Universitat Politècnica de València
Departamento de Máquinas y Motores Térmicos

LIFE CYCLE ANALYSIS OF DIFFERENT POWERTRAIN TECHNOLOGIES FOR DECARBONISING ROAD TRANSPORTATION

Doctoral Thesis
Presented by:
Shashwat Tripathi
Supervised by:
Prof. Antonio Garcia

Valencia, 27th June 2023

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Abstract

Several studies in the past have shown that despite having zero tailpipe emissions in a fully electric vehicle, it does have emissions when evaluated on a life cycle basis. Technology development over the years by humankind has constantly led to an increase in energy dependence. Unfortunately, this energy comes mainly from fossil-based sources that are limited. One major consumer of fossil-based energy sources is the transportation industry, which uses fossil-based petrol and diesel as fuels. These fuels are burned in internal combustion engines to produce energy due to their high calorific value. Since these are carbon-based fuels, it generates carbon dioxide during the combustion process, which is a greenhouse gas and leads to global warming. Therefore, there has been very strict monitoring and regulation of its emissions from the automotive tailpipes over the years. In recent years, different regions across the world have planned to completely stop the sale of conventional internal combustion engine-based vehicles. Thus, selling only zero tailpipe emission vehicles such as battery electric vehicles and fuel cell electric vehicles.

This is primarily due to the emission intensity of the electricity mix used to power the batteries and from the battery manufacturing process for battery electric vehicles. At the same time, the fuel cell vehicle depends mainly on the emission intensity of hydrogen production. Since current hydrogen production is very limited and carbon-intensive, battery electric vehicles are highly favoured to replace internal combustion engine vehicles soon. Another reason behind the push for this shift is the high efficiency of electric powertrains. Despite that, it is very challenging for battery electric vehicles to match the driving range of internal combustion engine vehicles due to the large difference in the energy density of batteries and liquid fuels, currently. Further, in real driving conditions, this driving range is

even more reduced for electric vehicles, even after having large battery packs on board. This is a major limitation for battery electric vehicles, especially for the ones meant for long haul routes, until an extensive charging infrastructure is developed.

Therefore, in this thesis, the emission reduction potential of electric vehicles is evaluated following a life cycle approach for passenger cars and city buses. This is done by comparing their emissions with that of conventional diesel and hybrid electric vehicles for real driving cycles by means of 0D numerical simulations. This is complemented with life cycle cost studies for the different vehicles to see which powertrain option can be efficient in terms of emissions but also cost. Moreover, low-carbon synthetic fuels are also evaluated as an alternative drop-in solution to replace diesel fuel and see the change it can bring on a life cycle basis for hybrid and conventional internal combustion engine vehicles. These evaluations are done for different locations globally to observe the local factors that affect the results of each powertrain option for the two vehicle segments.

Thus, this work is intended to evaluate the life cycle results for the policymakers and automobile manufacturers globally, for the emissions as well as the cost associated with each powertrain option. As an outcome of this research, several challenges are observed related to emissions and cost of the battery electric vehicles that need to be addressed before their mass adoption. Hence, the use of hybrid vehicles as a short-term solution to address the global emission reduction urgency is proposed for the road transportation sector. Which, in fact, may also be considered a long-term solution if powered with low-carbon fuels.

Resumen

El desarrollo tecnológico de la humanidad a lo largo de los años ha provocado un aumento constante de la dependencia energética. Por desgracia, esta energía procede principalmente de fuentes fósiles que son limitadas. Uno de los principales consumidores de fuentes de energía fósiles es la industria del transporte, que utiliza gasolina y gasóleo fósiles como combustibles. Estos combustibles se queman en motores de combustión interna para producir energía debido a su alto poder calorífico. Al tratarse de combustibles basados en el carbono, generan dióxido de carbono durante el proceso de combustión, que es un gas de efecto invernadero y provoca el calentamiento global. Por ello, a lo largo de los años se ha llevado a cabo un control y una regulación muy estrictos de sus emisiones por los tubos de escape de los automóviles. En los últimos años, diferentes regiones de todo el mundo han planeado detener por completo la venta de vehículos convencionales con motor de combustión interna. De este modo, sólo se venderán vehículos con cero emisiones de gases de escape, como los vehículos eléctricos de batería y los vehículos eléctricos de pila de combustible.

Varios estudios realizados en el pasado han demostrado que, a pesar de que un vehículo totalmente eléctrico no emite gases de escape, sí lo hace cuando se evalúa su ciclo de vida. Esto se debe principalmente a la intensidad de las emisiones de la mezcla de electricidad utilizada para alimentar las baterías y del proceso de fabricación de las baterías de los vehículos eléctricos. Al mismo tiempo, el vehículo de pila de combustible depende principalmente de la intensidad de las emisiones de la producción de hidrógeno. Dado que la producción actual de hidrógeno es muy limitada e intensiva en carbono, los vehículos eléctricos de batería son los más favorecidos para sustituir pronto a los vehículos con motor de combustión interna. Otra de las razones que impulsan este cambio es la alta eficiencia de las cadenas cinemáticas eléctricas. A pesar de ello, es muy difícil que los vehículos eléctricos de batería igualen la autonomía de los vehículos con motor de combustión interna debido a la gran diferencia que existe

actualmente entre la densidad energética de las baterías y la de los combustibles líquidos. Además, en condiciones reales de conducción, la autonomía de los vehículos eléctricos se reduce aún más, incluso con grandes paquetes de baterías a bordo. Esta es una limitación importante para los vehículos eléctricos de batería, especialmente para los destinados a rutas de larga distancia, hasta que se desarrolle una amplia infraestructura de recarga.

Por ello, en esta tesis se evalúa el potencial de reducción de emisiones de los vehículos eléctricos siguiendo un enfoque de ciclo de vida para turismos y autobuses urbanos. Para ello, se comparan sus emisiones con las de los vehículos diésel e híbridos eléctricos convencionales para ciclos de conducción reales mediante simulaciones numéricas 0D. Esto se complementa con estudios del coste del ciclo de vida de los distintos vehículos para ver qué opción de cadena cinemática puede ser eficiente en términos de emisiones, pero también de coste. Además, también se evalúan los combustibles sintéticos bajos en carbono como solución alternativa para sustituir al gasóleo y ver el cambio que puede suponer en el ciclo de vida de los vehículos híbridos y convencionales con motor de combustión interna. Estas evaluaciones se realizan en diferentes lugares del mundo para observar los factores locales que afectan a los resultados de cada opción de cadena cinemática para los dos segmentos de vehículos.

Así, este trabajo pretende evaluar los resultados del ciclo de vida para los responsables políticos y los fabricantes de automóviles a nivel mundial, tanto para las emisiones como para el coste asociado a cada opción de cadena cinemática. Como resultado de esta investigación, se observan varios retos relacionados con las emisiones y el coste de los vehículos eléctricos de batería que deben abordarse antes de su adopción masiva. De ahí que se proponga el uso de vehículos híbridos como solución a corto plazo para hacer frente a la urgencia de reducir las emisiones globales en el sector del transporte por carretera. Lo que, de hecho, también puede considerarse una solución a largo plazo si se propulsan con combustibles bajos en carbono.

Resum

Diversos estudis en el passat han demostrat que, tot i tenir zero emissions al tub d'escapament en un vehicle totalment elèctric, sí que té emissions quan s'avalua en funció del cicle de vida. El desenvolupament de la tecnologia al llarg dels anys per part de la humanitat ha provocat constantment un augment de la dependència energètica. Malauradament, aquesta energia prové principalment de fonts fòssils limitades. Un dels principals consumidors de fonts d'energia basades en fòssils és la indústria del transport, que utilitza gasolina i gasoil d'origen fòssil com a combustibles. Aquests combustibles es cremen en motors de combustió interna per produir energia a causa del seu alt poder calorífic. Com que es tracta de combustibles basats en carboni, durant el procés de combustió genera diòxid de carboni, que és un gas d'efecte hivernacle i provoca l'escalfament global. Per tant, al llarg dels anys hi ha hagut un seguiment i una regulació molt estrictes de les seves emissions dels tubs d'escapament de l'automòbil. En els últims anys, diferents regions del món han planejat aturar completament la venda de vehicles convencionals basats en motors de combustió interna. Per tant, venent només vehicles d'emissió zero com ara vehicles elèctrics amb bateria i vehicles elèctrics de pila de combustible.

