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Design for sustainability in automotive industry: A comprehensive review

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ABSTRACT

Presented manuscript investigates the current sustainability research within the automotive industry, through a comprehensive review of the different studies in vehicles' life cycle, disposal and end of life analyses, and the different sustainability metrics and models used to quantify the environmental impact. The sustainability research in this study targets the measures and studies at the three basic elemental levels involved; environmental, economic, and societal. The presented review categorizes the literature into four main research areas; the life cycle assessment approach, the end-of-life perspective, the design for X, and the light-weight engineering and material selection studies. Also, the text attempts to draw the link between these research themes and expose any inter-relationships, and discuss the physics behind some of the sustainability models presented to analyze the automobile sustainability.

Contents

1. Introduction

Nowadays, 96% of the world's transportation systems depend on petroleum-based fuels and products, with the global transportation systems accounting for about 40% of the world's oil consumption of nearly 75 million barrels of oil per day [1]. Furthermore, since 1960 the vehicle ownership in the United States had grown from about 74.4 million to more than 239 million in 2002 with an average

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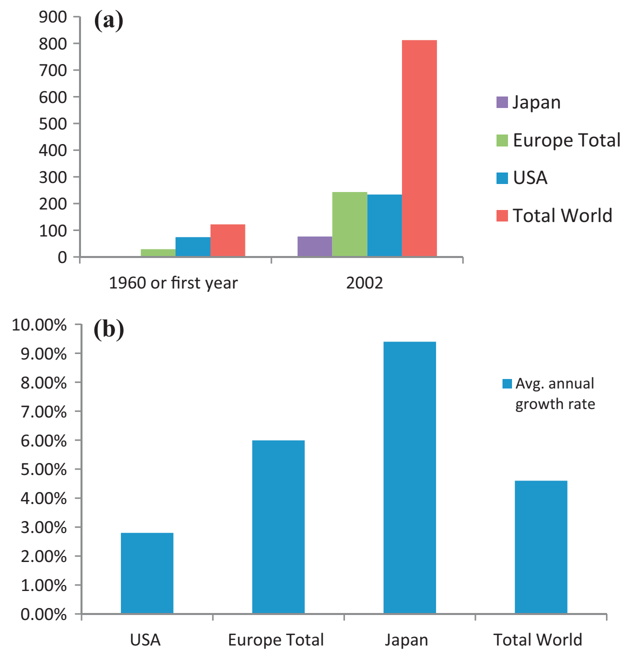

Fig. 1. (a) Historical vehicle ownership (millions), 1960–2002; and (b) average annual growth rate between 1960 and 2002.

annual growth rate of 3%. However, the global growth trend is much faster than US, with ownerships outside the United States climbing from about 47.6 million to over 573 million over the same period [2]. This global growth of vehicles as shown in Fig. 1 will result in significant increases in global fuel demand, material requirements, and air emissions. As a result, sustainability continues to become a critical issue for the automotive industry motivating more significant reductions to the overall environmental impact of vehicles worldwide, in order to ensure the automobile as a product is an environmentally sustainable one. At the same time, this trend adds more pressure on the original equipment manufacturers (OEMs) to not only come up with new solutions to minimize the environment impact through the usage of more efficient processes that preserve resources, but also to develop quantitative metrics to assess such impact and gauge improvement efforts [3–6].

According to Curtis and Walker the definition of designing for sustainability involves balancing social, ethical and environmental issues alongside economic factors within the product or service development process [7]. It ensures that the needs of both the business customer and society are met while protecting the ecosystem. This definition highlights the inherent complexity in sustainability accounting and tracking efforts.

Current review is structured into four main research themes; the first is the life cycle assessment for vehicles and vehicular components [8–23], while the second theme focuses on the relationship between the design-for-X principles and design for sustainability, and how design-for-X can be integrated to achieve specific sustainability goals [1,24–40]. The third and fourth research approaches cover the automobile end-of-life studies and the associated fuel economy of the light-weight engineering efforts [37–51]. The light-weight studies will highlight the material selection process for automotive body-in-white that compromises both the automobile functionality/manufacturability aspects and its sustainability. Lastly, the study discusses the presented sustainability models in literature in the area of automotive applications. The manuscript summarizes the studies and findings in the conclusion.

2. Automotive life cycle assessment (LCA)

Pennington et al. [9] as well as Sundin [39] defined the life cycle assessment or LCA as a method that is used to account for the environmental impacts associated with a product or a service from inception to end-of-life or cradle-to-grave. Typical life of any industrial product begins with the extraction and processing of its raw materials, then its manufacturing, distribution, use, and lastly by its end-of-life stage. Sundin [39] classified the life cycle assessment into four main stages: the material extraction, manufacturing, use and disposal, pictorially displayed in Fig. 2, while Ashby [10] added one more stage that is the transportation. Ashby [10] suggested that when assessing the life cycle environmental impact of the vehicle, energy during the use stage can be considered as an indicator of its environmental burden. However, LCA studies and assessment methods in association with the international standards ISO 14040, 14041, 14042, 14043 are important, especially at the inception and design phase [52]. Pennington et al. [9] and Govetto [41] categorized the ISO 14000 series into four phases; the goal and scope phase, the inventory analysis, the impact assessment, and interpretation phase.

With the first phase "Goal and scope" is set to define the purpose, the boundary, metrics and the units of the inputs and outputs that will be evaluated, while the second step or "Inventory analysis" basically deals with the data collection. The first two steps are further analyzed in the ISO 14041 [41,52]. The third phase or "Impact assessment" helps in evaluating the environmental consequences of phases one and two results, with the ISO 14042 guiding the construction of the third phase. Finally, the last phase or "interpretation" is designed to comment and draw conclusions on the three preceding phases or steps; the ISO 14043 articulates this last step [52].

The life cycle assessment for an automobile analyses the vehicle from the pre-manufacturing stage i.e. raw materials to its end-of-life stage, as displayed in details in Fig. 3 [25] for developed and developing countries. The LCA methodology suffers from two main challenges; the diversity and variations in materials, processing techniques, usage durations, and disposal routes, as displayed in and Figure 3 from [50]. The other challenge is the extended timeline associated with the LCA; according to Mildenberger and Khare

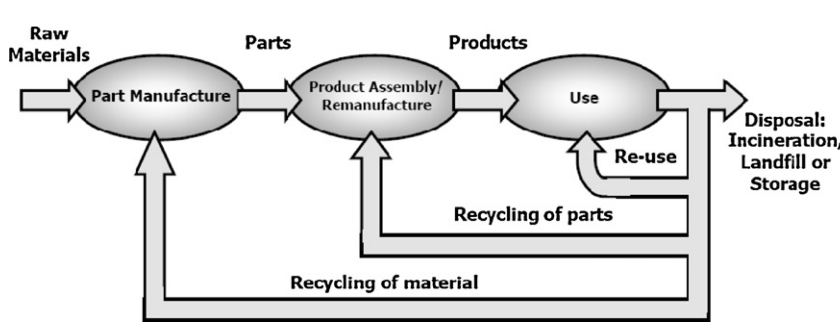

Fig. 2. The physical product life cycle [39].

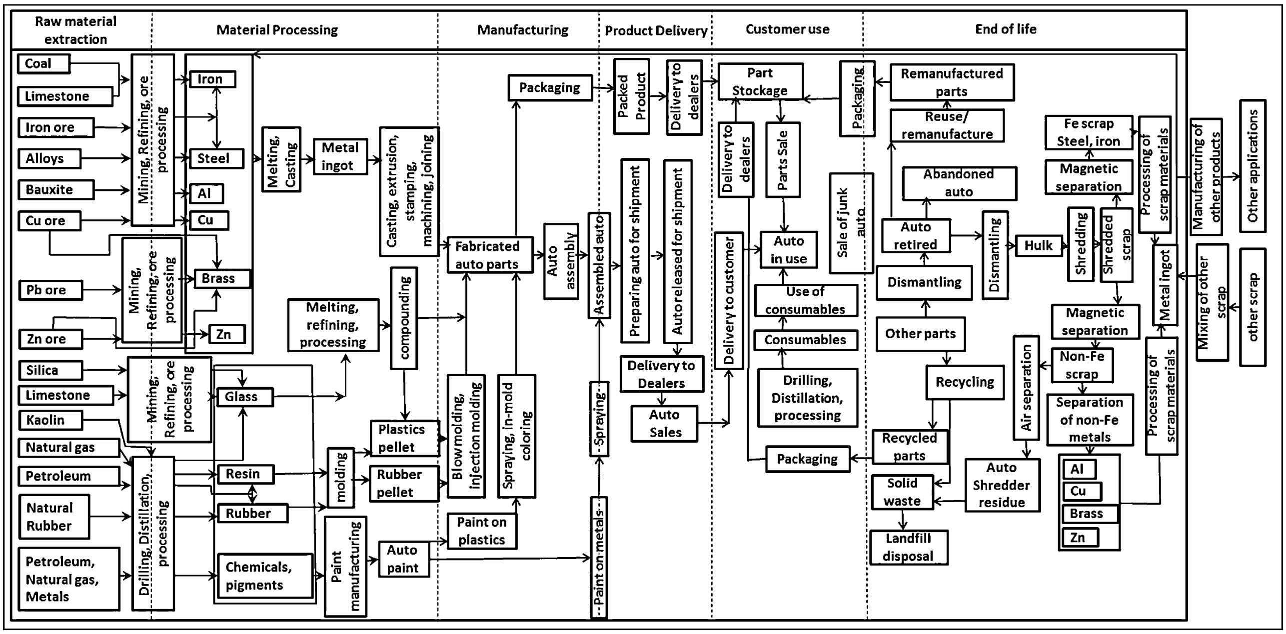

Fig. 3. Detailed LCA for materials used, manufacturing processes and end-of-life scenarios [50].

[25] the total life for a vehicle in developed countries ranges from 25 to 35 years while in the under-developed countries it reaches 45 years (Table 1). These challenges not only identifying the actual lifetime, but also the vehicle degradation while in use (e.g. loss of engine efficiency leading to more fuel consumption) and the real value of monetary units.

3. Design for X, and design for sustainability

Jawahir et al. [27] established the framework for the design for sustainability within the design-for-X (DfX) principles, as displayed in Fig. 4. The design for sustainability can usefully exploit the DfX methodology to conceive a sustainable product. The vehicle and its sub-systems can be adopted within the DfX (design-for-X) principles to help analyze its environmental impact from specific design aspects such as disposal-ability and operational safety. The following sub-sections review the application of design-for-X (DfX) for developing a sustainable automobile.

