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Life Cycle Assessment of C-Segment Gasoline Powered Passenger Car in India

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***Abstract*— This paper presents an evaluation of the environmental performance of gasoline driven mid-size passenger car in India using Life Cycle Assessment (LCA) approach. LCA study has been carried out in line with ISO 14040/44 standards. This assessment provides comprehensive overview of various environmental impacts during the different phases (production, use phase and end of life) of vehicle life cycle. LCA model has been developed using GaBi 6 software of thinkstep AG for the material production, assembly of the vehicle, use and end of life stages. Primary data has been collated for "average mid-sized" European petrol passenger car as described by the 2008 JRC IMPRO-car study and the same has been tailor made to Indian condition in GaBi model. The outcome of this study can be used to identify strategies for reduction of environmental impacts, prioritisation of environment improvement programs. This will also provide strategic guidelines to react to the introduction of new technologies, processes, materials etc. with respect to invest decisions and integration of environment criteria for automotive companies in India. Life cycle impact results can be also used to transparently communicate to various stakeholders.**

***Keywords*—Life Cycle Assessment, Automotive, Design for Environment, Product Stewardship**

I. INTRODUCTION

Over the years, the global passenger vehicle fleet has annually grown by about 5%, reaching about 900 million vehicles in 2013 and consuming more than 20 million barrels of crude oil per day. This fleet is expected to increase up to 1.7 billion vehicles in 2035 [1]. Several LCA studies carried out to evaluate the environmental performance of conventional passenger vehicles have been published during the last couple of years [3–8]. There has been increasing commitment from the automobile industries to address the challenging environmental issues. The prime objective of automobile industry is to show and prove the environmental friendliness in establishing green supply chain, environmental compatible production processes, state of art end of life technology and also demonstrate that the automobile Industry is not only going beyond to statutory requirements but also position itself at par with developing world class product in India.

Life Cycle Assessment (LCA) is one of the key tools for evaluating and assessing the environmental burdens associated with resource consumption, energy consumption, emissions, effluent and solid waste generation during the life span i.e. cradle to grave of the vehicle [9,10]. It helps in identifying the "hot-spots" with respect to various environment parameters at various stages of vehicle production. The study also facilitates in evaluation of impact during the various phases such as material sourcing, logistics, manufacturing, distribution and end-of- life stages. In view of this, a cradle to grave LCA study for a medium segment car has been carried out based on the data available in the public domain. The goal is to document by facts and figures the actual status of the environmental performance particularly focussing on energy consumption, Green House Gas (GHG) emissions and other life cycle impact indicators for the vehicle in a holistic manner while establishing the "product Stewardship" concept in the organisation. The study also aims to identify short term, medium term and long term strategy for reduction of environmental impacts, prioritisation of environment improvement programs and provide strategic guidelines to react to the introduction of new technologies, processes, materials etc. with respect to invest decisions and integration of environment criteria in automotive company.

Life Cycle Assessment (LCA) has been established as an effective tool in the automobile industry to support decisions during the development process concerning the ecological performance of vehicles. On the one hand, LCA provides detailed information on environmental parameters and impacts related to product life cycles. The key objective of the study aims to achieve the following aspects [5]:

a) Understand current status of environmental performance of the typical c-segment car in India which will enable in identification of optimisation potential by automotive companies.
b) Establish knowledge on value chain of the car in India and identify significant parameters for improving the sustainability of future products.

c) Effective support to fulfil existing and upcoming regulations on End-of-Life-Vehicles.
d) A comprehensive platform for communication with authorities, environmental organizations as well as with society.
e) Baseline for evaluating the product and production-site related environmental protection measures.

II. LIFE CYCLE ASSESSMENT AND ITS DRIVERS

Life Cycle Assessment (LCA) is the systematic analysis of the environmental impact of products during their entire life cycle. The life cycle of a product comprises of production, use and disposal phases. Environmental impacts are evaluated throughout, also including the upstream and downstream processes associated with the production (e.g. production of raw, auxiliary and operating materials) and with the disposal (e.g. waste treatment). Environmental impacts refer to all relevant extractions from the environment (e.g. ores and crude oil), as well as emissions into the same (e.g. wastes and carbon dioxide) [9, 10].

The International Organisation for Standardisation (ISO), provides guidelines for conducting a Life Cycle Assessment within the series ISO 14040 and 14044[9,10].

The main phases of an LCA are:

- *Goal & Scope definition*, the product or service to be assessed is defined, a functional basis for comparison is chosen and the required level of detail is defined.
- *Inventory analysis* of extractions and emissions. An inventory list of all the inputs and outputs of a product or service.
- *Impact assessment* the effects of the resource use and emissions generated are grouped and quantified into a limited number of impact categories.
- *Interpretation*, the results are reported in the most informative way possible and the need and opportunities to reduce the impact of the product(s) or service(s) on the environment are evaluated.

The life cycle approach holds great potential for environmental and broader sustainability work. Through its systemic cradle-to-grave approach, it reduces risks of sub-optimization and problem-shifting from one part of the life cycle to another or from one type of impact to another. It brings new insights about how action in one stage of the product life cycle may lead to upstream or downstream effects far away from the point of action, perhaps in vastly distant geographical locations as well. In this respect it is an empowering concept that brings new opportunities for influence, beyond organizational or national borders.