Això es deu principalment a la intensitat d'emissió del mix elèctric utilitzat per alimentar les bateries i del procés de fabricació de les bateries dels vehicles elèctrics amb bateries. Al mateix temps, el vehicle de pila de combustible depèn principalment de la intensitat d'emissió de la producció d'hidrogen. Atès que la producció actual d'hidrogen és molt limitada i intensiva en carboni, els vehicles elèctrics amb bateries estan molt afavorits per substituir aviat els vehicles amb motor de combustió interna. Un altre motiu de l'empenta d'aquest canvi és l'alta eficiència dels motors elèctrics. Malgrat això, és molt difícil que els vehicles elèctrics amb bateries coincideixin amb l'autonomia dels vehicles amb motor de combustió interna a causa de la gran diferència en la densitat energètica de les bateries i els combustibles líquids, actualment. A més, en condicions reals de conducció, aquesta autonomia es redueix encara més per als vehicles elèctrics, fins i tot

després de tenir grans paquets de bateries a bord. Aquesta és una limitació important per als vehicles elèctrics de bateria, especialment per als destinats a rutes de llarg recorregut, fins que es desenvolupi una àmplia infraestructura de càrrega.

Per tant, en aquesta tesi, s'avalua el potencial de reducció d'emissions dels vehicles elèctrics seguint un enfocament de cicle de vida dels turismes i autobusos urbans. Això es fa comparant les seves emissions amb les dels vehicles dièsel i elèctrics híbrids convencionals per a cicles de conducció reals mitjançant simulacions numèriques 0D. Això es complementa amb estudis de cost del cicle de vida dels diferents vehicles per veure quina opció de propulsió pot ser eficient en termes d'emissions però també de cost. A més, els combustibles sintètics amb baixes emissions de carboni també s'avaluen com una solució alternativa per substituir el combustible dièsel i veure el canvi que pot comportar en el cicle de vida dels vehicles híbrids i convencionals amb motor de combustió interna. Aquestes avaluacions es fan per a diferents ubicacions globalment per observar els factors locals que afecten els resultats de cada opció de tren motriu per als dos segments de vehicles.

Així, aquest treball pretén avaluar els resultats del cicle de vida dels responsables polítics i fabricants d'automòbils a nivell mundial, tant per les emissions com pel cost associat a cada opció de propulsió. Com a resultat d'aquesta investigació, s'observen diversos reptes relacionats amb les emissions i el cost dels vehicles elèctrics amb bateria que cal abordar abans de la seva adopció massiva. Per tant, es proposa l'ús de vehicles híbrids com a solució a curt termini per abordar la urgència global de reducció d'emissions per al sector del transport per-carretera. La qual cosa, de fet, també es pot considerar una solució a llarg termini si funciona amb combustibles baixes en carboni.

Do not go where the path may lead,
go instead where there is no path and
leave a trail...

-Ralph Waldo Emerson

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Nomenclature

Latin

AC_{EV} – Assembly Cost of Electric Vehicles

AC_{HEV} – Assembly cost of Hybrid Electric Vehicle

AC_{ICEV} – Assembly cost of Internal Combustion Engine Vehicle

BC_{EV} – Battery Cost of Electric Vehicle

$BCap_{EV}$ – Battery Capacity of Electric Vehicle

$BCap_{HEV}$ – Battery Capacity of Hybrid Electric Vehicle

C_{Diesel} – Diesel Consumption

C_{E} – Cost of Electricity

$C_{Electricity}$ – Electricity Consumption

C_{Eff} – Charging Efficiency

C_{F} – Cost of Fuel

C_{LCA} – Life Cycle Cost

C_{Main} – Maintenance Cost

C_{T} – Cost per Trip

CO_2 – Carbon Dioxide

$CO_{2\,ADR}$ – CO_2 emissions from Assembly, Disposal and Recycling

$CO_{2\ Main}$ – CO_2 emissions from Maintenance

$CO_{2\ Maintenance}$ – CO_2 emissions from Maintenance

$CO_{2\ manufacturing}$ – CO_2 emissions from Manufacturing

$CO_{2\ P}$ – CO_2 emissions from Production

$CO_{2\ TTW}$ – Tank to Wheel CO_2 emissions

$CO_{2\ WTT}$ – Well to Tank CO_2 emissions

$CO_{2\ WTT\ Diesel}$ – Well to Tank CO_2 emission footprint of Diesel

$CO_{2\ WTT\ Elec}$ – Well to Tank CO_2 emission footprint of Electricity

$CO_{2\ WTT\ Electricity}$ – Well to Tank CO_2 emission footprint of Electricity

$CO_{2\ WTT\ Elec\ 2030}$ – Well to Tank CO_2 emission footprint of Electricity in 2030

$CO_{2\ WTT\ Elec\ 2050}$ – Well to Tank CO_2 emission footprint of Diesel in 2050

$CO_{2\ WTT\ Fuel}$ – Well to Tank CO_2 emission footprint of Fuel

$CO_{2\ WTW}$ – Well to Wheel CO_2 emissions

$Cost_{Energy}$ – Energy consumption cost

$Cost_{Diesel}$ – Cost of Diesel per unit

$Cost_{Electricity}$ – Cost of electricity per unit

$D_{Average}$ – Average deviation

$E_{Charger}$ – Efficiency of the Charger

EC_{E} – Energy consumption from electricity

EC_F – Energy consumption from fuel

EC_{ICEV} – Engine cost of the Internal Combustion Engine Vehicle

EBC_{HEV} – Engine and Battery Cost of Hybrid Electric Vehicle

EMC_{HEV} – Electric Motor Cost of Hybrid Electric Vehicle

EMC_{EV} – Electric Motor Cost of Electric Vehicle

EMP_{EV} – Electric Motor Power of Electric Vehicle

EMP_{HEV} – Electric Motor Power of Hybrid Electric Vehicle

F_{ADR} – Assembly, Disposal and Recycling emission Footprint

$F_{battery}$ - CO_2 Footprint for the battery

F_{comp} – CO_2 Footprint for a component

$F_{component}$ – CO_2 Footprint for a component

F_{DC} – CO_2 Footprint for Diesel Combustion

F_{EP} – CO_2 Footprint for Electricity Production

F_{FP} – CO_2 emission Footprint for Fuel Production

$F_{TTW\ Diesel}$ – Tank to Wheel emission Footprint of Diesel

$F_{WTT\ Diesel}$ – Well to Tank emission Footprint of Diesel

$F_{WTT\ Electricity}$ – Well to Tank Footprint of Electricity

LCD_{comp} – Life Cycle Distance of a Component

$LCK_{Component}$ – Life Cycle Kilometres of a Component

N_{main} – Number of maintenance times

$N_{Replacement}$ – Number of Replacements

OC_{EV} – Other costs for Electric Vehicle

OC_{HEV} – Other costs for Hybrid Electric Vehicle

OC_{EICV} – Other costs for Internal Combustion Engine Vehicle

VW_{EV} – Electric Vehicle Weight

VW_{gross} – Vehicle Weight gross

VW_{HEV} – Hybrid Electric Vehicle Weight

VW_{ICEV} – Internal Combustion Engine Vehicle Weight

W battery – Weight of the battery

W comp – Weight of a component

W component – Weight of a component

W vehicle – Weight of the vehicle

WTT GREET – Well to Tank emission footprint from GREET

WTT CT – Well to Tank emission footprint from Climate Transparency

Greek

$\sum$ – Summation

ϕ – Equivalence ratio

λ – Lambda

η – Efficiency

€ - Euro

¥ - Yuan

$ - United States Dollar

Initials and Acronyms

AD – Articulated Diesel

ADR – Assembly Disposal and Recycling

AH – Articulated Hybrid

BEV – Battery Electric Vehicle

BMEP – Brake Mean Effective Pressure

BRT – Bus Transit System

BS – Bharat Stage

BSFC – Brake Specific Fuel Consumption

CAPEX – Capital Expenditures

CARB – California Air Research Board

CCS – Carbon Capture System

CT – Climate Transparency

DB – Diesel Bus

DOE – Design of Experiments

EB – Electric Bus

ECU – Electronic Control Unit

EF – E-Fuels

EPA – Environment Protection Act

EU – European Union

EV – Electric Vehicle

FCEV – Fuel Cell Electric Vehicle

GE – Germany

GHG – Greenhouse Gases

GPS – Global Positioning System

GREET – The Greenhouse Gases, Regulated Emissions, and Energy use in Technologies Model