3.1. Design for manufacturing (DfM)

In a vehicle manufacturing phase the (DfM) methodology comprise several guidelines; including but not limited to, the product adoption at the company level, the product family, the product structure, and components [28]. The DfM have been used with focus on cutting both the production lead time and its cost. A derivative of the DfM is the design for assembly or DfA [19], which focuses on the assembly and fastening strategies. Examples of DfA design guidelines include, the reduction of number parts and part variations through eliminating parts' adjustments [53–56].

3.2. Design for recyclability

Design for disassembly, design for remanufacturing and design for recycling can be classified under the umbrella of design for end-of-life or what so called in literature design for recyclability.

Kuo [26] stated that the aim of design for disassembly is to ensure that a product or system can be disassembled at minimum cost and effort. Luttropp and Lagerstedt [36] found that adopting design for disassembly strategy not only helps speeding up disassembly process, but also helps in recovering a larger proportion of system components.

The aim of design for remanufacturing is to return vehicle parts and sub-assemblies to an acceptable performance level for re-assembly, enabling its materials to be re-used in their highest value state, hence preventing waste and reduce the use of virgin resources [24]. Many components are discarded with slight degradation due to wear, or corrosion as resulted from the thermal or the environmental exposures. Design to enable disassembly with provision to replace or refurbish worn parts can also enable significant savings, even when the cost of removing and returning the discarded part to the point of remanufacture is included [26]. Coulter et al. [24] and Palmer [45] suggested that the viability of remanufacturing depends on how efficient the disassembly is, how strong and stable is the demand for standardized parts, and the positive perception of remanufactured content. Today's market feature several remanufactured parts such as alternators, starter motors and water pumps [29,57]. These provide competitive alternatives, but are still restricted to the automotive aftermarket segment [9,24,58].

Recycling implies that materials are processed out of one form and remade into a new product [30]. The ultimate goal of recycling is to save resources, however, this goal may be motivated by other reasons that aim to save money or preserve the environment [31].

Table 1
Life cycle of the vehicle in developed, developing and under-developed countries [25].

	Concept and design (years)	Manufacturing (years)	Use phase (years)	Total life (years)
Developed countries	4–5	7–8	10–12	>25
Developing countries	6–8	10–12	15–20	>35
Under-developed nations	N/A	N/A	20–25	>40

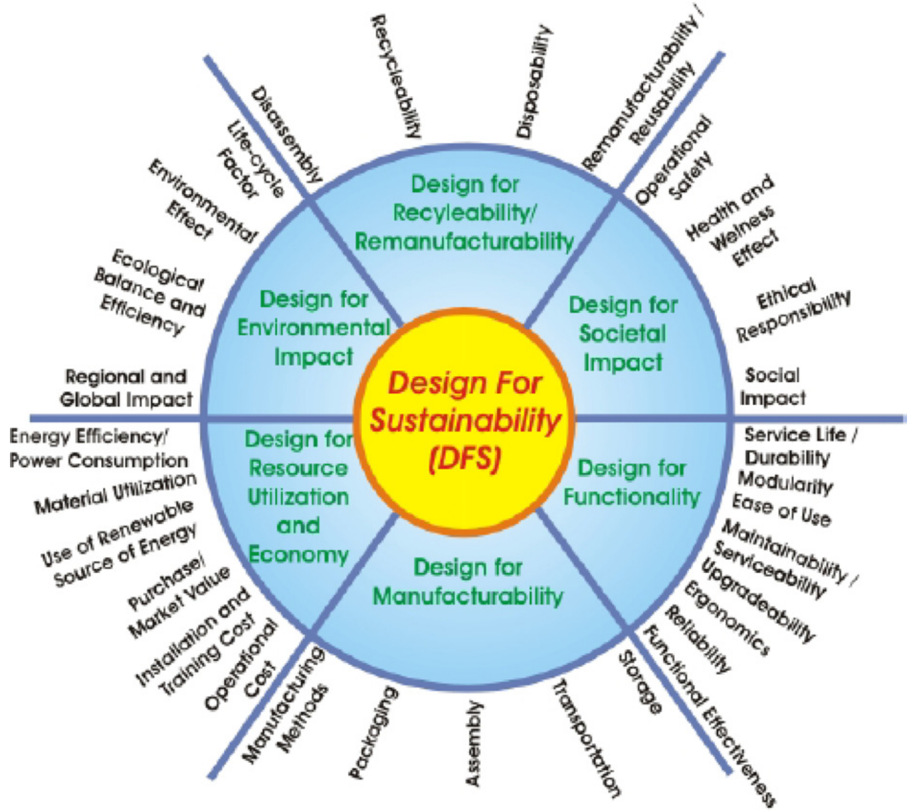

Fig. 4. Major elements contributing to design for sustainability [27].

However, any discussion of recycling should take into account that recycling involves the remanufacturing phase as its core part. This implies that it is not enough to find innovative methods to collect items or take them apart, but new technologies must also be developed to make use of the potential feedstock [32,45]. From an economic point of view, this is necessary to maintain an additional source of materials to the market and reduce the waste generation [59,60].

According to Ashby [10] and Boon et al. [61], the use of recycled material not only minimizes the consumption of virgin raw material, energy and water, but also plays a role in reducing waste, air and water pollution, and associated energy consumption. Bulucea et al. [34] and Graedel and Allenby [47] suggested avoiding mixing of materials in assemblies, to be one of the important rules of the design for recyclability to facilitate the process of dis-assembling, sorting and collecting these materials. Reuter and van Schaik [31], supported this argument by indicating that the number of different plastics and non-plastic materials used in a product should be minimized to enhance the product recyclability. As an example, nearly 90 kg of the 162 kg of plastics in a BMW-3 series can be economically recycled in compliance with BMW recycling standards [49].

According to Graedel and Allenby [47], there are different levels of recycling. The lowest is the linear material flow system where all the materials used in the vehicle are land-filled at the end-of-life stage (Fig. 5). While, the highest is "closed loop recycling," in which a product components are remanufactured into the same kind of product type, without the addition of any virgin material unless necessary. Truly closed loop recycling systems are difficult to attain, hence they are considered an ultimate goal in any recycling scenario. If a material cannot be contained in a closed loop, it will often times be remanufactured into a lower grade substance, or combined with first-use material. In order to acquire maximum value, materials should travel through as many different quality levels as possible. For example, steel is an item that can be remanufactured in a quasi-closed loop scheme while aluminum can be recycled in a fully closed loop system [43,47]. More than 90% of the steel that goes into making a new vehicle is virgin steel, and recycled steels from automobiles will find application in civilian structures such as buildings and bridges but not new cars [50,62].

Vehicles, however, cannot be 100% recycled [63]. This is due to the product complexity, and its material diversity. Steel and plastics, for example, cannot be completely remade into products of the same quality as the original. They can be remade into either a lesser grade products, or mixed with a different material to form a new substance [64].

Reusing materials is sometimes classified as one type of recycling, although it is not technically "recycling" because it does not involve any reprocessing [65]. But regardless of how it is formally classified, reuse certainly tops the hierarchy of how products should be dealt with in an environmentally responsible manner [27,33].

3.3. Design to minimize material usage

Reducing the amount of material used over the product life cycle is an effective method of reducing its environmental impact [35,43]. In case of fuel consumption, this strategy can be applied by reducing the vehicle's physical dimensions whenever possible, weight reduction by using alternative materials such as aluminum, high strength steel or carbon fiber reinforced polymers (CFRP) for vehicle bodies [36,66–72]. More discussion is in the next sections.

3.4. Design for durability

Durability is the probability that a product will function without failure over a specified period of time or amount of usage [48].

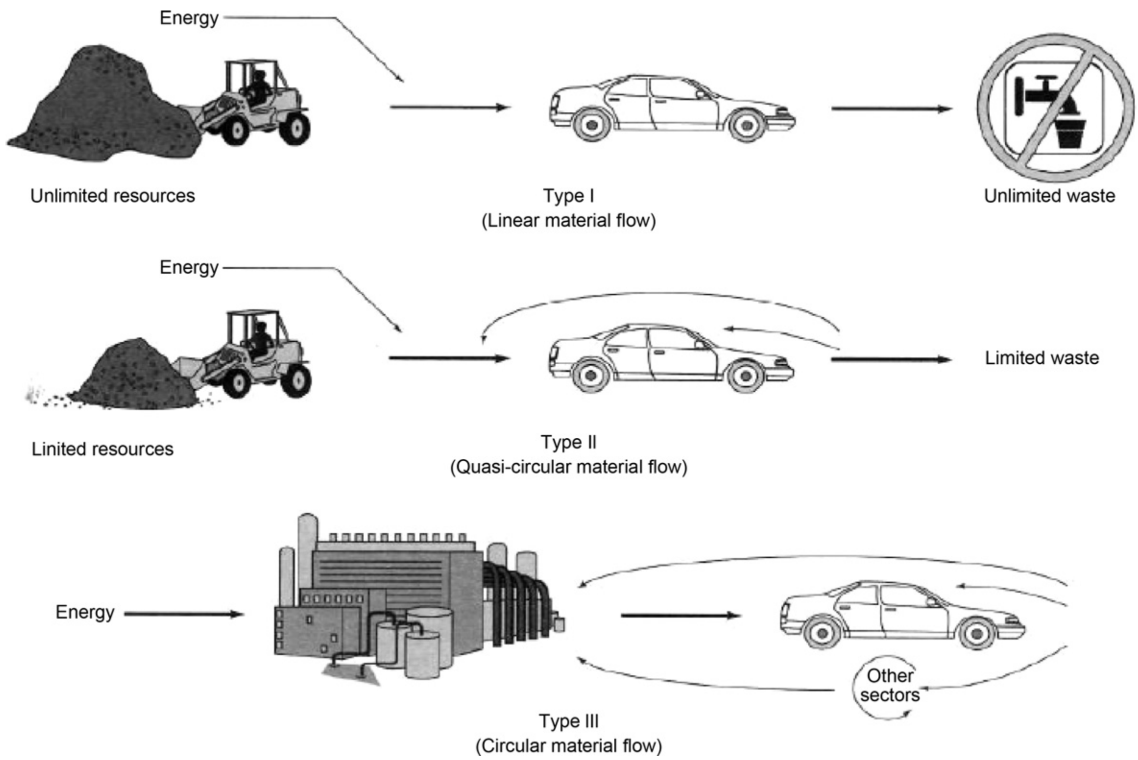

Fig. 5. Vehicle recycling models [47].