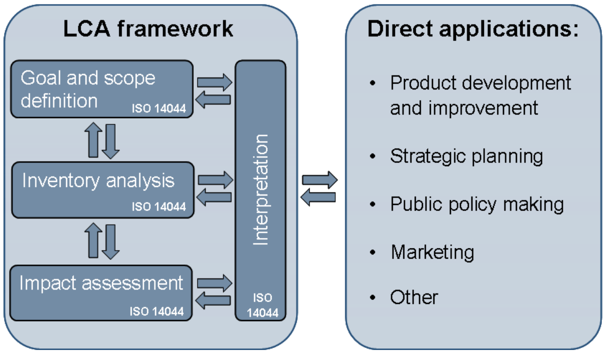


Figure 1. LCA Framework and Applications [9,10]

III. LCA METHODOLOGY AND APPROACH

A. *Goal of the Study*

The goal of this project is to carry out Life Cycle Assessment (LCA) of a C- segment gasoline powered vehicle in Indian condition to provide a comprehensive view of the life-cycle environmental profile. This assessment provides the foundation for meaningful consideration of product design alternatives and communication with stakeholders both internally and externally. The study will help in quantifying product environmental performance in easy to understand product information sheets to support environmental declarations and also identify opportunities for design improvement and provide approaches for future products. The study is carried out in accordance with ISO 14040 standards & use the approach of “cradle to grave” LCA by analysing all the upstream materials flow with the GaBi 6 software and databases [2]. The intended audience of this study include, manufacturer of the vehicle, government, customers, retailers and non-governmental organizations.

B. *Scope*

The scope covers the environmental information (on inventory level, single flow level) on vehicle for the entire life cycle (production, utilization and end of life phase). The material production includes the raw material extraction, production of the raw materials and auxiliary material production. The production contains the supplier manufacturing and the in-house manufacturing. The fuel production includes the raw material production and fuel production. The scope of the LCA study is defined in ISO 14044:2006 section 4.2.3.1, and among other things outlines the functions, functional unit, system boundary and cut-off criteria of the study.

C. Functional Unit

The functional unit provides a common basis for comparing the different vehicle options considered in the same segment. The functional unit selected for this study is C-Segment passenger vehicle travelling a distance of 150,000 km in India. The C-Segment is a European car size classification that corresponds to a “Small family car”, “Compact” and “mid-size” car.

D. System Boundary

This study considers impacts from “cradle to grave” and covers cradle-to-gate production of components needed for the assembly of the vehicle i.e. Extraction of raw materials, production of fuels & production of vehicle component parts; Upstream transportation of the raw materials and components/subassemblies and assemblies of the vehicle, Final assembly ,Use phase ,End-of-life of vehicle covering recycling, reuse and disposal.

For the sake of simplification and based on the availability of data in public domain, only raw materials production are considered as close assumption to supplier components/subcomponents made of respective materials.

The following sections describe the overall life cycle stages that constitute the system boundaries and the limits of the boundaries. Temporal, technological and geographical coverage are also described.

Figure-2 shows an overview of the life cycle of a vehicle and defines the boundaries of this study. Table-1 lists what is included within or excluded from the defined system boundaries.

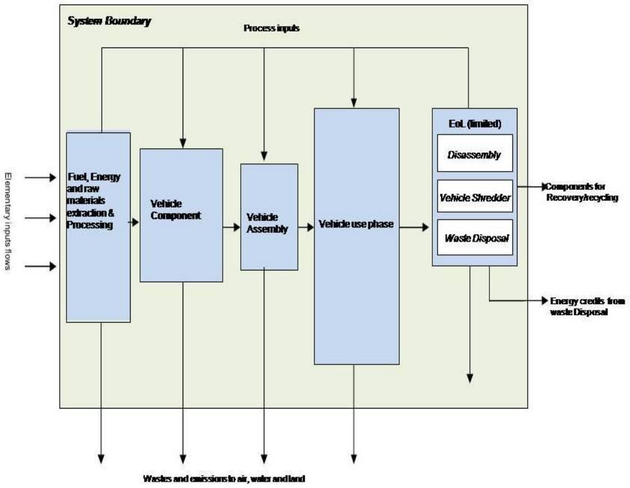


Figure 2: Life cycle of a vehicle and system boundaries

Table 1
Inclusion and exclusion in system boundary

Life cycle Stages	Definitions
Materials	Extraction, production of the raw materials
Upstream Transport	Transport of materials for various suppliers
Manufacturing process assembly (vehicle production)	Energy, fuel & raw materials used in the process of product vehicle
Use- phase	Emissions during the product use i.e. consumption of fossil fuel.
End of life	Recyclability potential of the scrap material

Activities that have been excluded from the assessment are summarised in Table 2

Table 2
Activities outside the scope of this study

Activity	Reason for exclusion
Construction of capital equipment, furnace rebuild (refractories) and moulds	It is expected that these impacts will be very small when allocated across the full production system of vehicle (hence can be excluded under the cut-off rules defined later)
Maintenance and operation of support equipment	It is expected that these impacts will be very small when allocated across the full production system of vehicle (hence can be excluded under the cut-off rules defined later)
Human labour and employee transport	These aspects are not the central focus of the study and are not easily attributable to product impacts

E. Vehicle Characteristics and Specification

The GaBi LCA models developed for the raw material production based on the material composition and assembly of the vehicles assessed are based on the “average mid-sized” European petrol passenger car as described by the 2008 JRC IMPRO-car study[11]. Detailed material composition of this “Root vehicle” can be found in Table-8 [11,12]. Assembly line data used in this study (sourced from the JRC IMPRO-car study) are also found in this Table-9 [11,12].

The characteristics for the vehicle used in the base scenario in this study are as follows:

- Mid-size petrol, exemplified by. VW Golf , Ford Focus, Renault Mégane
- Vehicle mass = 1240 kg
- Fuel =gasoline
- Fuel consumption = 6.667 l/ 100 km

The following BSIV emission standards of India have been applied for calculation of tail pipe emissions for 150000 km travelled during the life time of the vehicle.

- Carbon Monoxide (CO)-1gm/km (150kg)
- Hydro carbons (HC)-0.1gm/km (15kg)
- Nitrogen Oxides (NOx)-0.08 gm/km (12kg)
- Sulphur Dioxide (SO_2)- 50 ppm (0.74kg)

F. LCA Calculation Approach

On the life cycle of the studied product, the required or relevant inputs are brought to the system in set quantities.