GT – Gamma Technologies

HB – Hybrid Bus

HEV – Hybrid Electric Vehicle

ICE – Internal Combustion Engine

ICEV – Internal Combustion Engine Vehicle

INR – Indian National Rupee

IPCC – Intergovernmental Panel on Climate Change

IR – Internal Resistance

LCA – Life Cycle Analyses

LCD – Life Cycle Distance

MENA – Middle East and North Africa

OME – Oxy-Methylene dimethyl Ether

OMEx – Poly Oxy-Methylene dimethyl Ethers

OPEX – Operational Expenses

PV- Photo-Voltic

SUV – Sports Utility Vehicles

SW – Sweden

TCO – Total Cost of Ownership

TTW – Tank to Wheels

US – United States of America

VoC – Open Circuit Voltage

WE – Wind Energy

WTT – Well to Tank

WTW – Well to Wheel

ZEV – Zero Emission Vehicle

Chapter 1

Introduction

Content

1.1 Introduction

This thesis provides a techno-economic assessment of different road transportation technologies to understand their real decarbonisation potential. The first chapter is focussed on the background of this research work. This is done by presenting an overview of the environmental impact of the Transportation sector discussing mainly the problem of emissions related to it. Then the legislations and standards implemented globally in the Transportation sector are discussed to address the emissions issue by its monitoring. Further, variation in the electricity generation mix among different regions is highlighted to understand the limitations of EVs. Also, the effect of the variation in driving conditions among the different drive cycles is presented for the different vehicle powertrains. And finally, the life cycle environmental impact of the transportation sector is discussed. The last sub section presents the organization of the thesis with the description of the contents in each chapter and the interaction among them.

1.2 Environmental Impact

The human civilization has been, is and will remain highly dependent on the Transportation sector to ensure quick mobility and enhanced reachability.[1] Mainly on three different modes, i.e., Air, Water and Road, and each of them consumes energy for its operation. Historically and unfortunately, most of the energy demands of the entire transportation sector are met using fossil fuel-based sources to power the conventional Internal combustion engine vehicles (ICEVs).[2] This leads to a large amount of carbon dioxide (CO_2) emissions into the atmosphere from the tailpipes, and since it is a Greenhouse Gas (GHG), it causes Greenhouse effect.[3] Thus, GHG emissions coming from the Transportation sector is one of the main sources for Global Warming. Considering this tailpipe emissions aspect, Electric Vehicles (EVs) are being proposed as a primary substitute for the ICEVs, due to its zero tailpipe emissions.[4] The contribution of the different sectors, including transportation, on the total greenhouse gas emissions globally is shown below in the Figure 1–1.

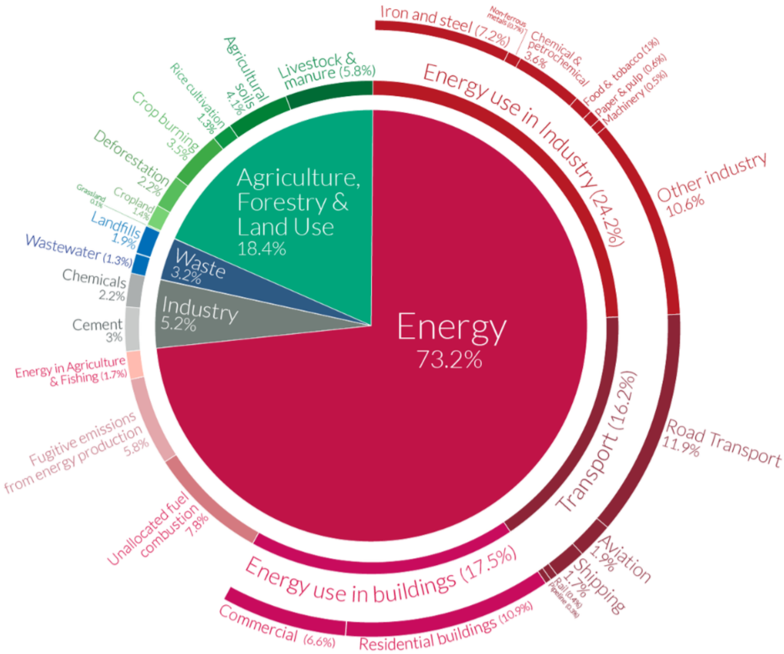


Figure 1–1: GHG emission from different sectors in 2016. (Adapted from [5]*)*

It can be seen in Figure 1–1 that the transportation sector alone contributed to more than 16%, out of which about 12% of the emissions were from the road transportation alone. The primary cause behind these emissions from the road transportation sector is the dominance of ICE vehicles that are run by burning fossil fuels. To avoid these emissions from the tailpipe of the ICEVs, EVs are being considered as its direct replacement to get rid of fossil fuel combustion and the pollution from the tailpipes associated with it. However, there are emissions still coming from the process of electricity generation to charge the batteries of the EVs.[6] Moreover, the production of batteries as well as the EVs impacts the environment in other ways such as, acid rain, depletion of resources, water depletion, etc.[7] Also, it is to be noted that during the use phase, the driving conditions has a great influence on the emissions of a vehicle.[8] For ex., the ICE performs quite efficiently at high-speed conditions and thus the emissions coming from it on a high-speed drive cycle for highway conditions can be very less as compared to its emissions for low-speed driving cycle, typical to a city with heavy traffic congestion. Moreover, in case of an EV, if the highway drive cycle distance is about 1000 kilometres, it won't be able to cover that distance as its battery pack will run out of energy to power the electric powertrain. Thus, a holistic approach is required to evaluate the right technology for the different vehicles depending on its operating conditions.

1.2.1 Pollution

Pollution is of several types, mainly including Air, Water, Soil and Noise Pollution, and the transportation sector affects each of them significantly.[9] Each of the three transportation modes (air, water and road) causes all the four types of pollution individually which is a problem for the well-being of the environment and human civilization. Evidently, Air Transport causes more Air pollution and Water transport causes more water pollution, but road transportation too causes each of them and is also integrated within human civilization. Thus, for a healthy and long-lasting life on land, road transportation needs a high level of scrutiny in terms of the pollution that it brings to the air, water, soil, and noise.[3] To reduce the GHG emissions and the air pollution due to the ICEV tailpipes, it is being debated to replace the ICEVs with EVs, as there is no tailpipe in the EVs at all. Several people advocating EVs are in fact claiming EVs as zero emission vehicles, which is not true. Because even though EVs doesn't emits GHGs from a tailpipe, it may still lead to GHG emission at the time of electricity production which is required to charge the battery pack. Moreover, if the electricity is only produced by coal, then the EV can be more polluting than an ICEV as we are shifting the emissions upstream and increasing it, while removing downstream emissions.[10] From the Figure 1–

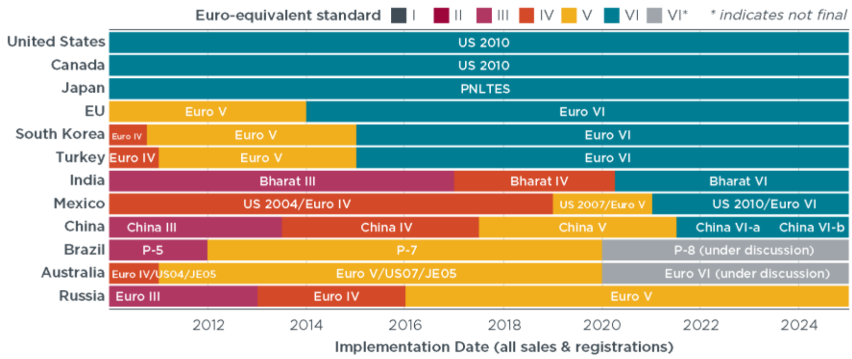
2 below, the difference between upstream and downstream emissions can be understood more clearly.