Hence, designing products to last longer reduces both resource use and waste generation. However, in some cases increasing durability may have an adverse effect if impacts from the complete product life cycle are considered, as the case with fuel consumption [40], where using older, lesser efficient engine technologies for long time harms the product environmental impact. So, the adoption of more environmentally beneficial technologies becomes crucial to increase the energy utilization efficiency or the emission control in vehicles [73]. This has been a concern in the case of adopting improved pollution control devices on cars such as the catalytic converters or the after treatment modules and sensors [40].

3.5. Design for energy efficiency

A major source of environmental impact is the energy consumed by a product during its use phase [10,74]. Apart from developing advanced lean-burn combustion systems to improve engine thermal efficiency, the applications of alternative light-weight materials in power-trains and vehicle structures are being investigated to improve fuel economy over the whole life cycle of the product. For example, using aluminum instead of steel in the chassis of a car will ensure greater fuel efficiency by reducing the total energy used over the life cycle of the car [11,15]. BMW, for example, have increased the proportion of plastics in their vehicle manufacturing to reduce weight and improve fuel economy [49]. The efforts to develop efficient vehicle designs have concentrated into three main areas; the use of light-weight materials (lesser density than steel), such as Al, Mg. This effort is typically challenged by the cost of these materials (Al cost of around 4–5 times that of steel) in addition to the difficulty involved in their manufacturability (mainly formability). Some automotive original equipment manufacturers, OEMs have started to use some integrated metrics to better evaluate the use of light-weight materials in their vehicles some of these metrics include the cost added per unit weight saved as in $\$/\text{kg}_{\text{saved}}$ and the light-weight engineering index L used by the BMW group illustrated in equation (1) [48,75]:

$$L = \frac{A \cdot C_{\text{torsional}}}{\text{mass}} \quad (1)$$

where $C_{\text{torsional}}$ is the torsional stiffness of the BIW, and A is the vehicle size, and mass is the mass of the BIW. Body in white (BIW) refers to vehicle's body sheet metal components upon completion of welding and before painting. By definition, BIW does not include moving parts (doors, hoods, and deck lids as well as fenders) the motor, chassis sub-assemblies, or trim (glass, seats, electronics, etc.) [48,50].

However, significant improvement in vehicle efficiency in terms of the mile per gallon requires larger reductions in the vehicle weight. To quantitatively describe the relationship between the vehicle weight and its fuel efficiency, several correlations have been proposed and are listed through [75]:

$$\text{MPG} = 895.24(\text{mass})^{-0.463} \quad (2)$$

$$\text{MPG} = 8627.4(\text{mass})^{-0.74584} \quad (3)$$

$$\text{mass} = 2.015 \cdot \text{FE}^2 - 194.85 \cdot \text{FE} + 6375.54 \quad (4)$$

where the MPG is the mile per gallon and the mass is the curb weight in Lbs, while the FE is the fuel economy.

The second approach to light-weighting is based on using stronger materials through using modified steel alloys and grades such as the dual phase DP, transformation induced plasticity TRIP steel which have a high and sustained work hardening effects in addition to the phase transformation strengthening (bake hardening) effects. The use of stronger steel grades allows automobile designers to use thinner gauges meaning lesser weight. The third approach is based on using optimized cross-sectional shapes of structures to achieve better loading performance without increase in weight in addition to using Tailor Welded Blanks/Tubes/Coils TWB/T/C technology to custom make the blanks thickness and

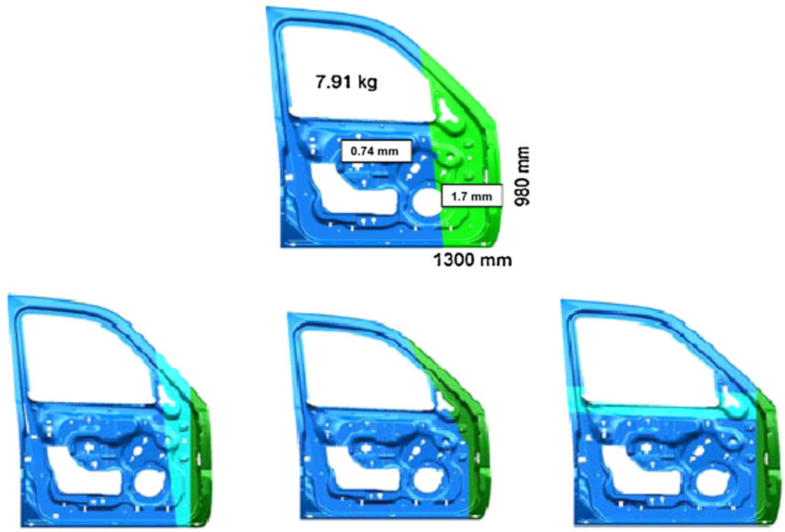

Fig. 6. Tailor welded blank applied for door inner [50].

grade according to their location performance criteria [76]; Fig. 6 shows a tailor welded blank applied for inner door.

4. Vehicle design for end-of-life

The European End-of-life Vehicle Directive requires car manufacturers from 2002 onwards to take back all newly registered vehicles that require disposal [44]. The material fluxes associated with the vehicles disposal have become increasingly important. The annual waste flux due to end-of-life for passenger vehicles with less than eight seats and vans not exceeding 3.5 tons, in the European Union alone is estimated to be around 8–9 million tons [64].

The potential environmental impacts of such disposal efforts led to the establishment of new environmental policies in the European Union, associated with the concept of "extended product responsibility" [44,64]. So, the European Parliament approved the Directive 2000/53/EC which deals with End-of-Life of Vehicles (ELV) [64]. Ferrão and Amaral [64] summarized this directive to stipulate the technical requirements for car design as well as the minimum reuse and recovery rates for end-of-life vehicles as; (a) until July 2003: vehicles put on the market cannot contain lead, mercury, cadmium or hexavalent chromium, with the exception of some cases referred in the annex of the Directive. Also, (b) until January 2006; the reuse and recovery of 85% on a mass basis (recycling 80%) for vehicles produced after 1980. Additionally, the reuse and recovery of 75% on a mass basis (recycling 70%) for vehicles produced before 1980. (c) Until January 2015 – reuse and recovery of 95% on a mass basis (recycling 85%).

However, these targets should be met while ensuring that the ELV is delivered at a specialized treatment facility without additional costs to the vehicle owner. Fig. 7 shows the recycling and recovery rate of ELVs at European Union in 2008.

In the United States, the Union Oil Company of California (UNOCAL), in cooperation with the California Air Resources Board (CARB) and the California Department of Motor Vehicles introduced a scrappage program initiative in June 1990 in the Los Angeles Basin area, offering $700 for retiring eligible vehicles. As a result, they collected over 8000 cars, accounting for more than 2% of pre-1970s model year vehicles in this area, were retired [14,46].

The main design consideration for vehicles at their final stage is to ensure that, whatever disposal method for ELV is used, the vehicle materials should not create any hazard, i.e. avoiding the use of heavy metals and toxic substances [56]. To provide an example, the principal material used to inflate airbags contains a 50–150 g of sodium azide (NaN_3) which explosively decomposes upon impact, inflating the airbag virtually instantaneously while producing harmless nitrogen gas. This material is harmless following airbag deployment, but can damage shredding equipment if inadvertently left in vehicles that are being recycled. The vehicle manufacturer should therefore ensure that the airbags are properly disposed of before the vehicle is shredded [47].

5. Fuel economy and air emissions

Mcauley [1] stated that almost 87% of a motor vehicle's life cycle energy consumption is in the "use phase" of the vehicle as shown pictorially in (Fig. 8). Furthermore, other key environmental impacts such as air emissions occur predominantly in the oil extraction, refining and transportation to the customers; followed by vehicle "use phase" (More discussion in next sections).

In the wake of the OPEC oil embargo and the tripling of oil prices in the early 1970s, the U.S. Congress passed the Energy Policy and Conservation Act of 1975. This Act established the minimum Corporate Average Fuel Economy (CAFE) standards [1]. As shown in Table 2, the average fuel economy for a US passenger car increased from 20 mpg in 1980 to 27.5 mpg in 2009, while for US light trucks, its fuel economy increased from less than 19.5 mpg in 1980 to more than 23 mpg in 2009 [78]. This disparity in fuel efficiency has developed in North America because of the tremendous growth in the sports utility vehicles (SUV) sales, minivans, and pickup trucks. Federal and state governments have initiated numerous policies to move alternative fuels and energy sources into the US motor vehicle fleets. Outside the United States, many countries have put regulations in place to reduce fuel consumption and air emissions, including imposing high taxes on fuels to encourage energy conservation [79].

The primary pollutants from vehicles' use stage include carbon monoxide CO, nitrogen oxides NO_x, particulate matter less than 10 μm in diameter, sulfur dioxide, and volatile organic compounds (VOC) [50,79]. Large quantities of carbon dioxide, defines as "greenhouse" gas, are also released.

According to Mcauley [1], the US transportation activities account for one-third of the nation's total energy use and carbon dioxide emissions, nearly 80% of carbon monoxide emissions, 50% of nitrogen oxides, 40% of volatile organic compounds, and 33% of carbon dioxide emissions.