These inputs are included in the impact of the product studied after completing the following operations:

- The input quantity contributed or the emission is converted into the functional unit of the studied product.
- The environmental impact of this input is calculated from life cycle inventories, pre-established list of flow collected in the environment or emitted for the delivery of one unit of this input. These physical flows are translated into environmental impacts using characterization factors adapted to greenhouse gas emission.
- In order to determine the weights, material specification/composition, manufacturing processes of the various components, material & energy datasheets, use and maintenance phase data
- All impacts of each input and output is added for consistent environmental indicators, in order to propose a value aggregated at the desired level of analysis (the whole cycle including the use phase and end of life, under step, etc.)

G. Selection of LCA Methodology and Types of Impacts

CML 2001 (Nov 2010) method has been selected for evaluation of environmental impacts developed by Institute of Environmental Sciences, Leiden University, Netherlands. These indicators are scientifically and technically valid. Furthermore, they are relevant from the environmental point of view and provide a multi-criterion approach to the environmental issues. These indicators are widely used and accepted by the international community of LCA experts.

A set of environmental indicators were investigated including the following inventory flows and environmental impact categories: primary energy demand, global warming potential, eutrophication potential, acidification potential, photochemical ozone creation potential (smog formation potential) and total blue water consumption .

Global Warming Potential (GWP) [kg CO_2 equivalent]: A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare[13].

Eutrophication Potential (EP) [kg Phosphate equivalent] covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.[13]

Acidification Potential (AP) [kg SO_2 equivalent] measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials [13]

Photochemical Ozone Creation Potential (POCP) [kg ethane equivalent] measure of emissions of precursors that contribute to ground level smog formation (mainly ozone, O3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops [13]

Abiotic resource depletion potential (ADP) estimates the consumption of abiotic resources, such as extraction of metals, scarce minerals and fossil fuels. An abiotic depletion factor is determined based on the remaining global resource reserves and their rates of extraction. The results are expressed in kg antimony (Sb) equivalents for mineral resources, and in megajoules (MJ) for fossil fuel resources [13].

Ozone depletion potential (ODP) indicates the potential of emissions of depletion of the stratospheric ozone layer and increased ultraviolet radiation to the earth‘s surface.

The ODP is chlorofluorohydrocarbons (CFCs) and chlorinated hydrocarbons (HCs) for depleting the ozone layer. The release of these substances contributes to the expressed in kg CFC-11 (or R11) equivalents and its potential effects are felt globally [13].

Primary energy demand from renewable and non-renewable resources refers to energy resources directly drawn from the hydrosphere, atmosphere, geosphere or energy source without any conversion or transformation process, including renewable and non-renewable resources. Renewable energy includes solar power, wind power, hydroelectricity, biomass and biofuels while non-renewable energy consists of finite resources such as coal, crude oil, natural gas and uranium. Primary energy demand is expressed in megajoules (MJ) [13].

Life Cycle Inventories of water input/output [litres of blue water] It is a measure of the net intake and release of fresh water across the life of the product system.

This is not a complete indicator of environmental impact without the addition of information about regional water availability [13].

H. Data and Database Used

Data Collection

All data from the GaBi databases 2014 were created with consistent system boundaries and upstream data. Thinkstep Expert's judgment and advice was used in selecting appropriate datasets to model the materials and energy for this study and has been noted in the preceding sections. Detailed database documentation for GaBi datasets can be accessed at http://www.gabi-software.com/support/gabi/gabi-6-lci-documentation/ and http://database-documentation.gabi-software.com/support/gabi/gabi-database-2014-lcidocumentation/ [2].

Raw and Process Materials – Upstream Data

Data for all other upstream raw materials were obtained from the GaBi 6 database 2014 as given in Table 4.

Life cycle inventory for Energy

Thermal energy and electricity details are used specific to the Indian Condition. The inventory and the source used is GaBi 6 database 2014 as shown in Table-3

Fuels and Energy – Upstream Data

National averages for fuel inputs and electricity grid mixes were obtained from the GaBi 6 database 2014. Datasets on Indian average mixes for fuels (e.g. diesel), thermal energy and electricity were used for this study [2].

Table 3
Life cycle inventory databases for energy

Location	Description of the inventory	Source	Representativeness
Electricity, low voltage, at grid inventories			
India	IN: Electricity grid mix PE	GaBi 6 Database 2014	Indian Grid Mix (Hard coal 66.1%, Hydro 13.8%, Natural gas 9.9%, Heavy fuel oil 4.1%, lignite 2.2%, Others 3.9%)
India	IN: Thermal energy from natural gas PE	GaBi 6 Database 2014	India
India	IN: Petrol mix at refinery PE	GaBi 6 Database 2014	India

End of Life cycle inventories

Recycling of aluminum and steel has been modeled based on Indian Scenario. Suitable datasets has been used from GaBi database to incorporate the end of life phase.

Land filling of plastic components is modelled based on landfilling practices in India. The credit in context of Life Cycle Assessment means the reduction in environmental impact because of use of recycled material components. For example, the scrap generated or the material at the end of life of the product goes for recycling & is used for various purposes. This used material avoids the need of virgin material & hence the environmental impact is also avoided.