Figure 1–2: Upstream and Downstream emissions for the Road Transportation sector. (Adapted from [11]*)*

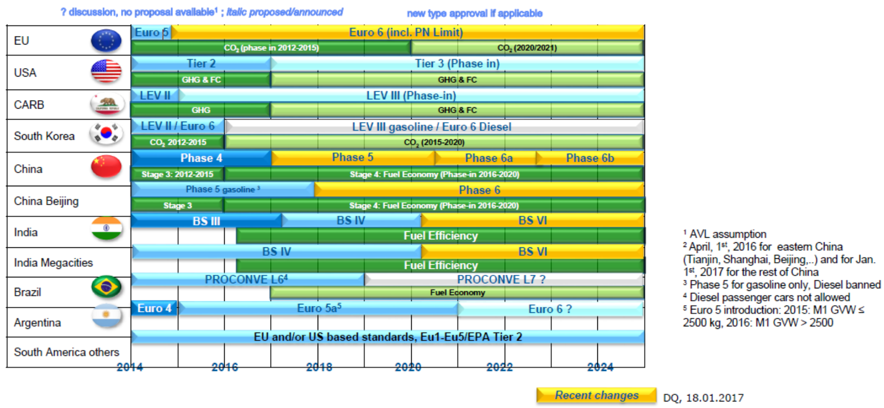
It can be seen in the Figure 1–2 above that the downstream emissions are not the only concern, but the upstream emissions are also important for the well-being of the environment. Further, in terms of soil and water pollution EVs are a worse option as it causes depletion of mineral sources, due to the extraction of several precious elements for battery and electronic component manufacturing and causes lots of eutrophication due to water depletion during battery manufacturing, also, EVs have high acid rain potential that effects both air pollution as well as soil pollution.[12] In terms of noise pollution ICEV vehicles are more polluting, mainly due to the high number of moving parts involved with ICE based vehicles that leads to high amount of noise and vibrations. This is valid for all transportation mode vehicles that are powered by ICE. The EVs have very low sound levels during its course of motion, with the sound of the rotation of the rotor of the electric motor being significant only. However, it is realised for the awareness of pedestrians as well as other vehicles, a certain level of sound is important too. It should not be high that causes noise pollution but should be adequate to act as an alarm for other being around and EV. Thus, it is very important to set the right laws and legislations to regulate these emissions properly to maintain a healthy human living for a sustainable future.[13] This is discussed in detail in the following sub-section.

1.2.2 Emission Regulations

Although the environmental impact of the transportation industry especially road transportation, is on the air, water, soil and noise pollution, its contribution to air pollution is being addressed mostly by policy makers and governments across the globe.[14] This is mainly due to extreme deteriorating air quality worldwide, especially in major cities with large number of vehicles. As the road transportation is a mix of different types of vehicles, these emissions regulations are mainly defined for two different types of vehicles: Heavy-Duty Vehicles (HDVs) and Light-Duty Vehicles (LDVs). The HDVs mainly include Trucks and Buses, while the LDVs includes passenger cars and vans, this is due the different scale of size of the powertrain of these vehicles. For an ICE truck, its engine capacity will be much greater than the engine of a small hatchback passenger car and so will be its emissions. Thus, the emission limits are set differently for HDVs and LDVs in every country across the world. These limits are imposed by the different government legislations that are specific to each country, and they are revised over the years to be more stringent to cut down emissions more and more. The timeline of these legislations adopted in major countries for the heavy duty and light duty sector are shown in Figure 1–3.



(a)



(b)

Figure 1–3: Emission regulations imposed for (a) heavy-duty and (b) light-duty vehicles across the world in the past decade. (Adapted from [15] *and* [14]*)*

As shown above in Figure 1–3, different emission standards have been enforced by the government of various regions and countries over the years to regulate the emissions from the ICE vehicles. These emission legislations mainly focus on CO_2 emissions and regulated pollutants. The regulated pollutants mainly include CO, NOx, HC, Soot, etc. It can be observed that the European Euro regulation has been a reference for all other legislations. Therefore, all the values are equivalent to previous Euro standard and are also considered from the tailpipe only. To continue being a benchmark in the legislation system, Europe has now planned to completely remove tailpipe emissions from new passenger cars and vans sale after the year 2035. This is a part of the EU green deal's fit-for-55 package that focuses on reducing about 55% CO_2 emissions by 2030.[16] The timeline of CO_2 emission reduction in Europe for the passenger car and commercial vehicle segment is shown below in Figure 1–4, highlighting the past trends as well as future targets.

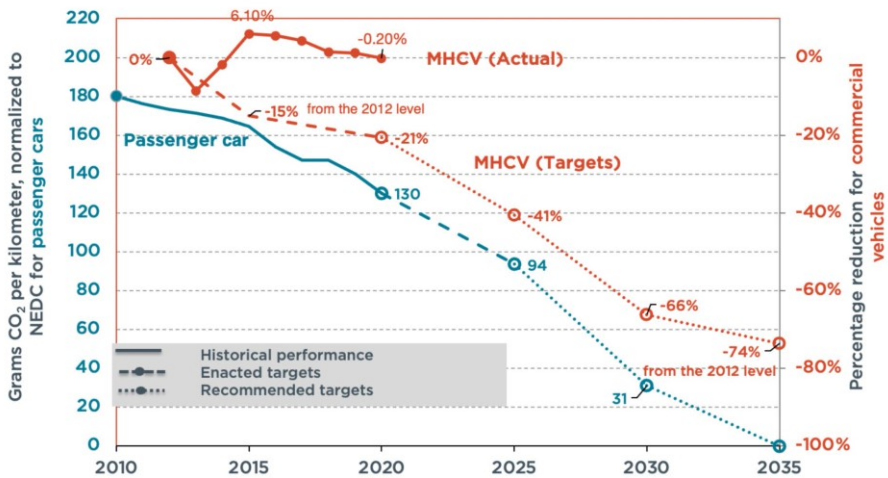


Figure 1–4: GHG emission regulations in Europe for passenger cars and commercial vehicles (Adapted from [17]*).*

From the Figure 1–4 above, while there is a 74% reduction target set for commercial vehicles in Europe by 2035, a 100% reduction target is set for passenger cars. Further, it is important to realise that these emission reduction targets are set for the tailpipe emissions of the vehicles only and not considering other emissions associated with upstream activities. The idea of zero tailpipe emissions for passenger cars means a ban on the ICE, since due to the carbon content in the traditional liquid fuels, its combustion will always lead to the emission of CO_2. Even with low carbon fuels there will be tailpipe emissions that will include CO_2 and other pollutants.[18] Thus, a complete phasing out of ICE based vehicles is planned in future by Europe as well as several other countries like the United Kingdom, United States of America, etc. Which means only the sale of fully electric powertrain vehicles will exist in the future as only they will have zero tailpipe emissions as they don't involve combustion. The Figure 1–5 below shows the plan to phase out the sale of ICE based vehicles around the world in the future.

