduce fossil fuel consumption and seek new clean and renewable energy alternatives, such as the synthesis of liquid fuels from waste as a means of approaching the goal of zero landfilling [57] and closing the cycle, or the use of a coproduct of one process as a resource for biofuel production, e.g., the biodiesel production from the residual oil of the ethanol production process [58,59].

5.1.3. Manufacturing and Remanufacturing

A rethinking of product design and recycling are subsequently discussed. Changes in production processes are based on better process control, equipment modification, technology change, and changes in input materials [48]. Each of these changes can reduce energy consumption, improving the process's energy efficiency and consequently reducing emissions.

Among the techniques presented by El-Haggar [48], one highlights the practices that are aligned with the objective of this study, such as (1) changes in the production process to consume less energy and material, while also considering the reduction of losses and leakages; (2) rethinking the product design to consume less raw materials; and (3) recycling.

The industry was responsible for 24% of global emissions in 2018 [60]. Specifically, the automotive industry produced 9% of all annual global GHG emissions in the same year [61]. The automotive sector not only emits CO_2 directly from vehicle fuel combustion but also indirectly from vehicle manufacturing itself and the materials and parts supply chain [62].

Green manufacturing, as in the system proposed by Deif [63], is related to the eco-friendly production process wherein the environmental impacts are considered in the efficiency planning and control. Several studies pointed to the reduction of energy consumption as a best practice in manufacturing, i.e., making its production processes more energy efficient [64–67]. Practices to reduce electric energy consumption in manufacturing result in less GHG emissions, since the life cycle is considered, and emissions for electricity generation might be considered. A best practice that can be considered in this case is the use of clean energy, such as solar energy [66].

In addition, green manufacturing can also indirectly contribute to decreasing emissions of GHG. Specifically, this can be achieved by producing vehicles with materials that facilitate reusing, recycling, and dismantling [68]. Green manufacturing of vehicles can also contribute to employing a rethinking of materials used to produce lighter vehicles [49]. This contributes to more efficient fuel consumption and, consequently, reduced GHG emissions.

In addition to the aforementioned best practices, the remanufacturing process can also contribute to reducing climate change and reaching a country's SDGs [69]. According to the Ellen MacArthur Foundation [38], remanufacturing is "a process of disassembly and recovery at the subassembly or component level. Functioning, reusable parts are taken out of a used product and rebuilt into a new one". However, to achieve the needed demand at end-of-life resulting in increased vehicle sales, policies must be directed toward improving remanufacturing technologies and encouraging remanufacturing by the automotive industry [69].

The study developed by Saidani et al. [70] deals with the end-of-life of heavy vehicles and their second life since most of them are refurbished or remanufactured; for example, in the United Kingdom, about 50% are refurbished and 43% are remanufactured. Almost all the refurbished heavy vehicles are resold, mainly in developing countries. In Sweden, around 50% are resold after five years. However, the study has pointed to the disparities between developing and developed countries, since, even in Europe, remanufacturing activities are not completely organized; thus, in developing countries, resold vehicles at their end-of-life stage are probably not refurbished or remanufactured to extend their life.

5.1.4. Distribution Transport and Redistribute

Optimizing the system of distribution is necessary to promote CE and can be represented by modeling approaches for closing and slowing resource loops [71]. Ways to promote emission reduction include choosing cleaner transport modes, energy-efficient logistics, and do-it-yourself (DIY) devices (such as 3D printers), reducing the necessity for delivery services [72]. Throughout the material flow process, the use of refined distribution procedures to reduce transport requests and encourage recycling and reusing waste, e.g., through a closed loop, can further decrease waste and GHG emission [73].

As for distribution, the best practices reported in the literature, such as Barbosa et al. [74], involve such measures as a choice of facility locations, implementation of a distribution center and freight consolidation centers in urban areas, and distance reduction utilizing routing optimization, for example. They also cited the use of time windows and off-peak deliveries as strategic measures to reduce the impact generated by the distribution activity, such as night delivery, as well as an information system focused on problems such as tracking and monitoring the fleet.

