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Review Article

Establishing the effectiveness of life cycle assessment to assess the environmental impact of passenger cars using biofuels: A Review

Denis Marchant[1,*], Jesper Chritensen[1], Huw Davies[1]

[1] *Centre for Future Transport and Cities, Coventry University, Priory Street, Coventry CV1 5FB, United Kingdom.*

[*]Corresponding author: Marchantd@Uni.Coventry.ac.uk

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ABSTRACT

Predictions and decisions made by legislators may be partially or wholly informed by the results of life cycle assessment studies, but the outcomes can vary significantly. This review seeks to establish whether existing life cycle assessment study results are accurate and if there are errors or deficiencies in life cycle inventory databases, chosen methodologies, or choice of life cycle assessment tool that may impact the outcome of life cycle assessment studies. The context of the work is set against the role bioethanol/gasoline blends might play in reducing the environmental impact of internal combustion engine-powered vehicles. The findings indicate inaccuracies exist and that there are various reasons for this. The accuracy of life cycle assessment results is affected by differences and inconsistencies that occur between life cycle inventory databases, the choice of life cycle inventory databases and life cycle assessment tools and because, in many cases, life cycle assessment methodology does not specify whether the biofuel content in the fuel is considered. The increase in the average age of biofuel-compatible passenger cars challenges the validity of results obtained by employing the commonly used approach based on fixed annual mileage profiles and lifetime activity. Uncertainty is a significant factor, and more attention should be paid to uncertainty analysis. Evidence shows the use of biofuels can deliver considerable environmental gains and reductions in CO_2, especially in blends containing a higher percentage of biofuel.

1. INTRODUCTION

The negative environmental impacts of road transport have been recognised for many years, primarily through the effects of gaseous tailpipe emissions on climate change and public health. Governments have introduced policies and regulations to tackle these environmental impacts, most notably in the United States of America (USA) through the Clean Air Act of 1963, first amended in 1965 by the Motor Vehicle Pollution Control Act, and in the United Kingdom (UK) and European Union (EU) through the introduction, in 1992, of the Euro Emissions Standards, which resulted in the introduction of a series of progressively more stringent standards relating to the acceptable limits for gaseous tailpipe emissions for new vehicles sold in the EU/UK and applicable to all new type approvals from the respective year of introduction.

Today, the EU is designing the next European vehicle emission regulations, Euro 7, which will likely be introduced in 2025. These standards are expected to deliver the lowest in-use emissions from any new ICE-powered vehicle. The government has indicated that the UK may introduce a new road vehicle CO_2 emissions regulatory regime in mid-2024 [1]. One of the measures used to inform such decisions is the outcomes of Life Cycle Assessment (LCA) studies, which various actors, including specialist consultants, have conducted, engaged especially to provide recommendations and suggestions to policymakers [2-3]. Whilst these studies have been conducted with the best intentions and in the belief that the methodological choices and robustness of the data were optimal for use in these assessments, the outcomes often show some variation and, hence, could have the potential to lead to the wrong decisions being made. An example is the work of Brandão et al. [3], who investigated the values published in the European Commission's Renewable Energy Directive (RED) and recalculated the climate-change impacts of a range of biofuels using internally consistent attributional and consequential modelling approaches to enable comparison of these approaches and concluded "the estimated results are highly dependent on the modelling approach adopted, to the detriment of the perception of the robustness of life cycle assessment as a tool for estimating the climate-change impacts of biofuels".

A considerable focus has been placed on reducing road vehicle greenhouse gas (GHG) emissions in the UK and EU. Significant progress has been made with this over the past two decades, and it is clear that reducing gaseous tailpipe emissions from road transport during the transition period to net zero remains a significant challenge [4]. Within the EU, emissions from the transport sector have risen from 1990 levels and now account for more than one-quarter of the EU's total GHG emissions, 70% of the overall GHG emissions being from road transport [5]. In 2017, GHG emissions from road transport comprised around a fifth of the UK's total GHG emissions [6], and the UK average new car CO_2 emissions rose in 2018, up 2.9% to 124.5g/km [7]. The EU and UK have planned to reach net zero GHG emissions by 2050. The UK government have stated that sales of cars and vans powered wholly by petrol or diesel will be banned from 2030. Still, the sale of new conventional hybrids with significant zero-emission capability and pre-used gasoline and diesel cars will be permitted. Similarly, the EU has proposed a comparable ban that, if adopted, would effectively end the sale of new petrol and diesel vehicles in the EU from 2035.

1.1 Fuel types and new vehicles

In the UK, there has been a change in the pattern of fuel type used by newly registered vehicles. In 2018, 64,000 ultra-low emission vehicles (ULEV) were registered; these vehicles were defined as ULEV because they emit less than 75g of CO_2/km from the tailpipe, representing an increase of 20% on those registered in 2017, and making up 2.1% of all new vehicle registrations [6]. However, new registrations of petrol-fuelled cars increased in 2018, while diesel ones decreased [6]. Set against an overall decline in vehicle sales in the UK and EU, attributed by most commentators to the effects of the COVID-19 pandemic, in 2020, ULEVs made up 8.5% of all new registrations in the UK [8]. In the EU, conventional fuel types accounted for 75.5% of total passenger car sales in 2020, and the number of new hybrid electric vehicles increased to 11.9% of the total passenger car sales, up from 5.7% in 2019 [9]. In total, 9,942,509 new passenger car registrations were recorded in the EU, excluding Malta, in 2020 [10]. Whilst there was a steady growth in the sales of new ULEV and hybrid electric passenger cars, ICE power versions still dominated new vehicle purchases.