Table 4
Database for Life cycle inventory of materials

Material	Description of the inventory	Source	Representativeness
ABS	Acrylonitrile-Butadiene-Styrene Granulate (ABS) Mix	GaBi 6 Database 2014	India
Aluminum	Aluminum sheet mix	GaBi 6 Database 2014	India
Copper	Copper mix (99,999% from electrolysis)	Gabi 6 Database 2014	India
Galvanized Steel	Steel sheet HDG	Gabi 6 Database 2014	India
Grease	Lubricants at refinery	Gabi 6 Database 2014	India
Harden Aluminum	Aluminum sheet mix	Gabi 6 Database 2014	India
Hardened Spring Steel	Steel billet (16CrMo4)	Gabi 6 Database 2014	India
HDPE	Polyethylene High Density Granulate (HDPE/PE-HD) Mix	Gabi 6 Database 2014	India
LDPE	Polyethylene Low Density Granulate (LDPE/PE-LD)	GaBi 6 Database 2014	India
Lubricant	Lubricants at refinery	Gabi 6 Database 2014	India
Natural Rubber	Natural rubber (NR)	Gabi 6 Database 2014	India
Paint	Solvent paint white	Gabi 6 Database 2014	India
PE	Polyethylene High Density Granulate (HDPE/-HD) Mix	GaBi 6 Database 2014	India
PET	Polyethylene Terephthalate Granulate (PET) via DMT	GaBi 6 Database 2014	India
Polyamide	Polyamide 6.6 Granulate (PA 6.6) Mix	GaBi 6 Database 2014	India
Polyester	Polyester (PET) fabric	GaBi 6 Database 2014	European
PP	Polypropylene granulate (PP)	GaBi 6 Database 2014	India
PU	Adhesive system polyurethane-prepolymer	GaBi 6 Database 2014	India
PVC	Polyvinyl Chloride Granulate (Suspension; S-PVC) Mix	GaBi 6 Database 2014	India
Thermoplastic	Thermoplastic copolyester elastomer (TPE-E)	GaBi 6 Database 2014	India
Poly Urethane	Polyether polyol and Toluene diisocyanate (TDI)	GaBi 6 Database 2014	India

Cut-off Criteria

For the material and energy input to the gate-to-gate data, no cut-off criteria were applied as it was intended to capture the complete material input. The following cut-off criteria were applied in the study to all upstream data:

1. *Mass:* If a flow is less than 2% of the cumulative mass input to the foreground processes of the model, it may be excluded, providing its environmental relevance is not a concern.
2. *Energy:* If a flow is less than 2% of the cumulative energy input to the foreground processes of the model it may be excluded, providing its environmental relevance is not a concern.
3. *Environmental Relevance* – If a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it will be included. Material flows which leave the system (emissions) and whose environmental impact is greater than 2% of the whole impact of an impact category that has been considered in the assessment, must be covered. This judgment has been done based on experience and documented as necessary. The sum of the excluded material flows has not exceeded 5% of mass, energy or environmental relevance.

Data Quality Requirements:

Data quality is judged by its precision (measured, calculated or estimated), completeness, consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, time period, technology). To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent, upstream LCA information from the GaBi LCI database were used. This upstream information from the GaBi LCI database is widely distributed and used with the GaBi 6 Software. The datasets have been used in LCA-models worldwide for several years in industrial and scientific applications for internal as well as critically reviewed studies. In the process of providing these datasets, they have been cross-checked with other databases and values from industry and science.

Technology Coverage

The region-specific energy supply chains for the respective Indian ones were exchanged throughout the whole value chain for electricity, thermal energy and steam, respecting the different fuels used and adapting the Indian-specific yields of the energy generation processes.

Geographic Coverage

The geographical coverage of this study covers assembly of passenger car in India with the materials sourced externally from suppliers within India.

Time Coverage

The representative upstream data (mainly raw materials, energies, fuels, and ancillary materials) were obtained from the GaBi 6 database 2014.

Assumptions & Limitations

- For modeling purpose, the bill of material has been classified using raw materials contributing to total weight of the car
- Steel has been classified into galvanized steel and hot rolled coil for closer representation of steel types, which is the major component of the vehicle as given in Table-5.

Table 5
Steel alloy material composition

Material	**Composition**
Total Steel Alloy	100%
Steel electro-galvanized coil	60%
Steel hot rolled coil	40%
Aluminum sheet	100%

- Aluminum has been represented under aluminum sheet as given in Table-5
- The use phase has been considered for 1.5 lakh Km.
- Close substitution for material and processes are considered from GaBi 6 dataset.
- Appropriate assumptions are made for the data, wherever required for the recycled content of materials.
- End of life of the product includes landfill and recycling. Due to limited primary information, assumptions regarding the recycle content in line with GaBi modelling principle are considered. Open loop recycling approach has been considered for modeling the end of life (Table-6)

Table 6
Scrap collection rate

Material	**Recycling rate**
Steel	80%
Aluminum	80%
Plastic	30%

Allocation Procedures

According to ISO a closed loop allocation applies, when a material is recycled into the same product system and the material does not undergo a change to its inherent properties (chemical, physical, etc.). In this case, it is assumed that recycled material (100%) replaces virgin material (100%).

Whereas an open loop allocation procedure applies to systems, where the material is recycled into other product systems and/or the material undergoes a change to its inherent properties.

A similar credit is given for the various materials at the end of life phase of the product. This methodology is tabulated below Table-7

Table 7
End of life credit

End of Life Material	**Credit given**
Steel	Recycling potential of steel sheet in form of secondary steel
Plastic	Landfill of Plastic Waste
Aluminum	Aluminum Ingot recycling in form of secondary aluminum ingot

IV. RESULT ANALYSIS

Material Composition of vehicle collected from 2008 JRC-IMRO European Study has been given in Table-8 [11, 12]. Average assembly line energy consumption is also collected from the same study as given in Table10 [11, 12].