Production return and distribution return comprise reverse logistics: production return involves the process by which firms might re-use, repair, or recover defective or superfluous products; distribution return can be represented by the removal from the market of an unsold product, or one not damaged during transport, as well as the redistribution from warehouses of products that can be renewed, such as pallets and packaging [75]. Therefore, reverse logistics is an important dimension of CE that enables the management of economic, social, and environmental challenges [71].

In addition, redistribution can include practices such as the reallocation of items or services no longer needed by some person or in some place [76]. This is considered together with collection, inspection, separation, reprocessing, and disposal as part of the recovery process category [77]. A redistribution system can be enhanced through a best practice, such as the reconfiguration of a local delivery system [78].

5.1.5. Use and Consumption and Reuse and/or Repair

The next set of studies outlined recommended practices for the use of urban vehicles in such ways as to reduce GHG emissions and air pollutants, exemplifying the consumption process:

- Low Emission Zones, prescribed by a law requiring drivers to have a special environmental sticker on their cars [79];
- A toll to combat traffic congestion implemented to discourage personal vehicle entry into urban centers and encourage people to use more efficient means, such as public transportation with increased availability [80];
- Use of the Friendly City concept to promote the development of comfortable living conditions and encourage citizens to stop using their cars, prioritizing a comfortable urban environment and a healthy city [81]; and
- Full or partial refund for the amount of electric energy used in the power supply to an employee using an electric or hybrid personal car, as well as taxation for the use of fossil fuel [80].

Based on Camacho-Otero et al. [36], collaborative consumption and sharing economy are ways to intensify the use of assets, valuing the use of idle resources rather than possession, and facilitating the reuse of products. The sharing economy can be conceptualized as a system where consumers give each other temporary access to the unused capacity of their goods, such as cars and houses, possibly for money [82].

Collaborative consumption is a series of resource circulation processes that help consumers obtain and supply, on a temporary or permanent basis, important resources or services through direct interaction with other clients or through an intermediary [83]. These actions happen in organized systems or networks, in which participants perform sharing activities in the form of rent, loans, and negotiation or the exchange of goods, services, transport solutions, space, or money [84].

The sharing economy is represented by activities such as: strengthening the use of durable goods, recirculating goods, sharing productive assets, and exchanging services [36]. Initiatives applied to transport include carpooling, car-sharing with or without a driver, and freight transport [85].

There is potential to reduce GHG emissions, as well as local air pollution, noise, traffic congestion, etc., due to the decrease in the use and production of private cars, since most of these initiatives are in cities whose problem with transport is greater. Among the environmental impacts caused by individual vehicles, production of automobiles through the extraction of raw materials; the transformation of materials and assembly of automobiles; replacement and production of spare parts, such as tires, batteries, lubricants, and coolants; fuel transformation processes that precede fuel consumption; and fuel consumption on the road are considered [85].

Other relevant best practices support reduced emissions, such as those indicated by Barbosa et al. [74]: (i) vehicle occupancy optimization, (ii) use of different types of vehicles to carry out deliveries and collections, (iii) shifting freight transport to cleaner modes (modal shift), (iv) use of vehicles with greater energy efficiency (fuel consumption), (v) use of alternative vehicles (propulsion systems), and (vi) reducing the weight of vehicles.

In addition, there are recommendations for the improvement of vehicle development: (i) the use of low rolling resistance tires, (ii) fleet renovation and modernization, (iii) promotion of improvements in vehicle aerodynamics, (iv) preventive maintenance of vehicles, (v) use of cleaner energy sources, and (vi) use of additives to improve the energy efficiency of fuels [86].

Additionally, integrated urban planning initiatives offer substantial opportunities for reducing the carbon footprint: a shift to public transportation can significantly reduce emissions; projects to upgrade bikeways and sidewalks can provide large emission reductions; the combination of rapid bus transit and walking offers potential for substantial mitigation of the CO_2 generated in urban transport, while lowering costs of mobility, and the adoption of a short-term and a long-term strategy for addressing carbon emissions are all important best practices [87].

5.1.6. Collection and Transport

End-of-life vehicle collection is a rapidly growing waste stream, so specific collection activities are required to avoid environmental pollution and resource depletion fed by the old linear economy model, "make-take-use-dispose" [88]. Thus, there is a variety of waste collection and transport methods aligned with CE [23]; improving the efficiency of this activity generally includes a reduction in the number of vehicles and containers involved in the process, and route optimization [89].