1.2 The average age of passenger cars

Recent data from the UK Department for Transport Driver and Vehicle Licensing Agency, the Society of Motor Manufacturers and Traders (SMMT) and the European Automobile Manufacturers Association (ACEA) also indicates that the average age of passenger cars in the UK and EU have increased. As shown in Figure 1, the average age since the first registration of passenger cars in the UK has risen from 6.7 years in 1994 to 8.6 years in 2020 [11]. The average age of a UK-registered passenger car in 2020 was 9.3 years for petrol and eight years for diesel [8], and in the EU, the average age of a passenger car in 2019 was 11.5 years, with the oldest being older than 16 years [12]. This extension to ownership may even be exacerbated by the downturn in new car sales following measures to prevent the spread of COVID-19 throughout 2020 and 2021, including national lockdowns, manufacturing plant closures and shortages of critical components such as semiconductors.

ICE's will continue to be included in most new light vehicles in the medium term. If the average lifetime of passenger cars, both currently on the road and those sold before the government ban on the sale of new petrol- and diesel-powered vehicles, increases, the consequence could be increased GHG emissions during the transition to net zero and a delay in reaching the 2050 net zero target. This situation reaffirms the need for continuing strategies and policies designed to lower tailpipe emissions from new ICE's and from the passenger car fleet overall [13], including the adoption of a higher proportion of renewable fuels and bioethanol/ gasoline blends, especially those with higher biofuel content [14].

A recent study has been conducted to consider whether the government bill to ban new ICE car sales in Sweden by 2030 will meet the national policy requirements for the transport sector or the economy-wide net zero target set for 2045. This study concludes that the full effect of such a ban will be delayed due to the lifetime of cars and that an earlier ban on the sale of new ICE car sales or an increase in the use of biofuels is needed [15].

1.3 Aims of this review

Numerous LCA studies for evaluating GHG emission and their environmental impact have previously been completed. However, the datasets and assumptions used in these LCA's may no longer be valid as LCA assessments of passenger cars are sensitive to multiple factors, including lifetime mileage [16-17], fuel blend and type, fuel consumption, etc. New data and consumer trends that are emerging, combined with the effects on usage caused by the global Coronavirus Covid-19 pandemic and other factors, including the adoption in the UK, from September 2021, of a new biofuel blend (E10) to become the standard grade, comprised of 90% gasoline (by volume) and 10% ethanol (by volume), challenge the existing assessments of environmental impact. Therefore, this review seeks to answer three key questions, namely, whether existing LCA study results are sufficiently accurate, hence, whether predictions and decisions made by legislators, informed by these results, are optimal, and if there are errors or deficiencies in Life Cycle Inventory (LCI) databases, chosen methodologies or choice of LCA tool that may significantly impact the outcome of LCA studies of vehicles using biofuels. Finally, what role can the increased use of biofuels, particularly bioethanol/ gasoline blends, play in reducing the environmental impact of ICE-powered vehicles.

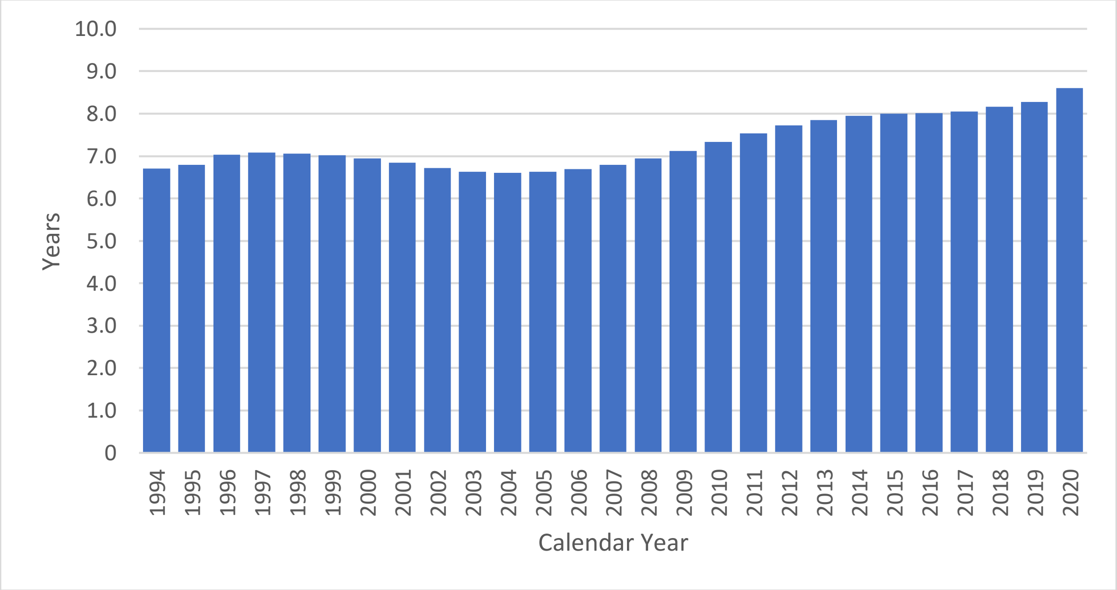

Figure 1. The average age of a licensed car in Great Britain (Adapted using data with permission from the Department for Transport Driver and Vehicle Licensing Agency [11] Contains public sector information licensed under the Open Government Licence v3.0. Open Government Licence v3.0)

2. REVIEW METHODOLOGY

The authors chose to use data from the UK and EU for this study as there is a close alignment between the respective legislation, vehicle specifications, fuels, and consumer habits. Additionally, there is good availability and access to comprehensive and accurate data from the UK and the 27 EU countries that comprise a sizeable market. However, it is recognised that the general findings are equally applicable to other countries, especially those findings and recommendations associated with LCA and LCI.