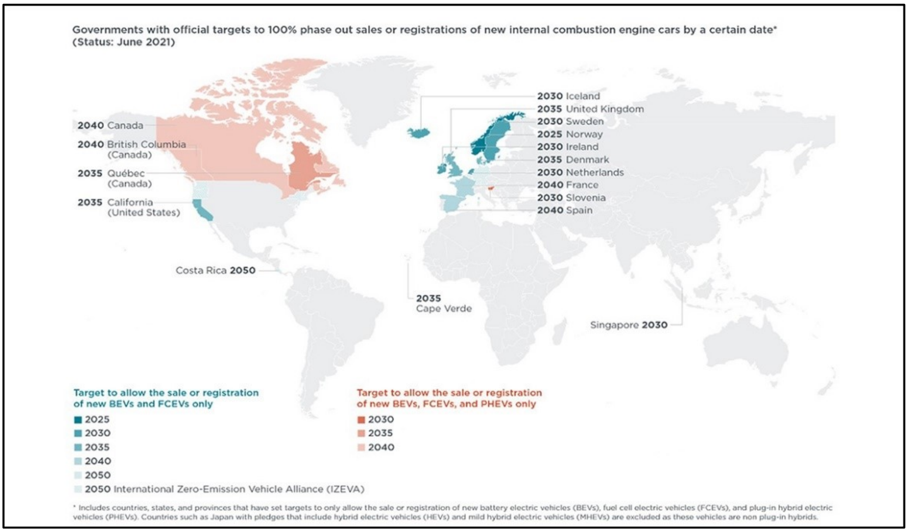


Figure 1–5: Future targets of different regions globally to ban the sale of ICE based vehicles. (Adapted from [19]*)*

The Figure 1–5 above shows that several countries in the Europe as well as in North America are going to be the first countries to stop the sale of new ICE based vehicles. This will mean that only battery and fuel cell electric vehicles will be sold because they have zero tailpipe emissions as they don't have one. Despite the zero tailpipe emissions there are still going to be emissions coming from the use phase of the EVs which will depend on the source of electricity production for charging its batteries.[20] If the electricity generation pathway is carbon intensive, relying on fossil fuels like coal and natural gas, then there is not much help in the decarbonization as there could be even higher emissions compared to the conventional ICEVs. Hence, the regulations must be set by considering the total use phase emissions at least, considering the complete Well-to-Wheel process, if not the entire life cycle phase. It is also interesting to note that several countries are now delaying or modifying its targets by including Plug-in Hybrid Electric Vehicles. This is an indicator of the fact that a realization is now happening among the policy makers that a complete switch to fully electric vehicles is not really the optimal solution.

1.2.3 Electricity mix

The electricity mix basically refers to the mix of technologies used to produce electricity. Depending on different geographic locations and resources of different countries or regions, this varies significantly. This is very important for the implementation of EVs as an alternative to the conventional ICEVs. For example, in a country like China where coal is the primary source of production, the EVs charged from its national electricity grid is not going to help much for the decarbonization of its road transportation sector. However, in a country like Brazil, where most of the electricity generation is done from hydroelectric power plants, the EVs may have a significant impact for decarbonization.[21] The Figure 1–6 below shows the carbon emission intensity of the different electricity generation technologies as claimed by the Intergovernmental Panel on Climate Change (IPCC).

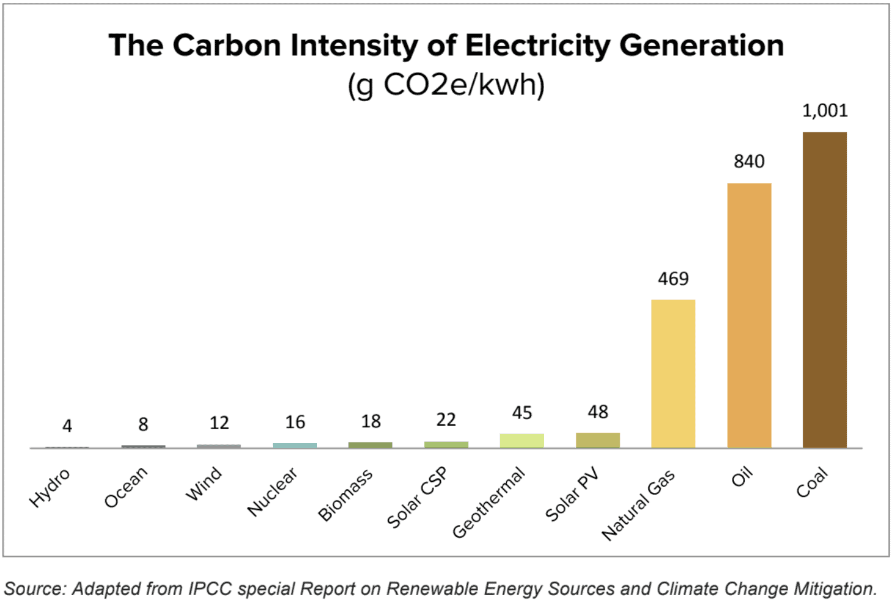


Figure 1–6: Carbon emission intensity of different electricity generation technologies. (Adapted from [22]*)*

In the Figure 1–6 above, it can be seen clearly that while using fossil-based electricity production the emission intensity will be very high. Thus, it can be said that as most of the electricity globally is still generated using fossil-based fuels, the emission intensity of the electricity production is still quite high. The ideology of EVs being a perfect alternative to ICEVs for decarbonization doesn't really stands true globally. It is important to have a clean source of electricity for charging the EVs, for it to decarbonize the transportation sector significantly. Based on the carbon intensity variation among the different countries or regions, the adoption of EVs needs to be assessed. This means that the focus should be on the local electricity mix and not just national or continental electricity mix. Although, the European policies are set collectively by the European commission, there electricity mix is not the same to set such kind of policies that is based on the false assumption of EVs being a decarbonizing option everywhere. The global variation in the electricity emission intensity can be seen below in the Figure 1–7.

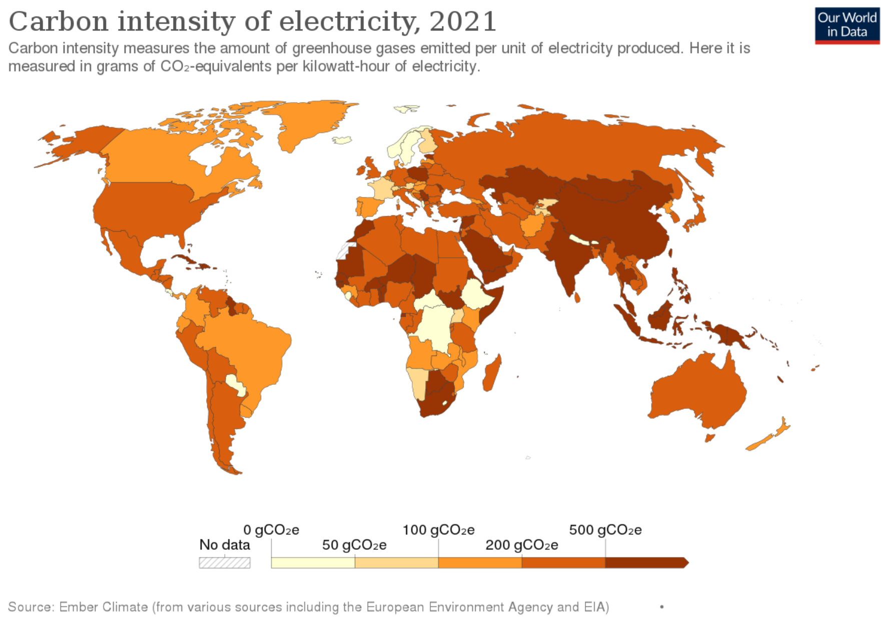


Figure 1–7: Global variation of the electricity emission intensity. (Adapted from [23]*)*

It can be seen in Figure 1–7 above that the countries in dark orange are where the electricity grid is carbon intensive, and its electricity mix is not clean. Even in Europe there are several countries which are non-green, showing that the EVs may not work as a decarbonizing alternative there.[24] Further, with increase in the electricity demand due to growing number of EVs, the source used to fulfil it can be fossil fuels as its cheaper which will increase the emission intensity for the electricity production even further.[6] This should be understood well as it is well known that each country has their own electricity mix and will depend on the sources it has access to. Thus, for an increased demand it will be easier or sensible to use fossil fuelled power generation plants that are pre-existing instead of installing new renewable electricity generation plants, which is limited by availability of renewable energy in that region. In fact, in large countries like the United States of America (USA), this variation can be even observed within the states.[25] Thus, the local electricity mix needs to be considered to evaluate the real decarbonization potential of an EV depending on its use case. Varying electricity emission intensity within the US is shown below in Figure 1–8.