An important factor associated with waste collection and transport is urban traffic jams that interfere with the flow of the service fleet. Furthermore, garbage truck circulation can be responsible for delays in traffic flow and consequently generate additional congestion [90], especially when going through many roundabouts to the landfill [84].

Another consideration is economics, where the aim is to minimize the cost of collection and transport [23]. Economopoulou et al. [85] analyzed the contribution of waste transport, keeping in mind the minimization of annualized capital investment and annual operating cost of the entire waste treatment chain and taking into account financial incentives or disincentives, e.g., possible revenue from selling products or services. Concerning waste management systems, Das and Bhattacharyya [91] proposed an optimal waste collection and transport scheme focused on minimizing route length and considering the costs and profits involved.

Analyzing the environmental aspects of waste collection and transport, some studies considered factors such as route selection and optimization, as well as route length [23,92]. Several studies also addressed energy consumption and the emission of air pollutants, particularly CO_2, as an important indicator to be considered because of climate change [93–95]. Bektas and Laporte [93] presented an extension of the classical vehicle routing problem, with a broader objective function that includes total GHG emissions, and Demir et al. [89] performed a comparative analysis of several vehicle emission models to identify ways to minimize the harmful effects of road freight transport on the environment.

Moreover, transport planning from the point of waste collection to the landfill needs to pay particular attention to the correct assessment of the whole burden of the waste management systems [90]. Calabrò et al. [96] demonstrated that the effectiveness of waste management systems strongly depend on an integrated system that presents efficient separate collection, high energy recovery, and extremely limited landfill disposal. Under these circumstances, Chi et al. [97], e.g., analyzed the importance of the separate collection to the entire environmental performance of a waste system, and Pérez et al. [98], using the life cycle assessment (LCA) methodology, presented a calculation of the impact on climate change related to waste collection vehicles.

Another important issue that must be highlighted is the responsibility of the goods supply sector to promote reverse logistics for the customer, thus managing collection and return of any damaged or defective goods due to the need to exchange or the desire to cancel the purchase [99]. The use of technology, such as an omnichannel, which corresponds to a digital connection mechanism with consumers, is an example of a best practice that seeks to facilitate the return of products immediately in the delivery phase or from an agreed date and time, thereby, recovering products unsuitable for an intended purpose and at the same time reducing the number of unnecessary trips for collection [100].

It is also important to note that some best practices applied to distribution and transport can also be applied to collection and transport, such as night-time collection and distribution and the use of information systems to track and monitor the fleet, discussed in Section 5.1.4.

In addition, transport-related problems include waste collection, making it crucial to also consider indirect transport through delivery operations between transfer stations to and from the processing plant [86]. Thus, computational optimization techniques are fundamental to the development of a robust transfer station grid, which can be designed to deal with all possible realizations of future projects of transport infrastructure and technological solutions [101], as well as to optimize waste routing between the existing transfer stations and processing plants [91].

5.1.7. Waste and Recycle and Emissions

In the progress towards more sustainable urban policies, the waste management system is a highly challenging issue, because many regions worldwide use landfilling as a main waste disposal method, especially in developing countries [102]. Thus, waste management plays a fundamental role in a CE as it establishes a long-term path with long-term targets for decreasing the volume of landfilled waste and increasing recycling and reuse [90].

A key factor for proper waste management is knowledge about waste production and its trends. Specifically, regarding the generation of waste by road transport, the continuously growing population and urbanization and the intensive use of private vehicles seen in recent decades is causing waste from the ELVs to increase significantly [103], including items such as end-of-life tires [104]. There is, in addition, the rising consumption of resources used for vehicle propulsion and the resulting environmental pollution [105].

In order to assist with waste management, the United Nations highlights five key factors: (i) establishment of policies and regulations, (ii) support of institutions, (iii) adequate financial mechanisms, (iv) stakeholder participation, and (v) supporting technologies, which can be incorporated through diverse strategies, such as remanufacturing or retreading, and through the integration of the structure of reverse logistics [106].