Four main types of research methodology were considered, namely, traditional or narrative, systematic, meta-analysis, and meta-synthesis. Careful consideration was given to defining the specific purpose of the review and the questions to be answered, alongside a recognition that an overwhelming amount of publications exist; hence, there was a need to be selective in the material used. Although a systematic review, where a search is conducted to identify all previous studies, was likely to be the most accurate due to the certainty that all relevant data had been included [18], this methodology was not used as it was not practical given the amount of available published work. Similarly, the meta-analysis and meta-synthesis methodologies were not used as the use of statistical methods or the generation of a new interpretation of the study area were not required; instead, the principal objective was to provide the authors and readers with a comprehensive and unbiased analysis of the research in the defined area; therefore, the traditional/narrative methodology was chosen.

Search terms (keywords) listed in Table 1 were derived using carefully selected key concepts, including vehicle type, powertrain, fuel type, life cycle stage, system boundaries, product or system studied, e.g., passenger car, and vehicle life/ temporal effects. Appropriate databases and exclusion criteria were also specified (see Tables 2 and 3), which are essential to ensure the quality and rigour of the review and facilitate repeatability whilst reducing the number of searched publications to those most directly relevant to the research questions.

Table 1. Key concepts and keywords/phrases.

Key concept	Keywords/Phrases
Vehicle type	Passenger car, light duty vehicle, conventional vehicle
Powertrain	Internal Combustion Engine (ICE), Hybrid Electric Vehicle (HEV), Internal Combustion Engine Vehicle (ICEV), Plug-in Hybrid Electric Vehicle (PHEV)
Fuel type	Gasoline, Diesel, Biofuel, E10, E20, E25
Life Cycle stage	Use phase
Impact category	Greenhouse Gas Emissions, Tailpipe Emissions, Environmental impact, Global Warming Potential
Lifetime activity	Lifetime mileage, Driving mileage, Vehicle age
Life Cycle Assessment tool	GaBi, openLCA, SimaPro, Umberto

Table 2. Databases used.

Database
Science Direct
Google Scholar
Scopus
Web of Science
Wiley Online Library
IEEE Explore
ProQuest Science Database

Table 3. Exclusion criteria.

Exclusion Criteria	Description
Year of Publication	Priority given to more recent publications (Circa 2010 onwards)
Language	Only publications written in English were considered.
Location	Priority given to EU and UK

3. LIFE CYCLE ASSESSMENT

LCA is an established method for assessing the environmental impact of a product, process or service. It is commonly used to analyse the contribution of the individual life cycle stages to the overall environmental burden. This may be for formulating policy or prioritising product or process improvements for comparison purposes. Several proprietary software tools are available; some of the most commonly used software are listed and described in Table 4.

Table 4. Most commonly used LCA software and associated LCI databases.

Software Tool	Company	LCI Databases included	Optional Databases
SimaPro	PRé	• EcoInvent. • Agri-footprint. • US Life Cycle Inventory database. • ELCD • EU and Danish Input Output. • Industry data 2.0 (includes data from Plastics Europe, ERASM, World Steel). • Swiss Input/Output database.	• Quantis World Food LCA Database. • EXIOBASE. • DATASMART LCI package. • WEEE LCI database. • IDEA Japanese Inventory database. • Social hotspots database. • Environmental Footprint database. • ESU world food LCA database. • AGRIBALYSE.
GaBi	Sphera	• Ecoinvent. • US LCI.	• Offers a data-on-demand service.
Umberto	I Point Group	• Ecoinvent. • cm.chemicals	• EstiMol.
Open LCA	GreenDelta GmbH	Free to Download: IMPACT World+ Product Environmental Footprints. Evah OzLCI2019. EXIOBASE. ARVI. Agribalyse. NEEDS. ELCD. BioEnergieDat.	Available to purchase: • Ecoinvent. • UVEK LCI data. • The Evah Pigments Database. • LCA Commons. • IDEMAT. • cm.chemicals. • IDEA. • Agri-footprint. • Soca. • EuGeos' 15804-IA. • PSILCA. • ESU World Food. • LC-Inventories.ch. • Social Hotspots. • ProBas. • Bioenergiedat. • Worldsteel. • Ökobaudat. • openLCA LCIA methods.

The international standards ISO 14040:2006 and ISO 14044:2006 described the principles and framework for LCA and were last updated in 2022. Figure 2 illustrates how an LCA study consists of four stages, [19] these being Goal and Scope definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. It can be seen that the four stages are dependent upon each other, and the interpretation of the LCA does not rely on the LCA being finished. Indeed, there are cases where the goal of an LCA can be satisfied by performing only an inventory analysis and an interpretation. Such cases are normally described as a Life Cycle Inventory (LCI) study. In complex assessments, continuous interpretation of the results can be helpful and potentially lead to a more accurate assessment.