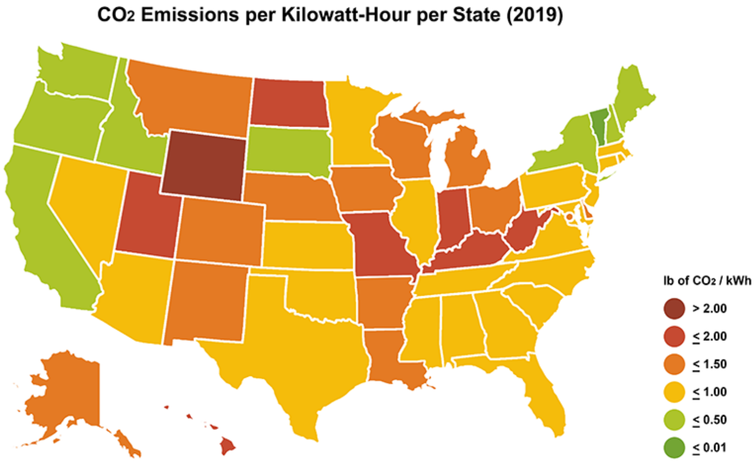


Figure 1–8: Variation in the electricity emission intensity within the US. (Adapted from [26]*)*

1.2.4 Driving condition

Another important aspect that effects the emissions out from a vehicle is the driving condition or the drive cycle under which it is operated.[27] Traditionally, the emission legislations that are passed or implemented in a country, states that the emission values from a vehicle must be below the limit for a specific drive cycle. Such drive cycles are referred as homologation cycles as it is used for homologation purposes.[28] Previously, the New European Drive Cycle (NEDC) was used in Europe mainly for homologation purposes. However, certain OEMs tried to cheat the regulations and it was found that in real driving scenarios it was emitting way above the legislation limits. Thus, a new drive cycle World Harmonised Light Vehicle Test Protocol (WLTP) was framed and implemented globally. This new homologation drive cycle was made more in accordance with a real drive cycle by considering driving conditions that are experienced during real world use of a vehicle. Figure 1–9 below shows a quick summary of the WLTP cycle by comparing it to the traditional NEDC driving cycle.

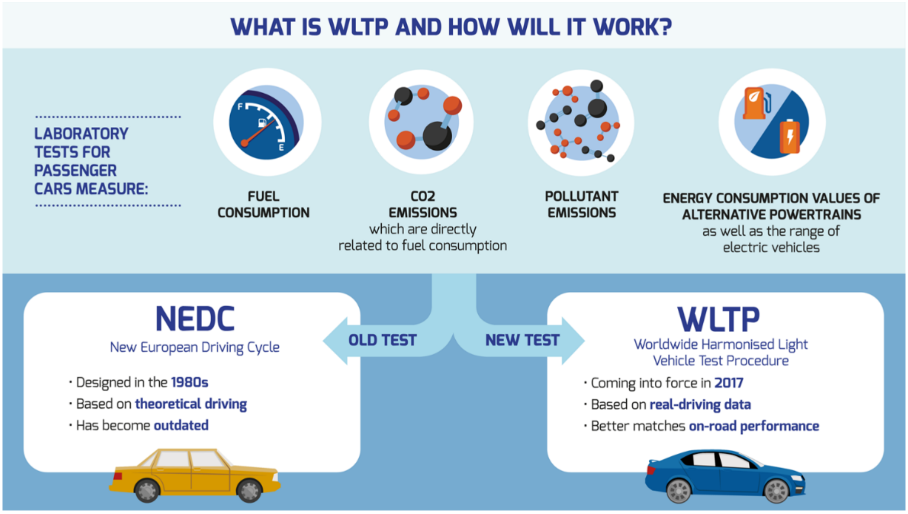


Figure 1–9: Summary of the WLTP homologation driving cycle. (Adapted from [29]*)*

Figure 1–9 above shows the main feature of the WLTP homologation driving cycle by highlighting its main feature and the need to replace the NEDC driving cycle. The drive cycle is very important for the vehicle's performance as it determines the efficiency of the powertrain, especially for ICE based vehicles. The speed is an important factor for an ICE based vehicle as the ICE performs well efficiently at high or medium speeds than at low speed. Similarly, an EV may consume higher energy when it is stuck in traffic while when it's not to cover the same distance.[30] In real world, the driving conditions vary significantly due to the variation associated with traffic, road grade, elevation, etc. Hence, the real-world emissions will surely be not the same as reported for a homologation cycle. Therefore, for an EV the range or the autonomy (in kilometres), reported for a homologation cycle, is not fully achievable in real drive conditions. Thus, it is important to not fully trust the homologation values as it can't account all the variation that are possible for a real-world drive cycle. The Figure 1–10 below shows a real drive cycle and the main parameters that effects its variability.

Figure 1–10: A sample real drive cycle and the parameters that effects it. (Adapted from [28]*)*

It can be seen in the Figure 1–10 above that a real driving cycle can be highly dependent on the traffic experienced in that dedicated route as well as other conditions such as the elevation but also the quality of roads among others. As these conditions are variable it couldn't be accounted in the homologation cycles that are used for testing the vehicles in the laboratories. Thus, the energy consumption or the emissions that are obtained from a vehicle on a homologation drive cycle is never a true representative of a real drive cycle. Further, in case of buses operating within a city the driving conditions are variable for each bus route as it will be a unique route covering different areas. The bus stop locations as well as the number of bus stops that are scheduled for each of the bus route will be different and will therefore affect the performance of the powertrain.[31] Hence, it is important to conclude that the importance of drive cycle is highly influential for the performance of the different vehicles in the real world. Thus, for a true picture of the energy consumption and the emissions the vehicles need to be evaluated on real drive cycles and not just on the homologation cycles.

1.2.5 Life cycle approach

To assess the overall environmental impact of the transportation sector, a life cycle approach is needed that keeps into account all the emissions.[32] The life cycle approach is important as it includes the emissions coming from all the phases of a product, mainly the manufacturing, use, maintenance, and disposal. In this way, the real environmental impact of any new product, including any transportation vehicle can be estimated. This is particularly important to enable a sustainable transition of the transport sector as it involves new technologies which are being considered to replace the old vehicles.[33] It is useful to understand that the new technology vehicle must be manufactured first, upon which it will be used, maintained, and disposed and the end of its life cycle. All the emissions from these phases will be added emissions if a new technology vehicle is used for this transition. The different processes involved during the life cycle of a vehicle are shown below in Figure 1–11.