In waste management, the major current environmental issues to be considered include not only proper treatment and disposal of waste but also the management of GHG generation by the system [107] and related cost impact [108]. Volume and physical composition of waste must be considered when exploring the correlation between urban waste management and GHG emissions due to differences in local environments and lifestyles that lead to a frequent variation in its amount and composition [109]. However, improving the waste management system is an expensive budget item, especially if adopted in developing countries [110].

Thus, waste treatment methods must be studied at the local level, considering facilities and peculiarities present in the region under analysis [109], as well as its budget for investment [110]. Furthermore, almost all waste management stages generate GHG emissions, making it necessary to design appropriate treatment methods, from source to final disposal, to reduce their environmental impact [107]. Specifically, for road transport, the impact on emissions from vehicles of waste collection is related to transport efficiency improvement and energy consumption reduction, which will permit urban solid waste management to achieve sustainability goals [109].

The environmental impact of waste management systems should be properly considered by authorities of both small and large cities to seek improvements, and thus fulfill waste policy targets [102]. The availability of information supported by valid and reliable methods is an essential condition for assessing the impact of these systems. LCA methodology is among those most commonly used for this purpose [90]. In addition, the concept of CE is complementary to key aspects on LCA, considering impacts and in turn solutions across the relevant systems [111].

In the transport sector, LCA research considers all of the environmentally significant processes throughout the vehicle life cycle [112], involving raw material extraction, component manufacturing, assembly, transport, distribution, vehicle use, and end-of-life treatment [113]. Thus, different propulsion technologies, including internal combustion, hybrid, plug-in hybrid, and 100% electric, were presented in various studies that focused on evaluating the eco-profile of vehicles [112].

For example, electric and hybrid engines are promising emerging technologies for propelling vehicles with the potential to reduce GHG emissions from road transport [114] since they are more energy-efficient than conventional internal combustion powertrains. In addition, with fully electric propulsion, there is zero direct emission, and thus no need for a tailpipe [115].

Electric vehicles also have considerably fewer parts and components than those propelled by a combustion engine. Thus, there is no necessity for any type of oil change, nor coolant water, nor sparking device, thus allowing less wear on the vehicle's engine components [116] and, consequently, prolonging their lifetime. These characteristics show that electric vehicles are an appropriate alternative for reducing emissions and waste generation.

Another technological alternative used to reduce GHG emissions from road transport is the use of hydrogen fuel cell vehicles. Hydrogen is an efficient clean energy carrier; thus, the fuel cell can generate direct current power to drive the vehicle. A more sustainable hybrid vehicle can be produced by integrating batteries and control system strategies along with a hydrogen fuel cell [117].

It is noteworthy that an adequate environmental assessment of different propulsion technologies (e.g., hybrid, plug-in hybrid, and 100% electric vehicles) requires investigation of all vehicle LCA stages (production, use, treatment, and disposal) across a wide range of impact categories [112] that represent environmental issues of concern.

Regarding emissions from the combustion of fossil fuels, carbon fixation from the atmosphere is possible through compensating actions, such as reforestation. However, more incisive technologies can be considered. According to WRI [118], direct air capture technologies aren't aimed at reducing emissions from industrial processes as proposed by carbon capture and storage (CCS) but remove carbon dioxide directly from the ambient air by chemical scrubbing.

Biofuels used in transport, such as sugar cane ethanol or biodiesel, have a closed cycle for GHG emissions and are considered the most suitable alternative fuel to displace the use of petroleum-based fuel. However, this closed-cycle does not consider non-carbon-based pollutants. The results of the study developed by Dias et al. [119] and Glensor et al. [120] show that the use of biofuels increased emissions of NO_x. Additionally, Moreira et al. [121]

inferred that augmentation of biodiesel blended in with diesel increases emissions of toxic elements that impact human health.

In addition, it should be mentioned that waste prevention through "Reduce, Reuse and Recycle" (3 Rs) represents one of the main directions of waste management in terms of CE, promoting the adoption of closing-the-loop production patterns within an economic system [122].

Since other Rs were addressed in previous sections, specifically regarding recycling, it is important to elaborate public policies and regulations for the development of an ELV collection and recycling network that covers most of the territory, promoting the proper dismantling of vehicles in authorized and well-distributed facilities [103].