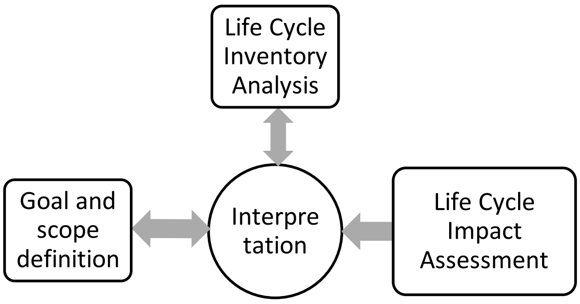

Figure 2. The four stages of an LCA study according to the ISO 14040 guidelines.

3.1 Consequential and attributional LCA

There are two recognised forms of LCA modelling, these being consequential and attributional. Attributional LCA describes the environmentally relevant flows through a product system and its sub-systems. In contrast, consequential LCA describes how environmentally relevant flows change in response to a possible change in the system. The goal of the study to be undertaken will influence the choice of LCA that is chosen [20]. Ekvall et al. [21] claim that choosing between attributional and consequential LCA and its application is important since this strongly influences the LCA results. Consequential and attributional LCA answer different questions with different advantages and disadvantages. The choice between attributional and consequential LCA affects the system boundaries and influences the input data for the calculations. Attributional LCA uses average data, which reflects the actual physical flows.

In contrast, consequential LCA uses marginal data, which Finnveden et al. [22] state represent the effects of a small change in the output of goods and/or services from a system on the environmental burdens of the system. A fundamental matter in consequential LCA is identifying the unit processes that change due to a decision. This issue will, amongst other things, impact how the functional unit and reference flows are defined in the goal and scope phase.

As stated, attributional and consequential LCA answer different questions, and each has different advantages and disadvantages; therefore, it is impossible to say that one is better explicitly.

3.2 Uncertainties in LCA

Uncertainty in LCA is one of the key factors influencing the reliability and accuracy of LCA outcomes. Finnveden et al. [22] suggest the following definition: "the discrepancy between a measured or calculated quantity and the true value of that quantity". Research [22] shows that uncertainties are often not considered in LCA studies, although their influence can be significant. Indeed, many kinds of uncertainty may influence LCA results, some more significant than others, depending on the study type. Numerous classifications of uncertainty are given in the literature. Finnveden et al. [22] suggest - data uncertainty, model uncertainty, variability, epistemic uncertainty, etc. Barahmand et al. [23] suggest additional classifications such as choices, spatial variability, temporal variability, and variability between sources and objects.

Research by Barahmand et al. [23], who comprehensively reviewed 93 LCA studies conducted between 2019 and August 2022, indicated "that the most significant sources of uncertainty reported in the studies were uncertainty in the parameters of the models and processes, data variability, and uncertainties resulting from the use of different methodologies and databases". According to research by Bamber et al. [24], less than 20% of LCA studies published since 2014 report any uncertainty analysis, and of those LCA studies included in their research that included some form of uncertainty analysis, parameter uncertainty [25] was the main type accounted for.

The practice of quantifying and communicating uncertainty associated with the results of scientific studies is commonplace, and its importance within the scientific community is well understood. However, as noted by Bamber et al. [24], uncertainty reporting within the LCA community is not yet common, and, as observed by Finnveden et al. [22], uncertainty in LCA needs attention and development. Barahmand et al. [23] conclude that all published LCA studies should include a comprehensive uncertainty analysis

Inadequate assumptions or other errors will affect the final LCA results. The lack of quantified uncertainties means that it is impossible to determine confidence levels for LCA study results.

3.3 Data Collection

LCA is very data-intensive, and collecting data is arguably the most time-consuming and challenging task when performing an LCA. There are two types of data these being foreground and background data. Murali Krishna et al. [19] define foreground data as specific data needed to model the system, whereas background data is data for generic materials, energy, transport, waste management systems, etc. Foreground data is the 'primary data', which is accurate, authentic data collected directly from a specific process, product use or product system. Primary data may also be sourced from suppliers and distributors. Background data is the 'secondary data' not directly collected, measured, or estimated but sourced from existing life cycle inventory databases and literature.

When conducting LCA, it is desirable to use as much primary data as possible as this should ensure the best level of accuracy, leading to more reliable and credible results.

3.4 LCI databases

LCI databases provide the necessary inventory data to support the modelling. Some of these databases are incorporated in the respective software tools, whilst others are optional at extra cost. In the case of Open LCA, the user must download the databases into the LCA software. Some universally accepted guidelines are available for reference to inform methodology development, namely, ISO 14040:2006, which describes the principles and framework for LCA and ISO 14044:2006, which specifies requirements and provides guidelines for LCA.

The ISO 14040 and 14044 standards provide the essential framework for LCA; however, this framework leaves the individual practitioner with a range of choices, which can affect the validity of the results. Whilst flexibility is essential, the maintenance of quality and consistency is paramount. Hence, some additional guidance documents have been written, including the International Reference Life Cycle Data System (ILCD) handbook [26] written by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC) and the Product Environmental Footprint (PEF) Guide.