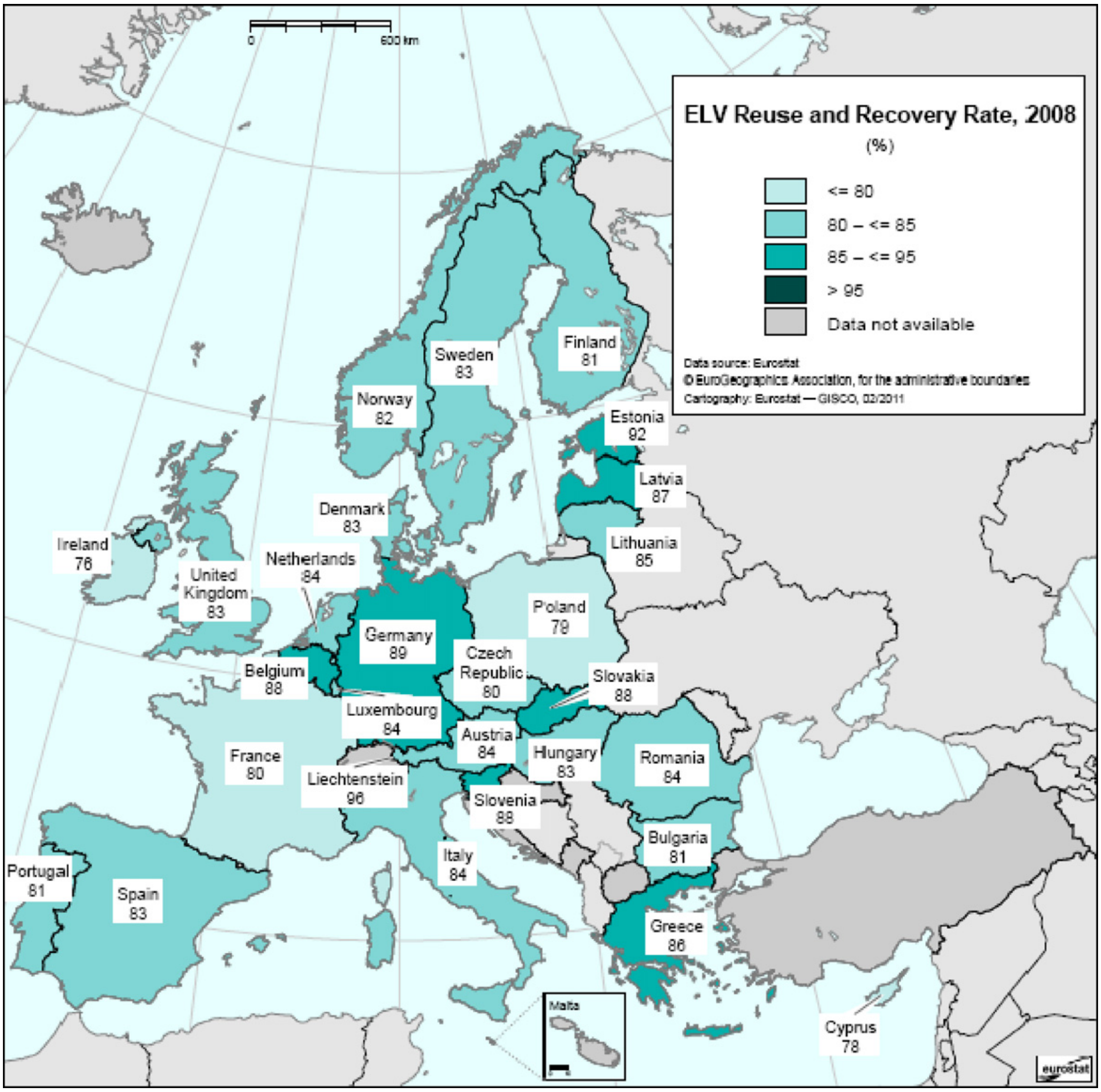

Fig. 7. The recycling and recovery rate of ELVs at European Union in 2008 [77].

Table 2
Average fuel efficiency of U.S. passenger cars and light trucks [78].

	1980	1985	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Average U.S. passenger car fuel efficiency (mpg) (calendar year)														
Passenger car[a]	(R) 16.0	(R) 17.5	(R) 20.3	(R) 21.1	(R) 21.9	(R) 22.1	(R) 22.0	(R) 22.2	(R) 22.5	(R) 22.1	(R) 22.5	(R) 22.5	22.6	U
Other 2-axle 4-tire vehicle	(R) 12.2	(R) 14.3	(R) 16.1	(R) 17.3	(R) 17.4	(R) 17.6	(R) 17.5	(R) 16.2	(R) 16.2	(R) 17.7	(R) 17.8	(R) 18.0	18.1	U
New vehicle fuel efficiency (mpg)[b] (model year)														
Light-duty vehicle														
Passenger car	24.3	27.6	28.0	28.6	28.5	28.8	29.0	29.5	29.5	30.3	30.1	31.2	31.2	32.6
Domestic	22.6	26.3	26.9	27.7	28.7	28.7	29.1	29.1	29.9	30.5	30.3	30.6	31.0	32.6
Imported	29.6	31.5	29.9	30.3	28.3	29.0	28.8	29.9	28.7	29.9	29.7	32.2	31.5	32.6
Light truck (<8500 lbs GVWR)[c]	18.5	20.7	20.8	20.5	21.3	20.9	21.4	21.8	21.5	22.1	22.5	23.1	23.6	24.2
CAFE standards (mpg)[b] (model year)														
Passenger car	20.0	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5
Light truck[d]	U	19.5	20.0	20.6	20.7	20.7	20.7	20.7	20.7	21.0	21.6	22.2	22.5	23.1

KEY: CAFE = corporate average fuel economy; GVWR = gross vehicle weight rating; mpg = miles per gallon; R = revised; U = data are unavailable.

[a] From 1980 to 1994, passenger car fuel efficiency includes motorcycles.

[b] Assumes 55% city and 45% highway-miles. The source calculated average miles per gallon for light-duty vehicles by taking the reciprocal of the sales-weighted average of gallons per mile. This is called the harmonic average.

[c] Beginning with FY 1999, the total light truck fleet ceased to be categorized by either domestic or import fleets.

[d] No combined figure is available for 1980. In 1980, CAFE standard for two wheels drive, and four wheels drive light trucks were 16.0 and 14.0 mpg respectively.

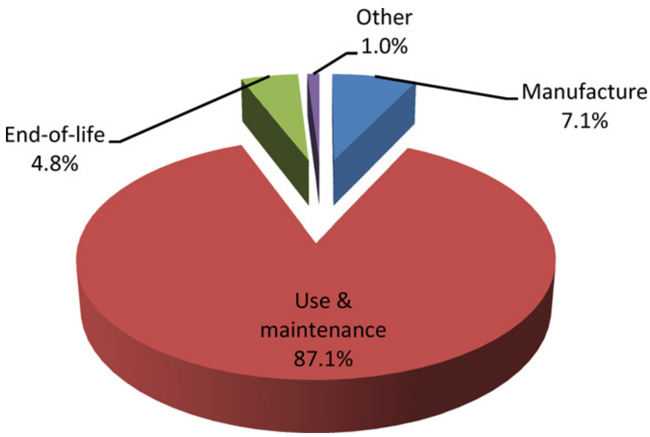

Fig. 8. Energy consumption in auto life cycle [1].

The Intergovernmental Panel on Climate Change (IPCC) concluded that these emission increases have apparent impact on the earth's climate and are believed to be responsible for a significant (1–2 °F) increase in the average global temperature since the pre-industrial times [69]. With the global vehicle usage expected to increase by a factor of 3–5 times today's level by 2050, the impact on global air quality, human health, and global climate could be extremely damaging if significant changes in vehicle design are not implemented globally to arrest these negative trends [69,79].

There are many vehicle design considerations that can impact vehicle air emissions and energy consumption including the use of alternative fuels or new engine technologies [69–71,77], reducing rolling resistance, improving vehicles' aerodynamics and drive train design, and reducing vehicle weight [1,11,15,48]. Ungureanu et al. [11] claimed that vehicle weight is the key source to achieve significant reductions in the life cycle energy consumption and the primary air emissions burdens. This is due to the fact that the rolling resistance and acceleration forces (the essential elements of transportation energy efficiency) are directly proportional to weight of the vehicle [11,70,71].

6. Automotive design and material selection for sustainability purposes

Today, the typical US family vehicle weighs about 1400 kg [1], with iron and steel accounting for the majority of this weight (Fig. 9). However, the new trends in vehicle light-weighting aims not only to enhance the vehicle fuel efficiency, but also to improve its driving performance while lowering its emissions at the same time [75]. This can be achieved to a high degree through the use

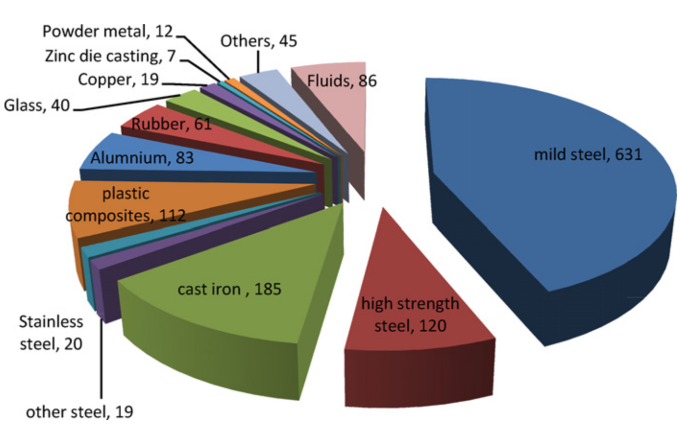

Fig. 9. Material distribution of total vehicle curb weight in kg [50].

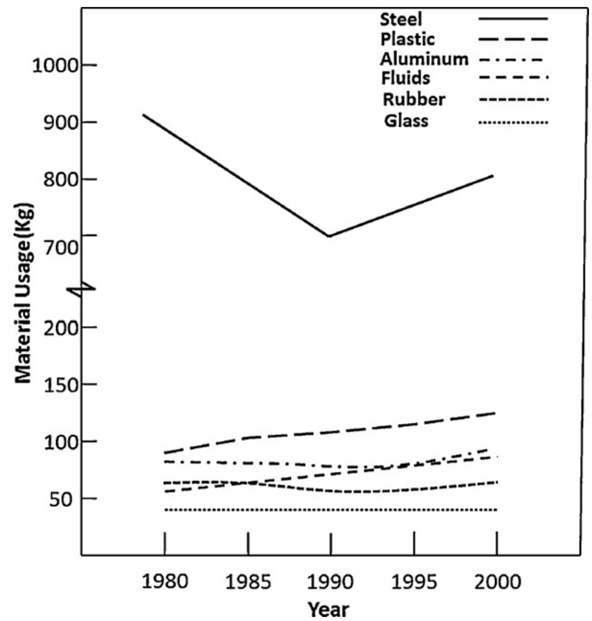

Fig. 10. Material use in the automobile bodies trends [75].

of lighter weight materials like aluminum and plastics [51]. Based on a national study, a 10% reduction in vehicle weight translates to a 5% increase in miles per gallon [75,80]. This in turn means that a sizable savings in gasoline and the accompanying emissions will be achieved with an annual build of 15 million passenger vehicles.

The average passenger vehicle weights declined from about 1527 kg in 1980 to less than 1400 kg in 1991 where OEM's tried to use less steel in the vehicles (Fig. 10). Over this same time period, the amount of plastics used in a typical US passenger vehicle increased from about 4.6% in 1980 to about 10–12% today [15]. However, with this shift in customer demand and preference to larger and heavier vehicles (e.g., SUVs) over the past 20 years, the average vehicle weight has increased with the average fuel efficiency declined [1].

6.1. Models for sustainable material selection for automotive applications

Several methodologies exist for incorporating the environmental concerns in the material selection process. Some methods emphasize selecting materials based on a single portion of a product's life cycle (e.g., end-of-life material recovery); while others attempt to consider the entire life cycle, either qualitatively or quantitatively.

Graedel and Allenby [47] provided a set of material selection guidelines as a set of qualitative selection methodologies. Material selection guidelines are simply rules-of-thumb such as "Choose abundant, non-toxic, non-regulated materials, if possible." Although using qualitative methods can help to classify materials as desirable or not desirable, still the prioritization of certain materials is difficult.