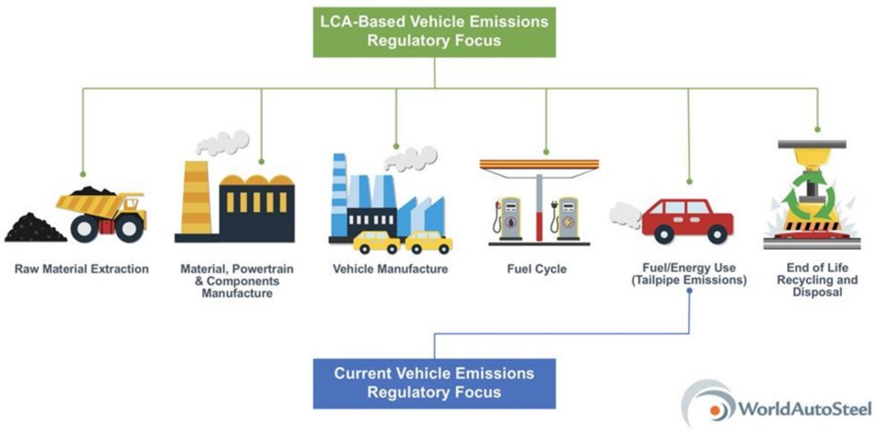


Figure 1–11: Processes involved in the life cycle of a vehicle. (Adapted from [34]*)*

Although, the electric vehicles do not have any tailpipe emissions, it does have life cycle emissions, which can be quite high based on the electricity generation source used to charge them. It is very sceptical if the saving from the use phase emissions of an electric vehicle can offset the added emissions into the environment from the other phases.[35] This seems to be very doubtful as the manufacturing emissions of the electric vehicles are very high due to the added emissions from the battery pack manufacturing.[36] In fact, in cases where a vehicle with large battery pack is operated using a carbon intensive electricity mix, it will be very much likely that there won't be any reduction in the emissions from the vehicle on the life cycle basis.[37] This is very much important for the policy maker to understand that replacing the old ICEs with EVs can be very much dependent on the local use case conditions and so it can't be enforced everywhere. Thus, it is beneficial to investigate alternative options which can be implemented to the current vehicle fleet, such as alternative fuels like e-fuels and biofuels.[38]

Moreover, considering the limited availability of all the rare earth metals, that are used in battery manufacturing, it makes more sense to have partial electrification instead of full electrification. This refers to the use of hybrid electric vehicles which are equipped with smaller battery packs and is charged directly from the ICE and regenerative braking with no need of external charging.[8] Also, due to added electrification, hybrid vehicles help in better fuel economy and thus have lower emissions from the use phase and can be very fruitful, especially in city driving conditions. Although, the presence of added electrification components like an electric machine, small battery pack, etc., does impact in additional manufacturing emissions, it is still very small when compared to the emissions added by large battery pack manufacturing.[39] Thus, it is important to consider all these factors and do the total emission calculation using life cycle approach for an unbiased analysis to see the true picture of emissions from the different vehicle technologies.

1.3 Economic Impact

Any product that has been developed to be sold in the market needs to be cost efficient unless it has a monopoly in the market and is the only option. In other cases where the new type of product is intended to replace the existing product type, the cost parity is very much needed among the products. Despite the new product being more technically advanced, its commercialisation will happen if it is offered at an affordable price to the customers. Similarly, despite the electrified vehicles being better in emission reduction it will only be attractive for the masses when it is pocket friendly and falls within their budget. As the electrified vehicles, hybrid, and full electric vehicles, have additional electric propulsion system installed its cost of purchase is quite high.[40] This high cost is due to several factors, the battery being the primary, due to the use of rare earth metals for its production.[41] This leads to significant increase in the cost of full electric vehicles as compared to the hybrid electric vehicles, due to the vast difference in the battery sizes among them.

However, it is also true that the electrified vehicles have an efficiency improvement and leads to lower energy consumption, which helps in cost reduction during the operation phase.[42] This is an important thing to consider as the cost that was added by the higher purchase cost of these electrified vehicles may get offset during the use phase of the vehicles. This too however depends on the efficiency improvement by the vehicle technology as well as the specific cost of energy for the local use case that is being evaluated. Further, it is also important to note that after buying a vehicle there are additional costs to be paid before legally procuring the vehicle.[43] These costs can be taxes, insurance, etc., which also varies locally as well as based on the vehicle type. Also, for smooth operation the vehicles must also be maintained from time-to-time, which also involves costs depending on the type of vehicle. Thus, all these costs that can be incurred during the life cycle of a vehicle must be accounted for an overall picture of the cost efficiency of a vehicle. Some major aspects that effect the cost efficiency of a vehicle are explained below.

1.2.6 Material costs

The material cost plays a major role in the production cost of the vehicles, and eventually in the purchase cost associated with each type of the vehicle.[44] Thus, it is important to estimate the materials used for producing any type of vehicle as the quantity of those materials and its specific cost will highly affect the end purchase cost of the vehicle. For instance, in the manufacturing of the conventional ICEVs, aluminium is the material that is most abundantly used and thus their purchase cost is highly affected by the variation in the cost of the aluminium. Similarly, for vehicles with a battery pack, the cost of the battery materials plays a very important role in determining the end cost of the vehicle.[45] As per the current state-of-the-art, the battery cathode is made up of several rare earth metals like, lithium, nickel, cobalt, manganese, etc., which are very costly.[46] Due to the high cost of these rare earth metals, the battery production costs are quite high and in turn takes the vehicle cost higher.

Further, these materials are referred as 'rare earths' as their availability in high concentrations is limited, which means its cost will be even higher once the demand increases. The increase in the cost of lithium, nickel and cobalt in the past are shown below in the Figure 1–12.

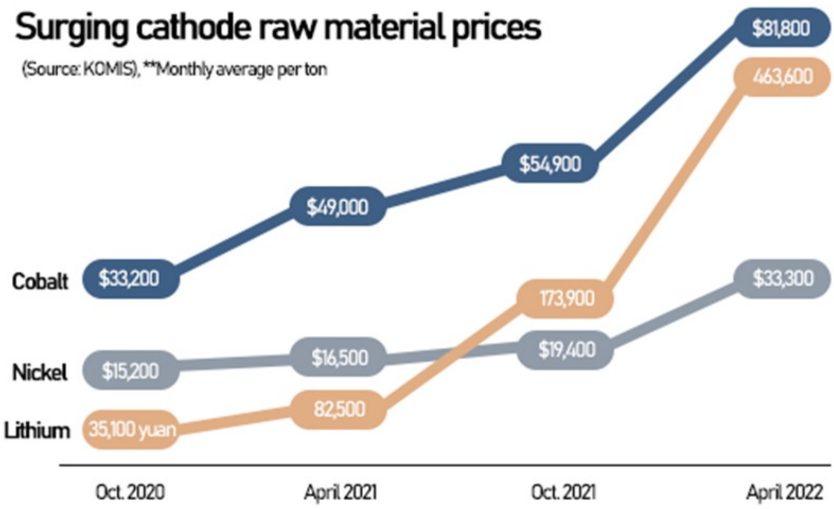


Figure 1–12: Increasing cost of battery cathode materials. (Adapted from [47]*)*

As seen in Figure 1–12 above, the cost of these battery cathode materials has only been seeing an upward trend. In future, as it is expected to have more and more sales of electric vehicles, these materials will be in even higher demand, which will up the cost even further.[48] It is therefore necessary to evaluate to what extent the transportation vehicles need to be electrified. Adding large battery packs on vehicles, to enable higher driving range or power bigger vehicles, will lead to high cost of the vehicle but also will be an overuse of the resource that is very scarce on the planet. Instead having smaller battery packs for hybrid vehicles may be a better option as it will enable the electrification of a greater number of vehicles. While it is being expected that the EV purchase cost[49] will go down in the future, with the overutilization of these sources it is in fact go further up. Therefore, a holistic and feasible action plan needs to be implemented considering the long-term consequences and not by only focusing on the short or mid-term consequences.