The overall objective of the ILCD handbook is to provide a common basis for consistent and quality-assured life cycle data and robust studies [27]. The ILCD handbook complements the general framework provided by the ISO 14040:2006 and ISO 14044:2006 standards. It consists of several documents, including a general guide on lifecycle assessment, a specific guide on lifecycle inventory, a guideline on lifecycle impact assessment (LCIA) methods (including a set of recommended LCIA methods) and a guide on review criteria. The PEF guide provides a harmonised European methodology for Environmental Footprint (EF) studies using a lifecycle approach [2].

Ekvall et al. [21][28] claim that the ILCD handbook is internally inconsistent regarding recommendations on choosing between attributional and consequential modelling and inconsistent with much of previous research in this area. The authors also note that there are inconsistencies with the recommendations on how to choose between average and marginal data in the LCI.

It has been recognised that using different LCA software and LCI databases can affect the study results. Kalverkamp et al. [29] state that there is limited knowledge available about how LCI databases may influence study results and work by Herrmann et al. [30], who undertook a comparative assessment of the SimaPro and GaBi LCA tools identified differences and concluded that these disparities appeared to come primarily from errors in the databases for both inventory and impact assessment. Similarly, Iswara et al. [31] noted wide differences in the results when comparing two different LCA tools using the same input variables.

Individual LCI databases may contain information from different sources and base years, which, when combined with other factors, such as the way the respective LCA software applies normalisation and weighting, may give rise to significant differences in the study results. It is, therefore, concluded that the practitioner should take notice of the potential for different results from the respective LCA software and consider this when making the initial choice of software. Further, the practitioner should take care when interpreting study results and seek to validate the findings whenever possible.

There is good agreement between researchers on the need for future research to establish how life cycle inventory databases influence study results and how practitioners decide on a particular database. E.g. differences and potential inconsistencies between inventory databases causing effects on the life cycle assessment results. Kalverkamp et al. [29] recommend modelling product alternatives using an identical set-up and different LCI databases to understand better the effects of using different databases. A similar recommendation is made by Silva et al. [32]. The Ricardo Energy and Environment report prepared for the European Commission [2] recommends a study to review available LCA inventories for automotive materials and production, stating that this would be useful for understanding the availability of up-to-date LCI data and highlighting areas for improvement.

3.5 Issues and recommendations compiled from studies into LCA methodology

Tables 5 and 6 list issues and recommendations compiled from numerous studies on LCA methodology and highlight many factors that can negatively affect the validity of results gained from LCA studies. Some other issues more specific to automotive-focused LCA studies are mentioned in the text in sections 4, 6 and 7.

Table 5. Issues identified in LCA studies.

Issues	Literature References
1. There is limited knowledge available about how LCI databases may influence study results.	[29]
2. The disparity in LCA results is likely due to errors in the inventory and impact assessment databases.	[30]
3. The data-intensive nature of LCA means that a lack of data can restrict the conclusions that can be derived from a specific study.	[22]
4. A typical LCA does not cover all environmental impacts equally well.	[22]
5. An LCA can include several uncertain methodological choices that may influence the results.	[22]
6. Uncertainty in LCA results can be greater than a Monte Carlo simulation will reveal, as a Monte Carlo simulation cannot account for incorrect data.	[30]
7. Challenges to the expansion and evolution of LCA include: - Gaps in data and knowledge. - Need to incorporate temporal and dynamic components. - Compatibility limitations resulting from differing scenarios and system boundaries.	[33-36]
8. The main sources of discrepancies are: - Missing Characterisation Factors (CFs) in some LCA software. - Additional CFs in some LCA software. - Different CFs for the same elementary flows.	[32][37]
9. Differences in implementing the impact assessment within the LCA software tools. Some differences are so large that they could influence the LCA decisions and conclusions.	[38]
10. The International Reference Life Cycle Data System (ILCD) Handbook is internally inconsistent regarding recommendations on choosing between attributional and consequential LCA modelling.	[21][28]
11. The variation in the results generated by different LCA software using the same input variables would influence the interpretation of the results.	[31]
12. The need to establish guidelines for using surrogate data to bridge gaps for bio-based products.	[39]
13. Consequential and attributional LCA – which type of process and, therefore, which kind of causal chains should be included and how to identify them are the main questions—dealt with differently by practitioners, leading to different results.	[40]
14. Significant difference between dynamic results with and without background process differentiation.	[41]

Table 6. LCA - areas for further development.

Recommendations	Literature References
1. Development of tools for consequential LCA.	[22]
2. Further development and maintenance of databases.	[22]
3. Revision of the ILCD handbook.	[21][28]
4. Studies need to be conducted on conversion factors in different LCA software programs and how the software determines the database and conversion factors.	[31]
5. Additional research is needed to develop and validate different approaches to bridging data gaps for bio-based products.	[39]
6. In some studies, adding temporal information to unit processes in LCI databases would enable a more accurate global warming impact assessment.	[41]
7. Modelling of product alternatives using an identical set-up and different LCI databases to understand better the effects of using other databases.	[29][32]
8. A generally agreed method should be applied for a given fuel production pathway to consider co-products in the lifecycle evaluation of biofuel energy use and environmental effects.	[42]
9. Review available LCA inventories for automotive materials and production, highlighting areas for improvement.	[2]