Alternatively, quantitative approaches for environmental material selection, rate the materials using specific indicators; such as: (1) single environmental indicator such as the Eco-Indicator used by Wegst and Ashby [81] or the energy content proposed and used by Ashby [10], or a set of environmental indicators (e.g., CO_2, SO_x, NO_x, a measure of grade of recyclability, and resource scarcity as suggested by Coulter et al. [24]. (2) An economic indicator such as the environmental cost used by Ermolaeva et al. [82].

Ashby [10] demonstrates that the performance index methodology may also be used to evaluate materials based on individual environmental parameters (e.g., energy consumption) in conjunction with other material factors.

Kampe [83] developed a model where a lifetime environmental load associated with the selection of a specific material can be routinely assessed as part of the overall decision making process. This model uses classical mass-based material selection indices developed by Ashby then it introduces some modifications to include the total energy consumption prior to, and during, service. For example, the required mass, m, for a beam of a design-constrained length, L and a fixed, 2:1 cross-sectional aspect ratio, capable of supporting an anticipated uniformly distributed load, W (e.g., N/m), along its length without experiencing overload failure can be expressed as [83]:

$$m = \left(\frac{3}{4\sqrt{2}} \cdot W \cdot L^{7/2}\right)^{2/3} \cdot \left(\frac{\rho}{\sigma_f^{2/3}}\right) \quad (5)$$

Kampe [83] extended the above material selection index to include the total energy expenditure, Q which is required to assure the beam availability for the design. This can be obtained by multiplying the derived mass by the energy content, q:

$$Q = \left(\frac{3}{4\sqrt{2}} W L^{7/2}\right)^{2/3} \cdot \left(\frac{\rho q}{\sigma_f^{2/3}}\right) \quad (6)$$

Table 3 provides specific examples for different materials properties and their index values. These indices indicate that steel would represent the heaviest option, whereas the epoxy-Kevlar composite the lightest. Further, this table indicates that a component fabricated from steel would require the least initial (pre-service) energy expenditure while titanium requires the most.

Starting from the initial energy expenditures required for each of the material options from Table 2, one can now consider how the material selection affects the product energy consumption over its entire lifetime in service. This requires the estimation of a proportionality, or exchange, constant that quantifies the value of mass in terms of lifetime energy consumption. Kampe stated that this value should rely on the magnitude of the desired lifetime, as well as the origins of how strongly the mass affects the energy consumption. Fig. 11 illustrates how an estimated value of the exchange constant might vary with the desired vehicle lifetime based on total mileage. According to Kampe [83], lifetime energy consumption (LEC) can thus be summed using the two components described above, and incorporating the exchange constant to maintain the units compatibility:

LEC = initial energy content + energy consumed over lifetime of vehicle, or in mathematical expression:

$$\mathrm{LEC}' = \frac{\rho \cdot q}{\sigma_f^{2/3}} + C_E \frac{\rho}{\sigma_f^{2/3}} \quad (7)$$

Equation (7) can be easily utilized to assess the lifetime energy consumption for any material option, given the material's properties and a value for the exchange constant for a desired lifetime. Fig. 12 illustrates a selection chart showing two lines of constant lifetime energy consumption; one computed using a 50,000 mile vehicle lifetime and the other a 200,000 lifetime, for a variety of materials. The LEC for steel was used as the basis for both.

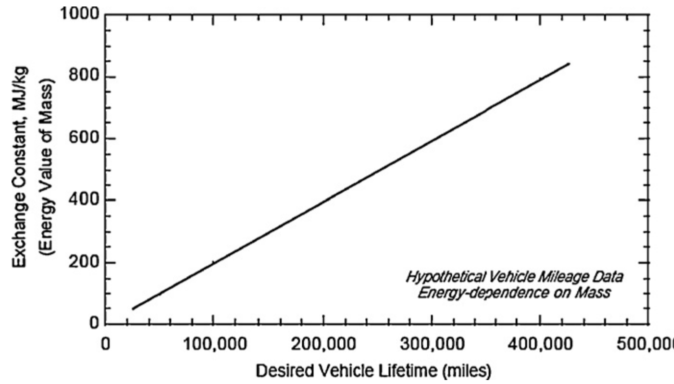

Fig. 11. Approximated relationship between vehicle mass and lifetime energy consumption, computed as a function of vehicle lifetime in miles [83].

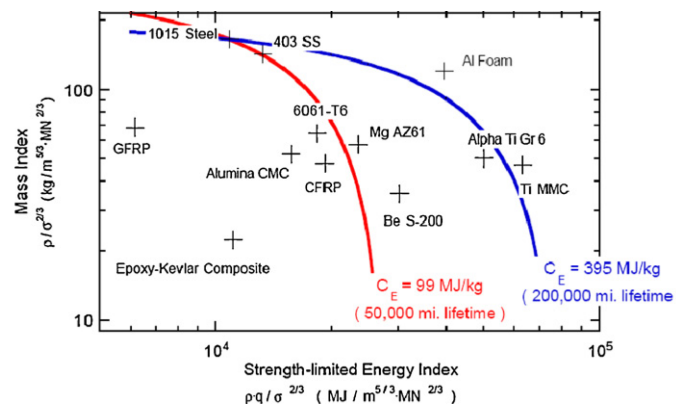

Fig. 12. The mass index plotted as a function of the energy index [83].

Materials with indices reside below the lines represent options that would result in lower LEC over the defined lifetime. The search region will be over the LEC line. By doing so, it can be shown that 6061-T6 aluminum, the carbon fiber reinforced plastic (CFRP), the alumina ceramic matrix composite (CMC), the glass-fiber reinforced plastic (GFRP) and the epoxy-Kevlar composite all considered good options in terms of life cycle energy relative to the steel for a defined vehicle lifetime of 50,000 miles, hence they represent more environment-friendly choices. Also it can be noted that, except for the latter two materials, all candidate materials require higher initial energy expenditures, but they need lower in-service energy expenditures. However, if the defined lifetime extension from 50,000 to 200,000 miles, then the materials of higher initial energy expenditure becomes more competitive or superior to that of the steel baseline material.

Basically, the main drawback of this model is the fact that it does not consider other life cycle phases (i.e. extraction energy and disposal energy). Usually, introducing these energy terms in any model would change the overall conclusions. For example, the recycling fraction of GFRP is almost zero while aluminum is almost 100%

Table 3
Representative material data and its implementation into mass and energy selection indices [83].

Material option	Density	Failure strength (MPa)	Energy content (MJ/kg)	Mass index $\rho/\sigma_f^{2/3}$ (kg/m^3 MPa$^{2/3}$)	Energy index $\rho \cdot q/\sigma_f^{2/3}$ (MJ/m^3 MPa$^{2/3}$)
1015 Steel	7850	328	66	165	10,893
6061-T6 aluminum	2700	270	285	65	18,420
Titanium alloy	4480	845	1000	50	50,143
Epoxy–kelvar composite	1325	460	500	22	11,118

recyclable. This in turn affects overall life cycle assessment of the material options.

One of the most comprehensive LCA models developed by Fitch and Cooper [84] called the life cycle energy analysis (LCEA), is used mainly for material selection. The basic idea behind LCEA for material selection is to estimate the life cycle energy (LCE) of a component where all life cycle stages are considered. The method is adapted from Sullivan and Hu [21] approach for estimating the life cycle energy of internal combustion and electric propelled vehicles. Typically, LCE may be used in conjunction with other environmental indicators to provide a more comprehensive evaluation for sustainable material selection. Fitch and Cooper [84] defined following terms to quantify the selection; E_{MP} – material production energy which is the total energy required to extract a raw material from the earth (e.g., mine ore or pump oil) and to process (e.g., wash, concentrate, or refine) it into a material product (e.g., ingot or rolled sheet). E_{PMP} – primary material production energy describes the material production energy for a primary (virgin) material. E_{SMP} – secondary material production energy to represent the material production energy for a secondary or recycled material. E_{MD} – material delivery energy is the transportation energy required to deliver a material product to a component fabrication facility, and E_{CF} – component fabrication energy is the total energy required to fabricate a component from a useable material form (e.g., ingot or rolled sheet), whereas E_{CD} – component delivery energy is the transportation energy required to deliver a component to a product assembly or maintenance facility. Also, E_{PA} – product assembly energy describes the total energy required to assemble a product from its individual components. E_{PD} – product delivery energy is the transportation energy required to deliver a product to its end user, and E_{USE} – use phase energy is the total energy consumed by the normal use of a product throughout its life. E_{MAINT} – maintenance energy describes the total energy required to maintain the intended function of a component or product throughout the use phase of the product; not including the energy consumed by the normal use of the product. And, finally E_{EOL} – end-of-life energy is the total energy necessarily consumed and actually avoided by the existence of a product after its intended life (e.g., all necessary transportation and disposal energies, and energy credits for the product's value as an energy and material resource).

In the LCEA methodology, the life cycle energy is estimated at the component level as the sum of energy use and between each stage of the life cycle for that component as described in equation (8):

$$\mathrm{LCE}_i \approx (E_{MP})_i(E_{MD})_i + (E_{CF})_i + (E_{CD})_{i1} + \cdots + (E_{PA})_i + (E_{PD})_i + (E_{USE})_i + \cdots + (E_{MAINT})_i + (E_{EOL})_i \tag{8}$$

Table 4
Summary table for LCEA [84].