Polices oriented to implement recycling practices is also important, such as the ELV Recycling Law [123] in Japan, created to promote waste collection and recovery by vehicle manufacturers and importers during the ELV recycling process, and also to apply recycling fees to be paid by vehicle owners and to provide processors registration and licensing [122], creating a new recycling system for proper processing and disposal of ELVs and their efficient use as resources [124].

Overall, main variations in environmental impact generated by vehicles have their origin in the distance between a disassembly plant and recycling plant and the nature of the vehicle components, such as the mass of the engine, fuel tank, parts, tires, wheels, battery, and remaining wreckage [125]. Specifically, for vehicle components, the recycling rate can be improved following separation and material selection techniques considered [126].

Ferrão and Amaral [127] indicated that separation of 68 parts, equivalent to 14% of vehicle mass and corresponding to a recycling rate of more than 80%, requires a total time of around one hour per vehicle and two employees dedicated to separating the components. In addition, gradual target regulation measures can be adopted for a more efficient recycling process, such as establishing a vehicle recovery rate [126].

Furthermore, according to Soo et al. [49], the steel recovery process through recycling and purification is responsible for increasing the environmental impact of its life cycle by 68% upon GHG-emission-related climate change. This indicates that even the recycling step in waste management can contribute to climate change and that investment should be directed towards new technologies for material recovery.

To solve, or at least minimize, problems from waste production and to stimulate the processes of prevention, recycling, energy, and material recovery in its disposal, it is necessary to promote system-wide planning within the supply chain, including the proper processing of waste and the definition of a structure for waste collection and transport. This could promote efficiency to reduce both total system costs and GHG emissions, based on actions for design optimization of municipal solid waste treatment related to waste management hierarchy, such as the method proposed by Šomplák et al. [128].

In addition, a strategic implementation of measures used to improve waste transport included in the CE stages can be defined based on (i) regulations; (ii) analysis of technical competence requirements for transport operations, waste management, and description; (iii) instructions for waste collection and transport in emergencies as defined by the Secretary of State; and (iv) encouraging the use of innovative technologies for a waste treatment capable of generating fuels and complying with laws such as the RTFO created in the United Kingdom [129].

5.1.8. Disposal and Treatment

Waste disposal has been a critical issue since the industrial revolution due to a significant increase in waste generation in cities [130]. According to IRP [131], material consumed by cities will increase from 40 billion tons in 2010 to 90 billion tons by 2050, which is more than the planet can sustainably accommodate. Thus, it is necessary to put into practice actions to minimize the adverse effects of the waste disposal process and its impacts on the environment [130].

Research and analysis of the actual situation of the management of ELVs is also important. An ELV is defined as a vehicle that is discarded by its registered owner as waste [132]. There are two losses involved in the absence of proper recycling and putting all the garbage in landfills: cost of disposal and cost of not selling this garbage [133]. For ELVs and oil residue disposal management, national guidelines and regulations can be developed and applied as a means of reducing environmental impacts [134].

Moreover, regulation development can be used as a best practice to forbid illegal channels of garbage collection and inadequate disposal, and allow manufacturers aligned with recycling facilities to recycle their products and those of competitors [26]. Citing an example of regulation in the transport sector, European Directive 2000/53/EC [135] has waste reduction that comes from disposal as its purpose and establishes goals for reuse, recycling, and recovery in vehicles' end-of-life phase [136].

About 75% of vehicle components are recyclable, especially metals, including aluminum, while 25% are characterized as hazardous waste [137]. In Europe, the major activity of the vehicle recycling system is metal recycling [135]. In Japan, car recycling has reached 95% [138]; in China, where the focus is mainly on scrap metal recovery and recycling, the rate is less than 70% [122]. In emergent countries, such as Brazil, only 1.5% of the fleet leaving circulation is recycled [139].

It is important to establish ELV management to avoid environmental pollution and to recover useful materials, mainly metals. Fluids and hazardous components, such as batteries, must be removed, then reused, and recycled. As opposed to metals, which can be easily and profitably be sorted, non-metallic residue, known as "car fluff" or "automotive shredder residue" (ASR), ends up in landfills in many European countries [140].