4. PREVIOUS AUTOMOTIVE-FOCUSED LIFE CYCLE ASSESSMENT STUDIES

Many automotive-focused LCA studies have been performed in recent years, mainly in three key study areas: Vehicle Type, Powertrain Technology and Type of Fuel [43]. The greatest number of studies on vehicle type are focused on passenger cars, and the largest number of studies on powertrain technology are concerned with conventional ICE, followed by Battery Electric Vehicles (BEV). Diesel and electricity are the most widely covered energy sources, followed by gasoline. However, Biofuels, Hydrogen, Natural Gas and Bio Methane received less attention in studies focused on passenger vehicles. The relative percentage of studies on biofuel use in passenger vehicles was lower than expected, given that the passenger vehicle fleet worldwide is very large and biofuels are now readily available and used in many countries, especially America, Brazil, Belgium, and Finland. These publications made up approximately 23% of the total and were appreciably less than those for each fuel type, i.e., gasoline, diesel, and electricity. The most popular Lifecycle Stages studied were Vehicle Component Production, Vehicle Use and Fuel Production. The LCA studies use various Study Subjects, Functional Units and System Boundaries. The most abundant lifecycle impact categories are Greenhouse Gas/ Global Warming Potential, Energy Demand, Air Quality and Toxicity.

All studies confirmed that the use stage dominated the overall lifecycle impacts for ICE-powered vehicles, including Hybrid Electric Vehicles (HEV's). Research published by Ricardo [2] states that the Tank to Wheel (TTW) and, to a smaller degree, the Well to Tank (WTT) impacts account for over 82% of GHG impacts for passenger cars and vans. Whereas, for BEV and Fuel Cell Electric Vehicles (FCEV), the impact attributed to vehicle production is much greater than for ICE-powered vehicles. Whilst it is generally accepted that a move away from fossil fuels to alternative energy vectors is essential to achieve the net zero target and sales of ULEV's (BEV and Plug-in Hybrid Electric Vehicles (PHEV's)) are growing in the UK and Europe, with ULEV's accounting for 8.5% of all new UK registrations in 2020, an increase of 125% on 2019, with BEV's accounting for 64% of new ULEV registrations in the UK during 2020 [8], gasoline and diesel-powered vehicles still dominate the new sales. Therefore, It is evident that ICE's will continue to be included in the majority of new light passenger vehicles in the medium term, and strategies to reduce their environmental impact rapidly are needed. In addition to introducing more stringent emissions standards such as Euro 7, there is scope to expand further the percentage of renewable fuels, especially higher blend biofuels, to significantly reduce emissions sooner whilst transitioning to a full battery electric light passenger vehicle fleet.

The present research reveals that there are currently wide variations in the results from LCA studies [44]. Given that the studies were mostly conducted from 2010 to 2021, the inputs and corresponding conclusions may no longer be entirely valid. For example, work undertaken in 2014 by Hamje et al. [45] predicted that there would be continued dieselisation of the EU passenger car fleet, triggering a continuing decline in gasoline demand. It can be seen that this prediction is incorrect as the demand for diesel-powered passenger cars has declined since 2015 following the diesel emissions scandal, and in the EU, the data published in 2021 for fuel type of passenger cars in use in 2019 shows the percentages to be 52.9% petrol and 42.3% diesel [12]. As stated in the 2018 Transport and Environment Reporting Mechanism (TERM) report [46], 'An important point to note in LCAs of ICEVs is the extent to which biofuels are considered in WTW GHG emissions' and 'in many cases, LCA methodology does not stipulate whether the biofuel content in the fuel is taken into consideration'. Work published by Brandão et al. [3] concludes that: "the estimated results are highly dependent on the modelling approach adopted, to the detriment of the perception of the robustness of life cycle assessment as a tool for estimating the climate-change impacts of biofuels".

Similarly, a meeting jointly organised by the Joint Research Centre (JRC) of the European Commission and Task 39 of the International Energy Agency's (IEA) Technology Collaboration Program on Bioenergy held in May 2019 also concluded that there are uncertainties with the individual entries in LCI databases and that LCA results vary from the actualities, due, in part, to location and allocation choices.

5. BIOFUEL

Research published in 2021 suggests that the biofuels E10 (gasoline with up to 10% ethanol by volume) and B7 (diesel with up to 7% biodiesel by volume) provide some environmental benefits and that impressive reductions in CO_2 are obtained from E85 and B100 biofuels, which are close to 2019 values for BEV's with extended range: 103g CO_2 vs 85g CO_2 eq/km respectively [47]. Data published by the UK government shows that 2020 renewable fuels rose to 5.9% of total road and non-road mobile machinery fuel, up from 5.1% in 2019, despite the effects of the national lockdown due to the COVID-19 pandemic. Biodiesel and bioethanol made up 64% and 22%, respectively, of verified renewable fuels, and the total verified renewable fuels achieved an average greenhouse gas saving of 82% when compared to fossil fuels [48], thus demonstrating the positive contribution that biofuels can make to GHG emissions reduction. These figures also show that there is considerable scope to achieve a higher proportion of renewable fuels, especially bioethanol, where its percentage as a proportion of the total of renewable fuel supplied in the UK has declined, as shown in Figure 3 [49], and therefore reduce GHG emissions still further.