Phase	Equation	Term definition
Material production energy	$(E_{MP})_i \approx m_i\left[(1-\psi_i)(e_{PMP})_i + \psi_i(e_{SMP})_i\right]$	$(E_{MP})_i$ = material production energy for a component made from material i (MJ) m_i = mass of a component made from material i (kg) c_i = recycled content fraction of material i $(e_{PMP})_i$ = primary material production energy per unit mass for material i (MJ/kg) $(e_{SMP})_i$ = secondary material production energy per unit mass for material i (MJ/kg)
Material delivery	$(E_{MD})_i \approx (E_{MD})_i \approx 0$	$(E_{MD})_i$ = material delivery energy for a component made from material i (MJ) $(E_{CD})_i$ = component delivery energy for a component made from material i (MJ)
Material fabrication	$(E_{CF})_i \approx m_i(e_{CF})_i \approx 0$	$(E_{CF})_i$ = component fabrication energy for a component made from material i (MJ) m_i = mass of a component made from material i (kg) $(e_{CF})_i$ = component fabrication energy per unit mass for material i (MJ/kg)
Product assembly	$(E_{PA})_i \approx m_i(e_{PA})$	$(E_{PA})_i$ = product assembly energy for a component made from material i (MJ) m_i = mass of a component made from material i (kg) e_{PA} = primary material production energy per unit mass for material i (MJ/kg)
Product delivery	$(E_{PD})_i \approx m_i(e_{PD})$	$(E_{PD})_i$ = product delivery energy for a component made from material i (MJ) m_i = mass of a component made from material i (kg) e_{PD} = primary material production energy per unit mass for material i (MJ/kg)
Use phase	$(E_{USE})_i \approx \rho_f(e_{MP})_f L_V\left(\frac{1}{\mathrm{MHFE}'} - \frac{1}{\mathrm{MHFE}}\right)$	$(E_{USE})_i$ = use phase energy for a component made from material i (MJ) ρ_f = density of fuel (kg/gal) $(e_{MP})_f$ = material production energy of fuel per unit mass(MJ/kg) LV = vehicle life (miles) MHFE = metro-highway fuel economy of vehicle without component (mpg) $(\mathrm{MHFE}')_i$ = metro-highway fuel economy of vehicle with component made from material i (mpg)
Maintenance and end-of-life	$(E_{MINT})_i \approx$ $m_f\left(\frac{L_V}{L_C} - 1\right)[(1-\psi_i)(e_{PMP})_i + \ldots + \psi_i(e_{SMP})_i]$ $+(e_{CF})_i + (1-\Phi_i)e_{DE} + \Phi_i[(e_{PMP})_i - (e_{SMP})_i]$ $(E_{EOL})_i \approx m_i[(1-\Phi_i)e_{DE}] + \Phi_i[(e_{PMP})_i - (e_{SMP})_i]$	$(E_{MAINT})_i$ = maintenance energy for a component made from material i (MJ) $(E_{EOL})_i$ = end-of-life energy for a component made from material i (MJ) m_i = mass of a component made from material i (kg) L_V = vehicle life (miles) L_C = component life (miles); assumed <LV c_i = recycled content fraction of material i $(e_{PMP})_i$ = primary material production energy per unit mass for material i (MJ/kg) $(e_{SMP})_i$ = secondary material production energy per unit mass for material i (MJ/kg) $(e_{CF})_i$ = component fabrication energy per unit mass for material i (MJ/kg) ψ_i = recycle fraction of material i e_{DE} = disposal energy per unit mass of material i

where: LCE_i = life cycle energy for a component made from material i (MJ).

Table 4 summarizes the life cycle phases, assumptions used and the developed equation for each phase as described by Fitch and Cooper [84].

Fitch and Cooper [84] study used the fuel efficiency algorithm that was originally presented by Sullivan and Hu [21], in addition the Metro-highway fuel efficiency is estimated for both the vehicle without a component and for the vehicle with a component for each material using.

$$\text{MHFE} \approx F(M_b - m_b)^{-\text{FEPI}} \quad (9)$$

$$\text{MHFE}' \approx F(M_b - m_b + m_i)^{-\text{FEPI}} \quad (10)$$

MHFE = metro-highway fuel economy of vehicle without component (mpg).

$(\text{MHFE}')_i$ = metro-highway fuel economy of vehicle with component made from material i (mpg).

F = constant used to balance equation = 1052.57 for 2270 lb (1030 kg) vehicle presented by Sullivan and Hu [21].

M_b = baseline vehicle mass (kg).

m_b = baseline component mass (kg).

m_i = mass of a component made from material i (kg).

FEPI = fuel efficiency percentage increase for a 10% weight savings = 0.50 for 2270 lb (1030 kg) vehicle presented by Sullivan and Hu [21].

In this paper, Fitch and Cooper [84] provided an example of this material selection approach for an automotive bumper-reinforcing beam, with Table 5 presenting the beam masses for the different selected materials.

The results of the life cycle energy analysis are presented in Table 6.

From sustainability point of view, energy consumption is only one aspect by which the material selection affects the environment. Some materials can be toxic, pose potential disposal problems, or cause the destruction of habitat. The selection of certain materials can also lead to increase global warming and changes in land use. Through its influence on vehicle emissions, material selection can also affect air quality (e.g., low level ozone and particulate matter).

Because energy consumption, like any other single metric, is unable to serve as a universal indicator of sustainability, being able to estimate other metrics as quickly and as easily as energy would be advantageous for material selection. However, most other metrics are still hard to estimate and quantify.

Table 5
Mass comparison for equivalent reinforcing beams [84].

Reinforced beam materials	Mass (kg)
PP/GF (unidirectional)	2.09
M220HT steel	2.50
M190HT steel	2.82
Al 7129-T6	2.84
PUR S-RIM 54% glass (chopped and mat)	2.90
PC/PBT (injection molded)	3.40
M160HT steel	3.44
140X or T steel	3.76
PUR S-RIM 41% glass (chopped and mat)	3.90
Al 6061-T6	3.90
PP/GF (direct melt/random)	4.50
PC/PBT (blow molded)	4.54
SMC	4.81
PP	6.80
180 Plannja steel	7.71

On the other hand, Kasai [22] presented a quantitative model to evaluate environmental burdens. This model used complete records for material design options and ranked the candidate materials as compared to the baseline model that is made out of Steel (STAM540H). Actual data was tabulated to rank candidate materials based on the %Weight saving, the total reduction of exhaust emissions, and the total energy savings (material production, part manufacturing, operation and recycling).

Kasai research presented an example of propeller shaft used in middle duty trucks. Table 7 shows the conditions and assumptions used [22], while Table 8 shows the results for estimated lifetime of 150,000 km [22].

This model has some drawbacks; such as some unreasonable assumptions were made including the effect of reducing the vehicle weight on the MPG to be around 9 L per 150,000 km per kg of weight reduction, and the assumptions used for the end-of-life scenario where all metals were assumed to be 100% recycled and plastics is assumed to be 100% land-filled.

Saur et al. [23] provided an example of life cycle assessment for automobile fender design. They ranked the candidate materials; steel, aluminum sheet, rubber modified polypropylene (PP/EPDM), nylon-polypropylene-neoxide blend (PPO/PA), and polycarbonate-polyethylene terephthalate (PC/PBT). In their study, different aspects of sustainability are used to interpret the LCA results, including: energy, resource depletion, water pollution, global warming potential, ozone depletion potential, air pollution, eutrophication potential (EP), photochemical ozone creation

Table 6
Life cycle energy analysis results for a bumper-reinforcing beam on a 1030 kg vehicle [84].

Reinforced beam materials	Material production energy (MJ)	Product assembly energy (MJ)	Product delivery energy (MJ)	Use phase energy (MJ)	Maintenance energy (MJ)	End-of-life energy (MJ)
PP/GF (unidirectional)	118	36	2	604	117	−1
M220HT steel	100	44	2	722	60	−41
M190HT steel	113	49	3	815	67	−46
Al 7129-T6	558	50	3	820	148	−409
PUR S-RIM 54% glass (chopped and mat)	143	51	3	838	145	2
PC/PBT (injection molded)	138	60	3	994	82	−56
M160HT steel	151	66	3	1086	90	−61
140X or T steel	766	68	4	1126	204	−562
PUR S-RIM 41% glass (chopped and mat)	214	68	4	1126	216	2
Al 6061-T6	255	79	4	1299	253	−2
PP/GF (direct melt/random)	539	59	3	982	447	−92
PC/PBT (blow molded)	258	84	4	1389	261	2
SMC	720	79	4	1311	597	−123
PP	309	135	7	2224	166	−143
180 Plannja steel	506	119	6	1962	443	−63

Table 7
Conditions and assumptions [22].

	Steel (former)	Steel (current)	Al	FRP
Material code (JIS or ISO)	STAM540H	STAM735H	Modified 6061-T8	EP – (CF + GF)70
Tensile strength (MPa)	540	735	365	400
Specific gravity	7.85	7.85	2.91	1.85
Weight of the part (kg)	20.2	17	13.7	6.2
Energy used for material production (MJ/kg)	25.3	26.8	233	100
Energy used for part production (MJ/kg)	53.8	57	293	100
Saving of fuel consumption (L/kg) due to weight reduction	0	9	9	9
Reduction of exhaust gas emissions (per kg) due to weight reduction	−21 kg CO_2	−21 kg CO_2	−21 kg CO_2	−21 kg CO_2
	−51 g NO_x	−51 g NO_x	−51 g NO_x	−51 g NO_x
	−172 g CO	−172 g CO	−172 g CO	−172 g CO
	−26 g SO_x	−26 g SO_x	−26 g SO_x	−26 g SO_x
Recyclability (%)	100	100	100	0

Table 8
LCI results for propeller shaft, total distance 150,000 km (diesel fuel has 38.5 MJ/L) [22].

	Steel (former)	Steel (current)	Al	FRP
Material code (JIS or ISO)	STAM540H	STAM735H	Modified 6061-T8	EP – (CF + GF)70
Weight of the part (kg)	20.2	17	13.7	6.2
Weight reduction (kg)	0	−3.2	−6.5	−14.0
(1) Saving of energy for material production (MJ)	0	−3.2	−6.5	−14.0
(2) Saving of energy for part production (MJ)	0	−55	+2681	+109
(3) Saving of energy for operation (MJ)	0	−118	+2927	−467
(4) Recovered energy through recycling (MJ)	−329	−277	−2202	−4743
Total energy saved = (1) + (2) + (3) + (4)	−329	−1534	+991	−5101
Total reduction of exhaust gas emissions for 150,000 km of operation	0	−67 kg CO_2	−136 kg CO_2	−294 kg CO_2
	0	−153 g NO_x	−331 g NO_x	−714 g NO_x
	0	−533 g CO	−1118 g CO	−2408 g CO
	0	−83 g SO_x	−169 g SO_x	−364 g SO_x
Solid waste at the end-of-life (kg)	0	0	0	6.2 (it is hard to separate FRP)

potential (PCOP), human-toxicity, eco-toxicity and the waste produced. Then each material was analyzed based on these metrics for further analysis in order to rank them in comparison to the baseline steel fender. Additionally, Saur et al. [23] suggested the use of subjective scores for each sustainability metric, this is done by surveying expert and non-expert people to score each of the above metrics. However, this methodology suffers from some drawbacks; specifically, the proposed LCA in their study is limited to the environmental impacts as one can see from the selected life cycle metrics. Also, other drawback is due to the difference in the scorings derived from policy statements, opinion polls among expert people (ecologist and material scientist) and the public. For example, the weights differ significantly between expert people and public (Table 9), however; expert people assumed worst case scenarios for emissions and pollutions and focused on the raw material scarcity, while the scorings assigned by non-expert people is based on lesser importance considerations such as energy consumption.