Table 8
Root vehicle materials composition

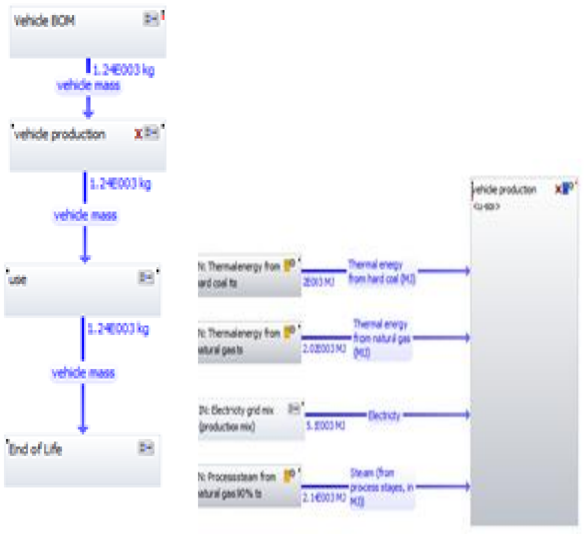
Materials	**(kg)**	**% of total**
Total content of ferrous and non-ferrous metals	*819*	*66.05%*
Steel BOF	500	40.32%
Steel EAF	242	19.52%
Total content of iron and steel	*742*	*59.84%*
Aluminium primary	42	3.39%
Aluminium secondary	26	2.10%
Total content of aluminium	*68*	*5.48%*
Cu	9	0.73%
Mg	0.5	0.04%
Pt	0.001	0.00%
Pl	0.0003	0.00%
Rh	0.0002	0.00%
Glass	40	3.23%
Paint	36	2.90%
<u>Plastics</u>		
PP	114	9.19%
PE	37	2.98%
PU	30	2.42%
ABS	9	0.73%
PA	6	0.48%
PET	4	0.32%
Other	27	2.18%
Miscellaneous (textile, etc.)	23	1.85%
<u>Tyres</u>		
Rubber	4	0.32%
Carbon black	2	0.16%
Steel	1	0.08%
Textiles	0.4	0.03%
Zinc oxide	0.1	0.01%
Sulphur	0.1	0.01%
Additives	1	0.08%
Sub-total (4 units)	*31*	2.50%
<u>Battery</u>		
Lead	9	0.73%
PP	0.7	0.06%
Sulphuric acid	4	0.32%
PVC	0.3	0.02%
Sub-total	*14*	*1.13%*
<u>Fluids</u>		
Transmission fluid	7	0.56%
Engine coolant	12	0.97%
Engine oil	3	0.24%
Petrol	23	1.85%
Brake fluid	1	0.08%
Refrigerant	0.9	0.07%
Water	2	0.16%
Windscreen cleaning agent	0.5	0.04%
Sub-total	*50*	4.03%
Total weight	***1240***	***100.00%***

Table 3
Assembly line energy consumption for "average" EU petrol car

Year: 2004		5.093.000 cars produced		
	MWh	GJ	MJ/car	kWh/car
Gas and coal	5 680 000	20 448 000	4 015	1 115
Electricity	7 210 000	25 956 000	5 096	1 416
District heating	3 020 000	10 872 000	2 135	593
Total	**15 910 000**	**57 276 000**	**11 246**	**3 124**

Figure 3 represents GaBi screenshots of different life cycle stages of vehicle.

Table-10 represents the total life cycle impacts for the vehicle for all the environmental indicators and also provides the contribution of impacts in different stages such as material production, vehicle production, use stage and end of life stage. Figure-4 depicts the percentage distribution of various impacts across the different life cycle stages.



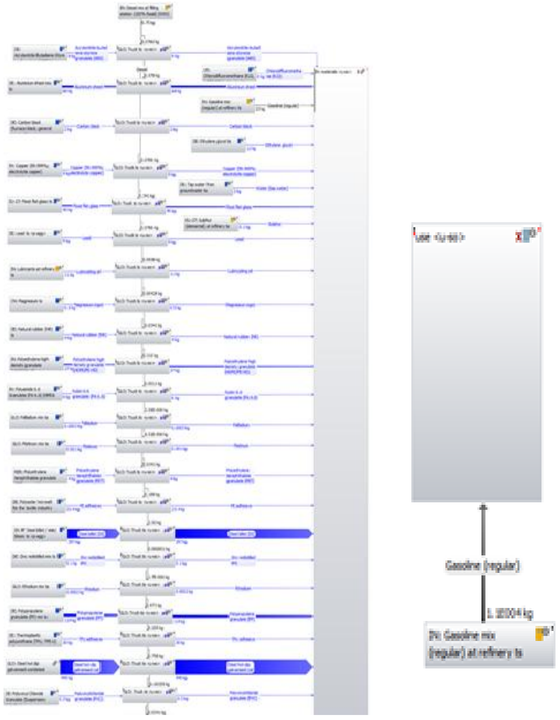


Figure 3: GaBi screen shots of life cycle stages

Table 4
Life cycle impact results across the value chain

Environment Indicators	**Total**	Material Production	Vehicle production	Use Stage	End of Life
ADP elements [kg Sb-Equiv.]	**0.09**	0.09	0	0	0
ADP fossil [MJ]	**619086**	51122	27357	559656	-19050
AP [kg SO2-Equiv.]	**105.47**	13.62	25.68	74.6	-8.44
EP [kg Phosphate-Equiv.]	**6.24**	0.92	1.26	4.51	-0.46
FAETP inf. [kg DCB-Equiv.]	**133.04**	19.03	5.13	113.69	-4.81
GWP 100 years [kg CO2-Equiv.]	**35166.9**	3572.21	2470.87	30982	-1858.8
HTP inf. [kg DCB-Equiv.]	**3397.44**	2875.04	747.23	1769	-1994.2
MAETP inf. [kg DCB-Equiv.]	**5902544**	1819122	3333623	2068283	-1318484
ODP, steady state [kg R11-Equiv.]	**1.37E-05**	1.39E-05	4.20E-08	2.6E-08	-2.2E-07
POCP [kg Ethene-Equiv.]	**15.74**	1.43	1.26	13.83	-0.79
TETP inf. [kg DCB-Equiv.]	**25.77**	12.85	5.82	15.16	-8.06