It is claimed that renewable ethanol reduces greenhouse gas emissions by more than 70% on average compared to fossil fuels such as petrol [50]. Ethanol has a hydrogen-to-carbon ratio of 3.0 compared to 1.85 for petrol and an oxygen content of 35% by weight and is classified as an oxygenate [51]. Due to ethanol's high octane number [14], it boosts the octane rating when blended with petrol [54], providing performance gains as well as contributing to the optimisation of the combustion process, in turn facilitating engine downsizing and/or turbocharging, especially with blends near to E20/25.

Despite having approximately 30% less energy content than pure gasoline and, in some cases, giving rise to increases in fuel consumption by as much as 4% for normal octane fuel blended with 20% bioethanol, the potential to allow the octane rating to rise could result in engine efficiency gains, thus, providing potential for fuel consumption improvements, and, as a consequence, further reductions in tailpipe gaseous emissions [53]. E10 is the reference fuel used for vehicle Mile Per Gallon (MPG), and UK government analysis based on average calorific values of fossil petrol and E10 suggests that fuel economy could be reduced by 1% - 2% when using E10, dependent on driving style and other factors [54].

The EU Renewable Energy Directive (RED, 2009/28/EC) mandated that by 2020, 10% of the energy used in the transport sector of each of the member states should be from renewable energy sources [55] and in the summer of 2021, the UK introduced E10 fuel as the primary petrol grade. Apart from the UK, E10 is currently available in 15 EU countries. However, the percentage of market share is quite variable, with a range spanning from 100% to 14%, even though most petrol-powered passenger cars manufactured after 2000 are E10 compatible and recent models are fully optimised to run on E10. Consumer take-up has been variable due to the availability of multiple petrol grades in some EU member states, leading, some believe, to consumer confusion.

Higher blends such as E20 and E25 have been established in Brazil and the United States of America (USA) for some years, and it is known that engines optimised to run on E20, a high-octane fuel, emit less GHG. The EU Fuel Quality Directive (FQD) does not currently allow for blends with more than 10% ethanol; however, the EU commission is believed to be in favour of the introduction of higher blends as part of the drive to meet the objectives set out in the Green Deal.

The adoption of BEV's will require significant investment in infrastructure, increased electrical generation and affordable vehicles if the targets set by governments are to be realised. Low-carbon fuels and biofuels can reduce GHG emissions during the transition to full electrification with little change needed to the existing infrastructure, vehicle hardware or manufacturing processes. Biofuels are a readily available solution that can play a significant role in helping to accelerate the reduction of negative environmental impacts from gaseous tailpipe emissions [56]. By increasing the blend percentage of biofuels with gasoline or diesel, significant CO_2 reductions can be obtained [57]; hence, it is vital that LCA models accurately reflect this.

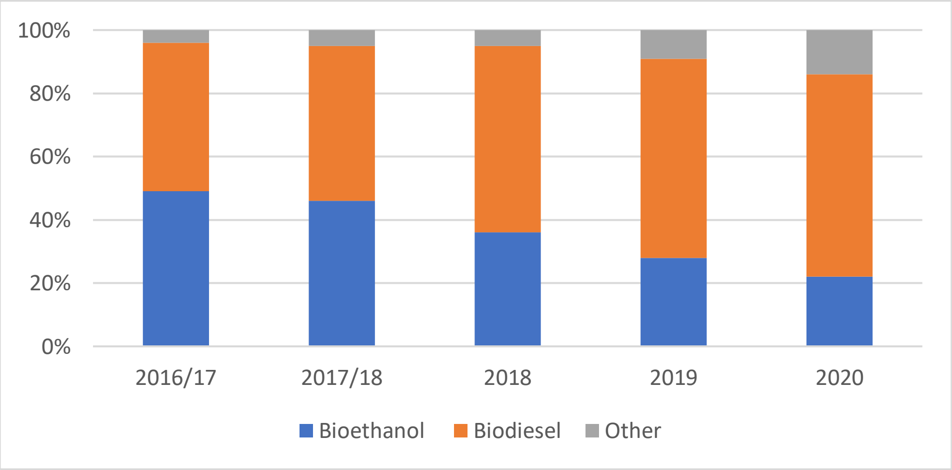

Figure 3. The percentage of renewable fuel by type supplied in the UK (Adapted using data with permission from the Department for Transport Driver and Vehicle Licensing Agency [49] Contains public sector information licensed under the Open Government Licence v3.0. Open Government Licence v3.0)

6. DISCUSSION

This paper's three questions were posed and subsequently investigated through the review. When considering the first question - whether existing LCA study results are sufficiently accurate, hence, whether predictions and decisions made by legislators, informed by these results, are optimal, it can be seen from the conclusions of related studies there is overwhelming evidence that there are currently wide variations in the results from LCA studies arising for several reasons, the main ones being listed in Table 5. It is also the case that many automotive-focused studies are quite dated, bringing their continuing relevance into question. A number of recent factors have disrupted previous trends and affected earlier predictions, examples being the impact on vehicle use due to the Covid-19 pandemic lockdowns, the rapid move away from purchasing new diesel-powered vehicles in the wake of the diesel emissions scandal, the increase in the average age of the passenger vehicle fleets in many countries and the adoption of different biofuel blends. LCA is a primary tool used to inform decision-making. This review revealed that biofuel modelling results vary widely due to methodological choices and assumptions. Hence, the continuing validity of some decisions and resultant policies could be called into question.