The final results of Saur et al. [23] research (Table 10) showed that the PP/EPDM ranked first while aluminum ranked fourth. Steel ranked in third place making the steel more environmentally friendly than aluminum.

6.2. Design consideration for sustainable vehicles

Current automotive designs are still based on metal-intensive uni-body structures manufactured using old infrastructures and processing methods some originating in the early 1900s. The need for sustainable products, however, will ultimately drive vehicle designs toward new materials such as hybrids (specifically composites, lattice based, segmented and sandwich materials) in addition to lighter weight metals and their composites. Some material alternatives can be up to 5 times lighter than ferrous metals (e.g. fiber reinforced plastics (FRP)).

Table 9
Scores assigned by policy statement team, expert and non-expert people for LCA [23].

Category	Policy GER, EU	Experts GER, EU	Population GER, EU
Energy	7	10	3
Resources	3	7	2
Water	1	1	1
GWP	9	10	6
ODP	10	6	10
AP	7	5	4
EP	4	3	4
PCOP	1	3	3
H-tox	8	8	8
ECO-tox	6	9	9
Waste	3	10	9

Plastics today make up less than 12% of the average vehicle's weight in the United States. According to Mcauley [1] using plastics in light-weight vehicles save 30 times more energy over the life cycle of an automotive than the energy required for its fabrication.

At the same time, using these new materials poses several manufacturing challenges mainly in its formability using the current press-based stamping; for example Mg can be better formed through casting and superplastic forming. At the same time, superplastic forming or injection-molding can't produce parts at the required cycle time for an automotive facility [85].

Table 10
Environmental theme evaluation for some materials that can be used in automobile fender [23].

	Al	Steel	PC/PBT	PP/EPDM	PPO/PA
Score	0.237	0.232	0.210	0.165	0.259
In%	91.5%	89.6%	81.1%	63.7%	100.0%
Rank	4	3	2	1	5

The newer vehicle designs would need to combine an ultra-light-weight design with an auxiliary propulsion system likely a hybrid or fuel cell assisted internal combustion engine, such approach could increase the vehicle's energy consumption efficiency 3–5 times the current designs while significantly reducing the tailpipe emissions as well [86]. A new manufacturing and service infrastructure based on advanced light-weight materials, such as plastics and composites, will ultimately need to be developed. Such development efforts and trends are under-way; for example ford has developed a customized superplastic forming process named the ford advanced superplastic forming technique (FAST) while General Motors (GM) uses a quick plastic forming technology [87].

These new manufacturing innovations could be designed to produce new and exciting automotive designs and architectures that not only enhance the passenger safety and but also provide shorter development times with more customization content and potential and at lower capital investment intensity as well [88].

Other design considerations include the incorporation of design features that facilitate the end-of-life vehicle recycling and recovery. To do this, the ease of disassembly the low number of materials and parts should be considered as critical design features. Nowadays, vehicles consist of approximately 15,000 parts. In plastics, a move toward parts consolidation into one polymer family sometime called "mono-material construction", that can lead to vehicle designs with improved recyclability as well as reduced parts count and vehicle weight [1].

Anastas and Zimmerman [67] highlighted two key principles required in Green engineering designs; (a) the design for separation and (b) to minimize material diversity. These principles are important from the vehicle end-of-life recycling and recovery perspectives.

Lutsey [89] and Stodolsky et al. [8] identified at least three ways to decrease the weight of a vehicle in order to improve its fuel consumption: reduce its size, optimize its design to minimize weight, and replace the heavy materials currently used in the vehicle construction. Because safety and performance are still perceived to be related to vehicle size, this might have led to more demand and interest for bigger cars. Thusly, automotive OEMs have investigated new alternative materials to reduce the vehicle weight without sacrificing its utility or size.

The selection of new materials for automobile bodies is driven by a series of techno-economic issues. When part of the body-in-white is replaced with a different material, there are associated changes in the design, the manufacturing, and the recycling that might pose additional expenses and risks outweighing the expected benefits [84]. At the same time, the best strategy for offsetting the risks and costs against the benefits of using a newer technology is to apply it where the current technology remains an acceptable alternative. Ferrão and Amaral [64] compared and analyzed the manufacturing costs of fabrication and assembly for aluminum and steel auto bodies for two vehicle classes; small fuel-efficient designs and mid-size designs; considering the aluminum prices in 2001 and using current aluminum fabrication technology. This study identified two keys obstacles for aluminum to become a substitute for steel; the first is the higher material cost and second is the higher tooling costs associated with aluminum panel forming and welding. The study also stated that it is unclear which aluminum design; space frame design or uni-body architecture is more economical and is better suited for mass production scenarios. In order to produce an aluminum intensive car (aluminum percentage in body in white >30%) with the same overall manufacturing costs as steel, the price of aluminum must drop down to be comparable to the cost of steel [15]. However, aluminum has the potential to become the primary material used in the auto body structures if new governmental legislations force the auto-makers to improve the fleet

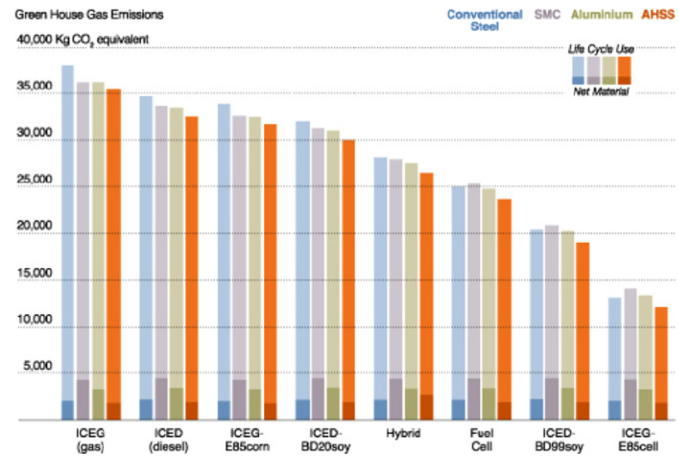

Fig. 13. Life cycle GHG's, varying by materials, power-trains and fuel sources [72].

fuel economy and percent recycled parts [70,71]. Mayyas et al. [75] used multi-attribute decision making tools, namely analytical hierarchy process (AHP) and quality function deployment (QFD) to rank several engineering materials for substituting the steel baseline body-in-white. This study concluded that steel is still the best choice in terms of functionality, cost and manufacturability.

Studies from the World AutoSteel organization on the life cycle assessment of different combination of vehicle bodies and power-trains [72]; with design options including steel, aluminum, sheet molding compounds (SMC) and advanced high strength steels (AHSS) for body construction, and power-trains including internal combustion engines, hybrid and fuel cell power-trains; showed that using AHSS steel generates much less environmental damages in terms of green house gases than mild steel or aluminum do, as shown in Fig. 13.

Assuming that the manufacturing and the assembly processes differ slightly, the environmental burdens are quite similar for both materials at the manufacturing phase, however the use stage generates the most environmental problems in terms of gaseous emissions. Petroleum refining and combustion are assumed to be the two primary sources of effluents. Having a fuel consumption improvement, the study concludes that the AHSS BIW generates less atmospheric emissions than aluminum BIW during the total operational stage. However, in post-use stage the environmental burdens for recycling the aluminum BIW structure are lower compared that those in case of mild steel or AHSS steel. Whether aluminum generates sufficient environmental and health benefits to offset its cost disadvantage is difficult to predict because these benefits must be weighed against the monetary cost.

Das [20] compared the energy usage and CO_2 emission for different BIW options made from conventional mild steel, aluminum and ultra light steel auto body (ULSAB) design at both the vehicle and fleet levels [20]. The main study finding indicated that the benefits of using aluminum in automotive components are significantly reduced when compared to the ULSAB counterpart than when compared to the traditional steel. Regarding the energy usage, the benefits of the lower energy used during the use stage, are compromised by the higher manufacturing energy consumption of aluminum. Thus having the energy saved during the recycling stage to be the main contributor to the total life cycle benefits of aluminum. In terms of CO_2 emissions, steel and ULSAB have the advantages in the early life cycle years, due to their relatively low energy use and low emissions during the manufacturing stage, which is diminished each year because of the better fuel efficiency of aluminum BIW [15,20]. From both the energy and CO_2 emissions perspectives, it would take about 4 years and 10 years, respectively, for aluminum vehicles to achieve life cycle equivalence with steel and the ULSAB. At fleet level, the benefits of aluminum are delayed, because vehicle replacement occurs over several years rather than all at once.

Significant challenges still lie ahead for the automotive industry and its design as well as the advanced materials industry in order to attain the sustainability goals. Yet, society must drive the industry toward sustainable product design in a long-term basis. The earth contains limited resources enclosed in a single life-sustaining atmosphere. Therefore, control of global air emissions as well as resource conservation is the major goals to attain long-term sustainability of all living species on earth.

7. Sustainability measures and models in automotive industry

Even though there are researchers who have introduced several methodologies to assess the environmental aspect of sustainability where the full environmental consequences of a product or a system is evaluated. Still there is no universally accepted method to quantify all the aspects of product sustainability [90]. Fiksel et al. [91] stated that the desire to assess all major aspects of sustainability, has pushed product designers to find new methods and tools to improve the existing standards and measurable factors in order to reduce the need for virgin raw materials, choose the right eco-friendly sources of energy, minimize wastes, and maximize the product end-of-life value. Following discussion discusses some of the methods developed by the automotive OEMs to assess such impacts based on their production infrastructures and production volumes.

7.1. Environmental product declaration (EPD) from Volvo

Implementing sustainability principles in designing and manufacturing new vehicles that is unique and specific to the company goals and product portfolio is becoming a priority for OEMs. Environmental product declaration (EPD) is one of such models that have been developed by the cooperation between Swedish Environmental Institute and the Volvo Car Corporation [47]. The purpose of an EPD is to enable customers to evaluate the environmental impact of different vehicles [92]. The EPD system covers all phases in the life cycle of a vehicle, from production of the raw materials to final disposal and recycling, and provides information on the environmental impact of each. With systems considered being large and complex as well as the approximations made in some cases especially large trucks, are limiting factors for EPD accuracy and reliability. Hence, the results should be treated as a guide to some of the more important environmental parameters in the life cycle of the product. Another limitation of EPD system is the unit used to assess the environmental impact, which is the environmental load unit (ELU) per kilogram of material used. Actually, ELU is a rating method that ranks the environmental impact of any material to the environmental impact resulted from 1 kg of methane (CH_4). However, the ELU still lack the international approval as it is considered as a non-standardized unit. The Volvo trucks EPD system is a derivative of the main EPD; where the Volvo trucks EPD is divided into four sections, also see Fig. 14:

- Materials and production: Which deals with the environmental impacts of raw materials production, manufacturing operations at Volvo truck plants in Europe, production at suppliers' plants and transport.
- Fuel and exhaust emissions: Deals with the environmental impact of exhaust emissions based on certification tests for each specified engine type.