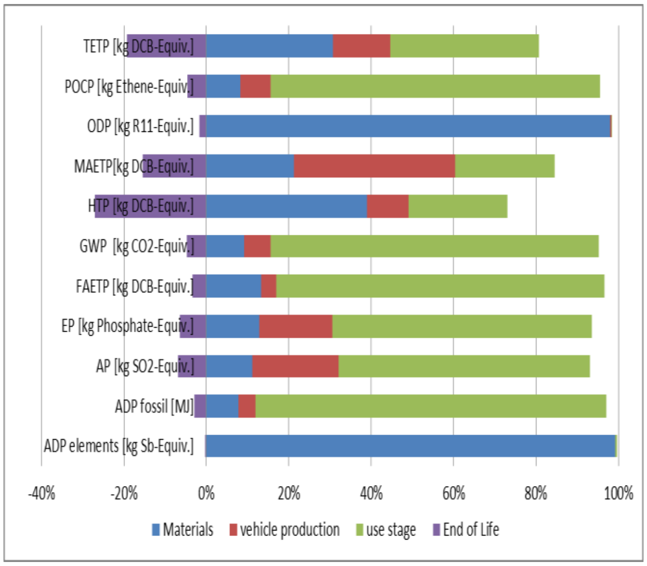


Figure 4: Percentage Distribution across life cycle stages

Figure-4 shows that the distribution of environmental impacts across various life cycle phases. The total product carbon footprint indicated by global warming potential is 35166 kg CO_2e for the life cycle of the passenger car wherein 30982 kg is contributed by use stage and 3572 kg is due to material production. The major contributor in ADP elements are Materials (99.72%), followed by vehicle production (0.10%), use stage (0.47%) and End of life (-0.29%). On the contrary, use stage accounted as (90.40%) in the ADP fossil element. For acidification potential use stage again contributes about (70.73%) and the vehicle production stage contributes to (24.35%). Eutrophication potential indicates that use stage contribution of (72.32%) followed by vehicle production (20.28%). In the FAETP element the impact of use stage is (85.46%) and of materials is (14.30%). Moving further in the GWP impacts, use stage shows (88.10%) followed by contribution of material production (10.16%). For human toxicity, contribution of materials (84.62%) with end of life credit (-58.70%).Marine eco-toxicity indicates the major impacts are from Vehicle production (56.48%) followed by use stage (35.04%). Whereas in the ozone depleting potential materials contribution goes well above to (101.15%) while rest remains very low including use stage (0.20%). For photochemical oxidation potential, use stage indicates contribution of (87.88%) and materials shows (9.09%). Terrestrial eco-toxicity impact reveals that materials and use stage impacts are evenly distributed as 58.83% and 49.85% respectively.

Table-11 shows the distribution of impacts of inventory level key environmental indicators across the life cycle stages.

Table 11
Life cycle impact results across the value chain

Indicators	Total	Material	Vehicle Production	Use	End of Life
Carbon dioxide (kg)	33665	3323	2373.9	29732	-1763.9
Carbon monoxide (kg)	172.7	20.2	1.5	164.2	-13.3
Nitrogen oxides (kg)	42.2	5.4	9.1	31	-3.3
Sulphur dioxide (kg)	68.4	8.4	17.2	48.3	-5.6
Hydrocarbons (unspecified) (kg)	15	0	0	15	0
Methane (kg)	60.6	8	3.4	51.9	-2.8
PED [MJ]	674453	61917	31764.9	604647	-23876
Blue water consumption [kg]	30413	19472	12622.2	4736.5	-6418.5

Figure-5 depicts the percentage impact contribution of different life cycle stages for key environmental indicators.

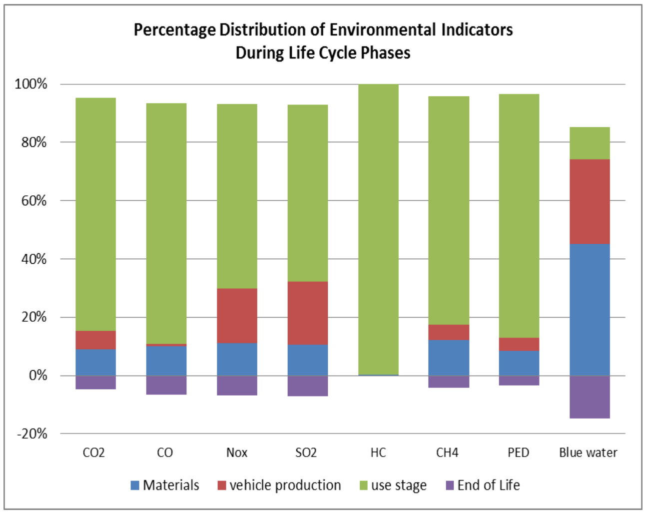


Figure 5: Life cycle impacts of key environment indicators

Figure-5 shows that carbon dioxide emission occurs largely during the use stage (88%) followed by material production (10%) and rest (7%) in the vehicle production stage with credit in the end of life stage (-5%). For carbon monoxide use stage contributes (95%) and materials production (12%).

Similarly for Nitrogen oxide, contribution of use stage (73%) followed by vehicle production (22%). Whereas Sulphur dioxide is accounted by use stage (71%) followed by vehicle production (25%). Impacts of hydrocarbons is almost 100% accounted by use stage. Emission of methane is again largely accounted by use stage (86%) and materials (13%). For primary energy demand, major contribution is due to fossil fuel consumption in use stage (90%) followed by materials production ((9%). Majority of blue water consumption is caused during the materials production (64%) followed by vehicle production (42%) and Use Stage (16%) with credit during End of Life (-21%).

Table-12 shows the impacts during the vehicle production stage due to various energy carriers. Figure-6 depicts the percentage impact contribution due of various energy carriers for the vehicle production. During vehicle production stage, ADP is impacted by electricity (91%) and thermal Energy of (9%). ADP Fossil indicates 74% due to electricity and rest 26% caused by thermal Energy. Moving further AP shows 91% accounted by electricity consumption and 9% contributed by thermal energy. For EP, the contribution of electricity (83%) and rest due to thermal Energy. Whereas for GWP, electricity takes 79% of the total impacts and 21% is contributed by thermal Energy. In HTP Electricity consumes (87%) and thermal Energy (13%).

In MAETP Electricity contributes (87%) and rest (12%) by thermal energy. In ODP, electricity accounted for almost 99%. For POCP and TETP, the impact of electricity is in the range of 87-89% while for PED, electricity contributes to 75% impact to total vehicle production.

Table-13 shows the contribution of various raw materials production to the different environmental impact categories. Figure-7 depicts the percentage environmental impacts contribution of raw materials to the various environmental impact categories.