After metals, plastics are the most used vehicle material and comprise 7–9.3% of the vehicle mass [52]. The percentage of plastic is increasing in newer vehicles [141]. Vehicles are being dismantled at shredder facilities that recover some materials, and also produce ASR [137]. ASR contains plastics, rubber, textile and fiber material, wood, and glass, which cannot be recycled and represents 20–25% of vehicle mass [52]. ASR can be classified as heavy fluff or light fluff that comprises about 75% of ASR. Due to its heterogeneity of substances, ASR must be characterized before being recovered [52].

Addressing this need, a shredder trial campaign was developed and performed in Italy in 2008, aimed at verifying the achievable productivity and energy recovery efficiency of ELV reverse supply chain by a careful application of best practices of dismantling. In the final separation of metals and before automatic crushing, it was detected that 8% of metals and 40% of polymers could still be recovered and, in order to optimize this performance, greater standardization is required in the procedure of dismantling and also in the technologies adopted [140].

According to Vermeulen et al. [52], energy can be recovered from the heat created during the incineration of combustible waste. Incineration as a solution to reduce the volume of waste [13] is often the preferred choice in countries lacking space for waste disposal, especially in developed countries such as Switzerland, Japan, France, Germany, Sweden, and Denmark [142]. However, hazardous waste incineration is not viable in these places [143]. ASR is considered a hazardous material in Europe if it is classified as containing hazardous substances [144] and cannot be used in energy recovery, save for when flue gas treatment is used to avoid the emission of hazardous pollutants [52]. However, most of the ASR in Europe is still landfilled [144].

It should be highlighted here that waste-to-energy (WTE), defined as a treatment process for energy recovery from a waste source—such as mixed municipal waste—in the form of heat, electricity, or fuels useable in transport, can create synergies with energy and climate policy without compromising the achievement of higher rates of reuse and recycling [145]. Specifically regarding supply chains, WTE processes are an effective way to produce energy and, at the same time, minimize the use of landfill space. Thus, WTE supply chains address issues of energy demand, waste management, and GHG emissions in line with the CE system [146].

Some measures used to achieve sustainability of ELV recycling were presented by Berzi et al. [136]. The authors suggested targets for increasing the recycle-recovery rate of ELVs and, consequently, decreasing the amount of waste for disposal and treatment, through the following objectives: reduction of waste generation, particularly hazardous waste (including innovation in vehicle design and forbidding the use of heavy metals, such as mercury and cadmium); availability of nearby collection facilities (including sending the vehicle to authorized treatment facilities, ATS); and treatment of ELVs. This includes reliable storage for avoiding environmental pollution, dismantling (reusing and recycling), utilizing standard coding for materials and making available vehicle-dismantling information, and configuring report and information systems [26].

In addition, it is necessary to consider strategic planning for multi-commodity waste network flow problems. Thus, optimization techniques must be used to minimize the total costs of waste treatment, i.e., the processing cost and the transport cost [147], as well as to reduce their impact on the environment [148].

Šomplák et al. [147] used computational optimization to find the minimum total treatment cost of a multi-commodity network flow problem in which waste is transported from waste producers (municipalities) for its final treatment in waste processors (incinerators, mechanical-biological treatment plants, landfills). The model provides an ideal total waste flow along the roads, railways, and other channels.

Building on this work, Šomplák et al. [148] proposed a mathematical model to analyze a network flow problem that considers the contribution to global warming potential by waste producers. The model allows the identification of means to minimize total costs of waste treatment and reduce GHG emissions. Therefore, the method can contribute to achieving targets for emission reduction in individual regions and for specific producers.

5.2. Transportation Best Practices and Their Association to the Sustainable Development Goals

As discussed in Section 5.1, it is noted that CE can be applied to road transport to promote climate change mitigation and reduce resource depletion through the incorporation of best practices. Throughout all that has been presented, it is important to emphasize the importance of keeping resources extracted and transformed into products in the system in order to close the loop and achieve the integration of all CE stages.

Furthermore, the best practices identified in this paper are related to SDGs and the adoption of a sustainable transport system. In this context, encouraging the use of second life batteries and other more durable and better functioning and modular products in the transport sector is aligned with "responsible consumption and production" (Goal 12). Likewise, route optimization, efficient logistics, tolls to fight traffic congestion, and vehicle occupancy optimization contribute to "sustainable cities and communities" (Goal 11).