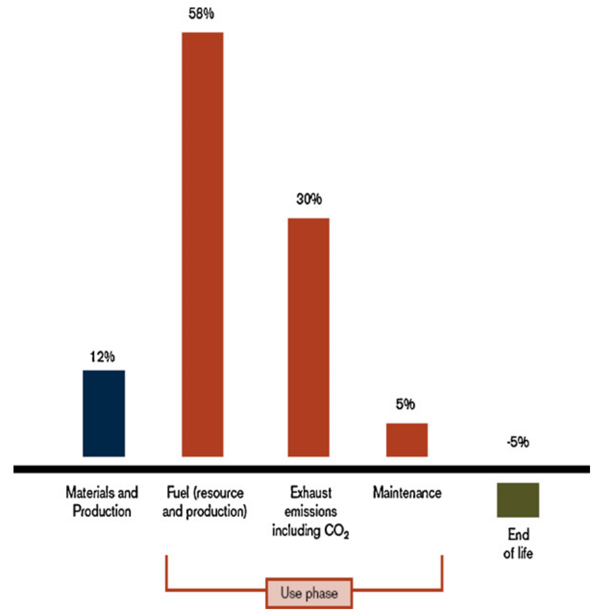

Fig. 14. Distribution of the environmental impact from a Volvo FH truck in long-haul operation [74].

- Maintenance: Deals with the environmental impact (based on average values) of the use of consumables and materials in preventive maintenance and parts production.
- End-of-life: Deals with the environmental impact of product disposal, waste management and the recycling of truck materials.

Volvo aims to ensure that every new product has a lower environmental impact than the one it replaces. Emissions of nitrogen oxides, carbon monoxide, hydrocarbons and particulates from Volvos trucks have been cut by 60–85% since the mid-1970s [92]. Volvo established a hard target to achieve further reduction of today's emission levels by two-thirds over the next decade. At the same time, the vehicles will become increasingly fuel efficient, which will reduce emissions of carbon dioxide.

7.2. Ford of Europe's product sustainability index (PSI)

Ford of Europe's product sustainability index (PSI) is a simple sustainability management tool that can be directly used by engineers, i.e., not by sustainability or life cycle experts. PSI is composed from eight indicators; mainly the life cycle global warming potential (GWP), life cycle air quality potential, sustainable materials, restricted substances and drive by noise, social (mobility capability and safety) and economic (life cycle cost of ownership) vehicle attributes [93,94]. Table 11 showed these eight indicators and their definitions. According to Schmidt and Taylor [93], Ford Galaxy and S-MAX were the first vehicles to use this tool from their inception phase. The results show significant improvements when compared to the predecessor models [95,96].

The limitations of this model come from the limited number of sustainability indicators used and the way these metrics are defined. Because, limiting sustainability model to eight indicators may be considered as a shortcoming of the model more than being a simplification. The PSI also defines the "life cycle cost" assuming that the cost is the sum of vehicle price and 3 years of service (See Table 2). This means that the PSI accounted for the vehicle cost from the company perspective not the total life cycle of the vehicle.

Table 11
Product sustainability index (PSI) metrics [92].

	Indicator	Metric/Method	Driver for inclusion
Environmental and health	Life cycle global warming	Greenhouse emissions along the life cycle (CO_2 and equivalent emissions from raw material extraction through production, use to recovery) – part of an LCA according to ISO 14040	Carbon intensity is the main strategic issue in automotive industry
	Life cycle air quality	Emissions related to summer smog along the life cycle (ethene and equivalent emissions) – part of an LCA according to ISO 14040	Potential trade-offs between CO_2 and non-CO_2 emissions
	Sustainable materials	Recycled and natural materials related to all polymers[a]	Resource scarcity
	Substance management	Vehicle interior air quality (VIAQ)/allergy-tested interior, management of substances along the supply chain	Substance risk management is key
	Drive-by-noise	Drive-by-exterior noise = dB(A)	Main societal concern
Societal[b]	Safety	Including EuroNCAP stars (including occupant and pedestrian protection)	Main direct impact
	Mobility capability	Mobility capacity (seats, luggage) to vehicle size	Crowded cities (future issues include: diversity – disabled drivers, etc.)
Economics	Life cycle cost	Sum of vehicle price and 3 years service (fuel cost, maintenance cost, taxation) minus residual value (note: for simplification reasons cost have been tracked for one selected market; life cycle costing approach using discounting)	Customer focus, competitiveness

[a] There are, of course, no materials that are inherently sustainable. All materials are linked to environmental, social and economic impacts. However, recycled materials and renewably grown, natural fibers represent an example of how limited resources can be used in a more sustainable way. The overriding factor is whether or not these materials have, in their specific application, a lower environmental impact through the product life cycle than potential alternative materials (see life cycle related PSI indicators and previous paper [93]).
[b] The social aspects are being refined and developed for the future. Please note that aspects related to labor, rights etc. are part of other Ford of Europe sustainability management tools such as the MSI.

7.3. Asian auto-makers and their sustainability approaches

The Japanese OEMs like Toyota, Nissan, Honda, Mazda, Mitsubishi, Daihatsu, Subaru, Hino, Suzuki and Isuzu have environmental reporting guidelines which attempts to correlate environmental costs with environmental benefits. The benefits include cost savings from reduced energy consumption, cost savings from reduced waste processing costs, sale of recyclable goods and other income from environmental technologies [98]. Nowadays, major Asian automobile manufacturers like Toyota, Honda, and Nissan are considering sustainability as a part of their manufacturing practices; for example, Toyota Corporation emphasizes three key areas of sustainability: reducing, recycling, and reusing. Knowing that lean manufacturing is widely adopted by Japanese auto-makers, Fliedner [97] discussed seven lean manufacturing principles and how they can save money through waste reduction and elimination (Table 12); however, Fliedner claims that these lean principles can lead to green manufacturing practices and hence support sustainable manufacturing at any facility that implements lean manufacturing principles.

One of the important sustainability approaches in Asia is “Hitozukuri and Monozukuri’ philosophy which deeply rooted in Japanese culture to respectively addresses educating human to be a responsible individual who can lead the world to a better place and making things with excellence, skills, spirit, zest, pride, and more [99,100]. Hitozukuri and Monozukuri aims to ensure balance and harmony with nature, where integration and synthesis play a major role. Monozukuri represents the maker’s philosophy of how to make things – this philosophy deeply rooted to Japanese tradition in Zen, Confucius’s teaching [99], two important pillars to support the century old Japanese culture. In fact, Monozukuri is a philosophy rather than technique or method. If “mono” is replaced with “hito” which means human, monozukuri becomes hitozukuri, or education in English; however, Hitozukuri has a much broader meaning and stresses a life-long process of learning. Hitozukuri emphasizes several different steps of human development, whose original form was emphasized by Confucius in his famous six different human development stages [99,100].

8. Summary

Nowadays, with the escalating fuel prices and awareness of environmental changes more attention is focused on order to develop sustainable products. At present automotive industry is considered the most influential industries in the world; hence both OEM’s and customers are looking for more sustainable vehicles in terms of fuel efficiency and less environmental impacts. This paper is an attempt to give the reader a comprehensive discussion about main topics related to sustainability in automotive industry. Discussion of life cycle assessment (LCA) was provided in Section 2. Also, some challenges associated with LCA have been highlighted like the actual lifetime, vehicle degradation while in use, and the real value of monetary units. Moreover, design-for-X and its implications on design for sustainable vehicles have been addressed in Section 3. This paper also discusses recycling and end-of-life vehicles, for example, European Union had set aggressive targets (>75% of the retired vehicle should be recycled and/or recovered by 2008).

The rest of the paper was organized in order to discuss material selection for sustainability purposes and evaluating the selection from energy and life cycle perspectives. However, life cycle assessment method requires an extensive amount of data inventory and it mainly quantifies the environmental impact of the vehicle over its life cycle. Actually, LCA does not deal with other sustainability aspects such as social impact, economic impact, and technical requirements.

After that the discussion proceeds to highlight two of the sustainability models that used by OEMs. Environmental product declaration (EPD) from Volvo and Ford of Europe’s product sustainability index (PSI) were presented and discussed in details. Basically, the major limitation of EPD comes from the area it covers; however, EPD only covers environmental impacts through the vehicle’s life cycle. On the other hand, Ford of Europe’s PSI lacks of

Table 12
Lean methods and tools with associated environmental benefits [97].

Lean method/Tool	Examples of observed environmental benefits
Kaizen events	• Uncovering and eliminating hidden wastes and waste generating activities
Value stream mapping	• Magnification of environmental benefits of lean production (e.g., reduced waste through fewer defects, less scrap, less energy usage, etc.) across the network; • Environmental benefits may be more broadly realized by introducing lean to existing suppliers rather than finding new, already lean suppliers
5S	• Clean windows reduce lighting requirements; • Spills and leaks noticed more quickly; • Reduced consumption of materials and chemicals when equipment, parts, and materials are organized and easy to find
Cellular manufacturing	• Smaller set-up times reduces energy and resource needs; • Fewer product changeovers reduces energy and resource needs
Pull approach	• Lower in-process and post-process inventory; avoids potential waste from damaged, spoiled, or deteriorated products; • Less floor space needed; potential decrease in energy use
Total preventive maintenance	• Increased longevity of equipment decreases need for replacement equipment and associated environmental impacts; • Decreased number and severity of spills, leaks, and upset conditions: less solid and hazardous waste
Six sigma	• Fewer defects which reduces energy and resource needs; avoids waste; • Focuses attention on reducing the conditions that result in accidents, spills, and malfunctions, thereby reducing solid and hazardous wastes
Pre-production planning	• Reduces waste at the product and process design stage, similar to "Design for Environment" methods; • Use of right-sized equipment lowers material and energy requirements; • Reducing the complexity of the production process ("design for manufacturability") can eliminate or streamline process steps; environmentally sensitive processes can be targeted for elimination, since they are often time-, resource-, and capital-intensive; • Less complex product designs can use fewer parts and fewer types of materials, increasing the ease of disassembly and recycling
Lean supplier networks	• Magnification of environmental benefits of lean production (e.g., reduced waste through fewer defects, less scrap, less energy usage, etc.) across the network; • Environmental benefits may be more broadly realized by introducing lean to existing suppliers rather than finding new, already lean suppliers

complete coverage of sustainability metrics and has some drawbacks in terms of life cycle cost assessment.

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