Concerning the second question - are there errors or deficiencies in Life Cycle Inventory (LCI) databases, chosen methodologies or choice of LCA tool that may significantly impact the outcome of LCA studies of vehicles using biofuels. It has been recognised that the use of different LCA software tools can affect the study results and that the practitioner should take note of the potential for different results from the respective LCA software's when making their initial choice of tool. As a result of this potential for discrepancy, in part attributed to the way the respective LCA software applies normalisation and weighting, the practitioner should take care when interpreting study results and seek to validate the findings whenever possible.

As previously mentioned, researchers have good agreement that differences and potential inconsistencies arise between inventory databases, causing effects on the life cycle assessment results, and there is a need for future research to establish how LCI databases influence study results and how practitioners decide on a particular database.

Finally, the question was asked - what role can the increased use of biofuels, in particular bioethanol/gasoline blends, play in reducing the environmental impact of ICE-powered light vehicles - it is clear that there is a sizeable body of evidence that suggests significant gains can be made through their adoption, primarily through bioethanol/gasoline blends with a higher percentage of biofuel such as E25 or E85 [58], and that there is merit in widening their use to reduce tailpipe GHG emissions during the use phase, thus, aiding the reduction in GHG emissions during the transition to BEV's as well as contributing to meeting the respective governments net zero targets, which could be put at risk if the lifetime age (and mileage) of ICE powered vehicles continue to rise.

It should be noted that the focus of this work has been directed predominately towards bioethanol blended with gasoline, particularly E10, as the UK government has just adopted this as the primary fuel grade. No independent research could be found to provide insight into its likely impact or the validity of the UK government's claims that the use of E10 fuel combined with an increase in the overall renewable fuel targets could cut overall transport CO_2 emissions by a further 750,000 tonnes a year, which they equate to be the equivalent of taking around 350,000 cars off the road [56]. Additionally, no consideration has been given to the wider issues of Indirect Land Use Change (ILUC), food vs. fuel and second-generation biofuels, as these matters are beyond the scope of this review.

7. CONCLUSION

The findings of the review presented in this paper indicate inaccuracies exist and that there are various reasons for this. The accuracy of life cycle assessment results is affected by differences and inconsistencies that occur between life cycle inventory databases, the choice of life cycle inventory databases and life cycle assessment tools and because, in many cases, life cycle assessment methodology does not specify whether the biofuel content in the fuel is considered. The increase in the average age of biofuel-compatible passenger cars challenges the validity of results obtained by employing the commonly used approach based on fixed annual mileage profiles and lifetime activity [17]. Bamber et al. [24] concluded that "more attention should be paid to uncertainty analysis in studies specific to the transport and infrastructure sectors, due to their higher basic uncertainty values". Evidence shows biofuels can deliver significant environmental gains and reductions in CO2, especially in blends containing a higher percentage of biofuel.

7.1 Recommendations for Future Investigation

Several recommendations are summarised from the review: LCA studies of the UK passenger car fleet should be conducted to assess biofuels' full potential, considering the TTW and WTT impacts. Given the increase in the average age of vehicle fleets in the UK and EU, modelling should be undertaken to quantify the environmental impact of such lifetime extensions. Lifetime mileage is a critical component in LCA modelling, and in most studies, a simplified approach based on fixed annual mileage profiles and lifetime activity is used. Weymar et al. [59] assert that "best guess" lifetime mileages provided by industry associations and car manufacturers are currently applied in automotive LCA. One aspect of the suggested work would be to propose an updated lifetime milage for use in LCA studies, which reflects the latest trends and consumer behaviour.

In most cases, the LCA methodology does not specify whether the biofuel content of automotive fuel is considered [46]. As the percentage of biofuels in gasoline and diesel increases, this is an essential feature for improvement in LCA to ensure accurate results are obtained. Additionally, knowledge of how the choice of LCI database and LCA tool may influence study outcomes and how practitioners decide on a particular database or LCA tool is limited. Research in this area would be helpful to provide a guide for database and LCA tool choice. Similarly, there is a need for research to establish the extent of any differences and potential inconsistencies between inventory databases and their effects on LCA results.

The development of a variance model for predicting water absorption and thickness swelling for an experimental design reinforcing PVC composite pipes was successfully carried out. The results showed that the model was characterised by a high R^2 value, indicating a very good fit between the experimental observations and model predictions. Furthermore, the adjusted R^2 value was within reasonable agreement with the corresponding R^2 value, confirming the fit of the models. An adequate precision value of 43.939 was obtained, indicating that the water absorption model has an adequate signal and can be used to navigate the design space.

Increasing the level of rattan and plantain peduncle increased the water absorption capacity of the composite pipe. This is due to the hydrophilic fibre materials, unlike the PVC material. Also, an increase in temperature and pressure reduced water absorption. This is contributed by a better mobility and distribution of the plastic component among the fibre (rattan and plantain peduncle) particles, thus covering a larger surface area of the hydrophilic fibre component.

The characteristics of thickness swelling for the production variables (PVC, rattan, plantain peduncle, temperature, and pressure) showed that increased PVC resulted in reduced thickness swelling of the composite pipes. However, with higher fibre (rattan and plantain peduncle) content, thickness swelling tends to increase as a larger share of the particle surface is insufficiently bonded and protected by the plastic component, and the greater connectivity between particles allows for easier moisture intrusion.

CONFLICTS OF INTEREST

The authors declare no competing financial interests or personal relationships that could have appeared to impact the work reported in this paper.

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