In the same context, reducing energy consumption in vehicle manufacturing and the RTFO are aligned with "affordable and clean energy" (Goal 7). Finally, actions such as guidelines and regulations for the disposal of ELVs and oil residues are best practices in line with "climate action" (Goal 13). In addition, it is essential to pay special attention to waste that cannot be treated and returned to the cycle and for which the only possible solution is disposal, providing a minimal impact on the environment, either in the emission of GHG or in its disposal in landfills.

In this study, the role of GHG emissions and air pollutant management is highlighted in the context of CE for transport. In addition, emissions from transport operations, which, unlike changes in vehicle parts and components, involve changes that are too complex to be conducted within a closed loop. Studies regarding pollutant emissions have pointed out the need for an extensive transition to more efficient and sustainable propulsion systems, capture technologies, and biofuel use.

During the literature review, studies on the CE applications in road transport focused mainly on stages that close the loop, such as waste and its disposal and treatment, disregarding other CE stages. Giving equal importance to all CE stages is needed to address all impacts on the road transport sector.

Considering high energy consumption and GHG emissions by the transport sector, CE stages oriented toward transport as well as the best practices that face these impacts are of prime importance. The contributions of this study remain in providing consolidated qualitative information from the literature to support transport decision makers in implementing ways to minimize waste and pollution emissions from the transport sector. In this context, to prioritize best practices through quantitative methods, Assis et al. [149] developed a methodology that applies SWOT analysis, sustainability balanced scorecard (SBSC), and the analytic hierarchy process (AHP), which could be applied to select best practices of each CE stage.

6. Conclusions

This paper addresses the CE concept for the transport sector and presents best practices that can support strategies to assist decision makers, given that strategy is still lacking in the literature. The concepts are divided into the first and second life cycles, presenting opportunities to close the loop. This study focuses on the urban scale since cities are major emitters of GHG and pollutants due to rapid economic growth and urbanization.

Important knowledge gaps were identified due to the limitations of existing studies investigating the subject. The main gap identified in this paper was the lack of studies that address all cycle stages. In general, there are studies focused mainly on the final CE stages, such as waste disposal and treatment. In addition, few studies considered transport as the main topic or presented the 7 Rs in the reverse cycle. Transport was only being used as a tool to optimize some processes, such as distribution and collection.

The proposed application of CE stages to the urban transport sector and the related best practices (Section 5) can assist transport decision makers and local and regional authorities in policymaking to develop strategies that reduce resource depletion, and in promoting measures for climate change mitigation. In addition, the closed loop of transport system must be encouraged.

Mobility solutions must take into account the economic, environmental, and societal aspects of sustainability as a model that contributes to improving people's quality of life, which is directly related to the needs and limits of natural resources. The current linear economy model is unsustainable; thus, moving toward a CE is becoming increasingly important. Value can be created due to the rational use of resources and minimization of environmental impact at all phases of the product life cycle in the transport sector.

CE best practices applied to the transport sector, obtained as a result of this study, could be considered by countries' efforts to reduce GHG emissions toward their Nationally Determined Contributions (NDCs) as a central element for implementing the Paris Agreement. In addition, it contributes reaching Sustainable Development Goals (SDGs), such as "affordable and clean energy" (Goal 7), "sustainable cities and communities" (Goal 11), "responsible consumption and production" (Goal 12), and "climate action" (Goal 13).

It is also worth mentioning, as a limitation of this study, that quantitative analyses were not considered, i.e., ones that do not compare and/or evaluate reduced amounts of resources or mitigated emissions from performance indicators, but a qualitative analysis is performed based on best practices applied to each CE stage identified throughout the literature review. A method to prioritize best practices should be applied to quantitative analysis, identified specifically for the CE stage wherein it will be adopted.

As a suggestion for future research, a further review can be done to establish indicators for quantifying the benefits of implementing the best practices at each of the CE stages, as well as identifying potential constraints for their application or implementation to fill the knowledge gaps identified. Further studies could be elaborated to encompass other transportation modes and their integration system. Another key aspect is to ascertain how new technologies implemented in the transport sector, such as how electric or hydrogen-powered vehicles can promote benefits for each stage of the CE, i.e., to use these advances not just as a best practice, but as the main objective under analysis.

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