Table 12
Life cycle impact results for vehicle production

	Total	**Electricity grid mix (production mix)**	**Process steam from natural gas**	**Thermal energy from hard coal**	**Thermal energy from natural gas**
ADP elements [kg Sb-Equiv.]	9.70E-05	8.84E-05	4.22E-06	8.35E-07	3.59E-06
ADP fossil [MJ]	27357.73	20177.02	2757.26	2081.33	2342.13
AP [kg SO2-Equiv.]	25.68	23.26	0.34	1.79	0.29
EP [kg Phosphate-Equiv.]	1.26	1.05	0.05	0.11	0.05
FAETP inf. [kg DCB-Equiv.]	5.13	4.57	0.08	0.42	0.07
GWP 100 years [kg CO2-Equiv.]	2470.87	1963.99	162.04	207.19	137.65
HTP inf. [kg DCB-Equiv.]	747.23	656.32	6.08	79.67	5.17
MAETP inf. [kg DCB-Equiv.]	3333623	2913803.6	15729.58	390728.28	13361.57
ODP, steady state [kg R11-Equiv.]	4.20E-08	4.15E-08	2.28E-10	1.03E-10	1.94E-10
POCP [kg Ethene-Equiv.]	1.26	1.1	0.04	0.09	0.03
TETP inf. [kg DCB-Equiv.]	5.82	5.23	0.04	0.52	0.03
gross cal. value [MJ]	31764.95	23917.92	3066.35	2175.97	2604.71

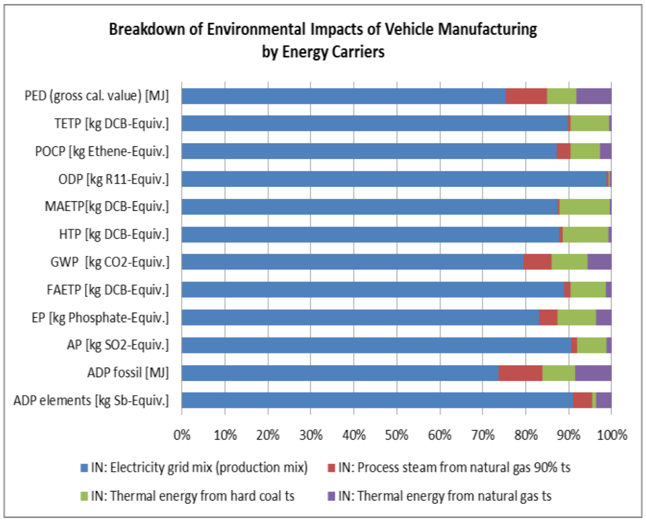


Figure 6: Impacts during vehicle production

Table 13
Life cycle impact results for materials production

	ADP_non	ADP-Fossil	AP	EP	FAETP	GWP	HTP	MAETP	ODP	POCP	TETP
Magnesium	1.02E-06	155.51	0.06	0.00	0.13	17.78	4.68	3341.71	2.75E-11	0.006	0.107
ABS	6.93E-06	779.70	0.05	0.01	0.55	28.87	35.64	921.65	3.43E-08	0.010	0.054
Aluminium	0.000276	7159.05	2.39	0.16	3.87	653.15	2240.43	1078056.43	2.77E-07	0.157	1.061
Base coat	6.00E-05	3103.64	0.21	0.03	0.80	133.33	26.31	16843.08	6.48E-09	0.078	0.191
Carbon black	1.72E-06	130.56	0.01	0.00	0.05	4.87	0.19	221.05	5.15E-11	0.001	0.002
Ethylene glycol	1.00E-05	413.90	0.03	0.00	0.13	13.21	0.61	792.16	4.55E-10	0.015	0.008
Lead	0.02574	181.05	0.35	0.00	0.09	15.09	7.81	699.00	6.30E-10	0.029	0.057
Natural rubber	2.34E-06	45.66	0.08	0.03	0.49	-3.46	0.23	434.66	4.86E-11	0.004	0.002
Polyester	3.27E-05	2250.23	0.16	0.02	0.49	103.82	2.98	3148.68	1.60E-09	0.038	1.069
Polypropylene	6.36E-05	7626.05	0.36	0.04	2.23	197.17	8.39	8773.71	1.74E-08	0.085	0.079
Polyvinyl Chloride	2.69E-06	15.04	0.00	0.00	0.00	0.64	0.02	30.89	1.80E-10	0.000	0.000
water	1.58E-10	0.00	0.00	0.00	0.00	0.00	0.00	0.09	2.84E-15	0.000	0.000
polyurethane	0.000398	2744.69	0.18	0.04	0.55	132.47	3.32	5247.67	2.73E-09	0.042	0.130
Zinc	0.000373	2.97	0.00	0.00	0.00	0.25	0.05	34.04	6.29E-11	0.000	0.001
Float glass	0.000118	528.28	0.36	0.04	2.28	45.02	194.59	86926.09	3.72E-09	-0.040	0.238
Sulphur	8.38E-09	3.37	0.00	0.00	0.00	0.07	0.01	3.91	3.62E-12	0.000	0.000
Palladium	0.000148	43.33	0.06	0.00	0.10	3.67	3.14	622.20	9.31E-11	0.003	0.032
Platinum	0.002141	446.71	0.58	0.02	0.48	42.03	15.69	5270.60	1.34E-09	0.028	0.173
GLO: Rhodium mix ts	0.001011	196.65	0.25	0.01	0.15	18.96	5.08	2209.15	6.34E-10	0.012	0.059
Steel hot dip galvanized	0.02206	11432.33	3.35	0.21	2.76	1101.24	137.05	267892.84	1.35E-05	0.539	1.643
Steel billet / slab/ bloom	3.18E-05	6914.89	3.30	0.18	0.89	687.62	104.28	230750.68	3.83E-09	0.335	3.656
Copper	0.041082	742.90	0.67	0.03	1.64	66.61	41.56	47993.26	8.37E-10	0.034	0.387
Diesel	2.76E-07	348.84	0.03	0.00	0.06	4.14	0.74	1633.77	2.18E-11	0.004	0.007
Gasoline	9.12E-07	1167.54	0.14	0.01	0.24	17.56	3.66	4314.79	5.59E-11	0.016	0.032
Lubricants	4.09E-07	526.02	0.13	0.00	0.14	16.24	2.95	2466.95	2.92E-11	0.012	0.034

It is very important to understand the environmental profile of material and its contribution to overall impacts due to material production. Lead and Copper are the major contributors for ADP (elements), whereas Polyester and Polypropylene are the moderate contributors. Similarly, in ADP- Fossil, Aluminum, Polypropylene and Steel hot dip galvanized are the major impactors followed by Copper and Lubricants. AP is mainly contributed by steel and paint followed by Lead. EP is primarily accounted by Aluminium and Steel while moderate impact was caused by ABS and Natural Rubber. GWP is mainly caused by Aluminum and Steel with medium impact due to magnesium and ABS. HTP is highly contributed by Aluminum with medium impact caused by Magnesium and ABS.

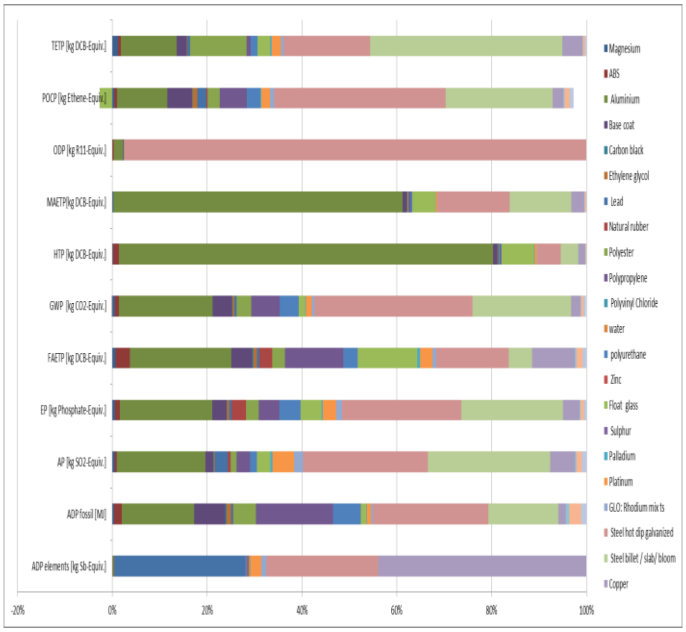


Figure 7: Impacts due to raw material production

V. RECOMMENDATIONS

About 60% of metal composition is steel; hence it is essential to use the steel which is produced from high yield manufacturers who produce steel with less raw material and energy. Usage of steel produced through the Electric Arc Furnace Method can be preferred. Light weighting is one of the key option as it will lead to reduction in weight of the vehicle resulting in enhanced fuel efficiency.10% reduction in tyre rolling resistance leads to 1% reduction in fuel consumption. Reducing the tyre rolling by using low rolling resistance tyres (LRRT) and regular control of their pressure through the tyre pressure monitoring system (TPMS). Reduction of Sulphur content in lower acidification potential. Currently most of the vehicles contain 6-10% of plastic. It is estimated that plastic content would increase by 10-15% in the future.

Hence, plastic recycling is important to reduce the life cycle impacts. Some of the innovations can further reduce the environmental impacts are power train enhancements with focus on improved aerodynamics and drag reduction, efficiency improvements through low friction design and reduced driveline friction, tail pipe abatement systems, IC engine and transmission innovations, High voltage electrical distribution systems, combustion improvements, components such as oil and water pump with variable speed, controllable air compressor, sensor electric accessory drive, dual fuel systems, pneumatic booster air hybrid etc., increased use of recycled materials, light weighting of the vehicle and aerodynamic design options.

VI. CONCLUSION

The LCA study indicates that GWP is significantly contributed by use stage (88%) for total life cycle impacts. Use stage contributes predominantly to most of the environmental indicators in the range of 35-90%) except abiotic depletion (element) and Ozone depleting potential. Raw material contributes significantly in abiotic depletion (element) to the tune of 99.7% and human toxicity (84%). Acidification potential and eutrophication potential are moderately contributed by vehicle production stage i.e. 24% and 20% respectively. End of life credits result in significant benefits to human toxicity and terrestrial eco-toxicity by 58% and 31% respectively. While evaluating the inventory level key environmental indicators, carbon dioxide emission is mainly contributed by gasoline combustion during the use stage followed by 10% accounted from material production. Similarly for carbon monoxide, use stage contributes to 95% followed by 12% from material production. Nitrogen dioxides is mainly contributed by use stage which includes the tail pipe emission as per BS IV standard and also due to production of gasoline in refinery. Sulphur dioxide emission indicates that use stage contributes significantly but major impact of use stage caused at the production of gasoline at refinery. Hydrocarbon emission is predominantly caused by use stage. On the contrary the blue water consumption is significantly contributed by material production (64%) followed by vehicle production (42%).Though vehicle assembly production does not have major impact on the life cycle impacts in comparison to material production and use stage emission for most of the environmental indicators, but results indicates that contribution of electricity consumption to the total vehicle production impacts varied from 74% to 99% of all the indicators.

Remaining energy carriers such as natural gas and coal contribute to the overall impact.. For most of the indicators, steel and aluminum contributed significantly to the overall impact. As vehicle is mostly steel intensive and production of aluminum in India being dependent on electricity which is mostly sourced from hard coal based grid mix. Copper has high abiotic depletion (elements) and aluminum has indicated high level of human toxicity. This study provides a broader overview of environmental performance. However, based on detailed bill of materials, manufacturing data at factory and collaboration with suppliers will help in assessing the in-depth impact due to vehicle as whole cascaded to major components, parts, sub-parts level.

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