1.2.7 Fuel and Electricity costs

The fuel economy of a vehicle is something that every vehicle owner or operator keeps in mind before the purchase of the vehicle. This is done to ensure savings from the vehicle's operational cost, which is due to the consumption of fuel or electricity, depending on the type of vehicle. As the ICE has quite a low efficiency, there is a lot of operational cost associated with it due to extensive use of fuel.[49] The cost of the fuel, i.e., gasoline and diesel, are thus a very important factor for the ICEV owners, therefore it is important to have good fuel economy of the vehicles. This enables the user to cover more distance with less refuelling cost of the fuel, however, despite an increase in the specific cost of the fuel itself can cause a big change. In such cases although the fuel economy is the same the operational cost of the vehicle will still be up as the cost associated with each litre of the fuel will be quite high.[50] Further, as gasoline and diesel are non-renewable sources of energy, its availability on the planet is also limited and so just like the rare earth metals, its prices have also been going up. These prices are also sensitive due to geo-political tensions or the policies of the oil-rich countries, primarily in the middle east. A variation in the cost of gasoline (petrol) over the past two decades is shown below in Figure 1–13 for some major countries.

Price of petrol per litre
1 litre = 0.26 gallons

	2001 average	2011 average	2021 September
Australia	$0.57	$1.23	$1.13
Brazil	$0.90	$1.60	$1.13
China	$0.40	$1.10	$1.17
India	$0.60	$1.16	$1.38
Iran	$0.22	$0.18	$0.06
Malaysia	$0.28	$0.58	$0.48
Nigeria	$0.28	$0.41	$0.40
Russia	$0.35	$0.82	$0.68
Saudi Arabia	$0.22	$0.18	$0.62
South Africa	$0.50	$1.19	$1.20
UK	$1.10	$1.90	$1.87
US	$0.38	$0.82	$0.93

Figure 1–13: Variation in the price of petrol in several countries since 2000. (Adapted from [51]*)*

As seen in the Figure 1–13 above, other than oil-rich countries like Iran and Saudi Arabia, all the countries have experienced only increase in the cost of gasoline over the past two decades. Even for Saudi Arabia, there has been an increase from 2011 to 2021 though there was a decline in the prices from 2001 to 2011. In case of Iran, as most of the countries have forbidden to do trade with it year-by-year, the gasoline prices have rather decreased as it has lower demand than the supply or availability. Hence, it can now be realized that fuel availability is at risk for the future and the fuel cost is shooting up significantly. However, this doesn't mean that the switch to electric vehicles from ICEVs is the solution for this problem. In fact, similar issue of cost variance is involved with electricity as well, due to the ever-increasing demand of electricity around the world.[52] One such reason behind it can be the increase in the price of crude oil or fossil-based energy which is the major source of electricity production globally. The

Figure 1–14 below shows the variation in the wholesale power prices across four main regions over the past few years.

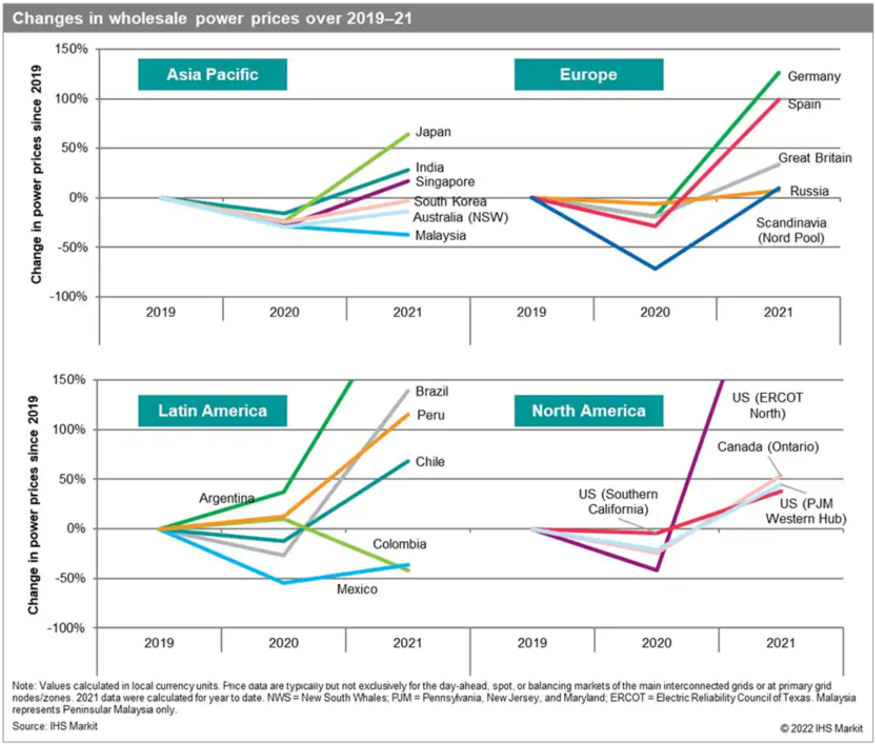


Figure 1–14: Variation in the power prices in the different global regions over the past few years. (Adapted from [52]*)*

The variation in the power prices as shown in the Figure 1–14 above is an indication of the increasing cost of power or electricity across the world. This increase in cost is a clear result of energy consumption or demand, as in 2020 when COVID-19 lead to the stoppage of industry and normal human activity the prices show a decrease. Later, in 2021, when things got back to normal and the industry re started its operations, the cost again started to go up and even higher than the 2019 levels. Hence, it is important to know that although EVs have a high efficiency and save a lot of energy, the increase in the specific cost of electricity can offset that saving. One such increase in electricity prices is observed in the Europe after the conflict between Russia and Ukraine, when Russia stopped the supply of natural gas to Europe.[53] These kinds of geo-political tensions with an oil-rich country can significantly impact on the energy security of a country or a region as powerful as Europe. The variation in the cost of electricity since the conflict between Russia and Ukraine can be observed below in Figure 1–15.

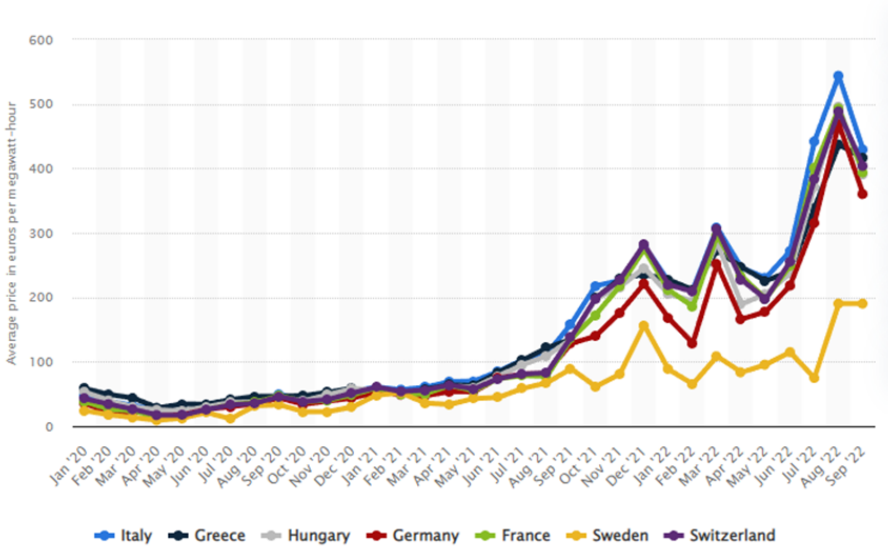


Figure 1–15: The cost variation within European countries due to the Russia-Ukraine conflict. (Adapted from [53]*)*

1.2.8 Life cycle approach

Finally, it can be said that for a holistic evaluation and a complete cost assessment it is important to consider all the costs that are involved with a vehicle for its entire life cycle. This kind of life cycle approach is important for the cost assessment as there can be one cost that can offset another. One such example is the added vehicle purchase cost due to electrification getting offset by the energy cost saving due to improved energy efficiency.[54] Also, it is observed from the previous sections that the energy cost is very variable from country-to country which can change the picture completely despite having higher energy saving from the electrified vehicles. Even the energy consumption values vary for the powertrains depending on the local driving conditions, so the evaluation needs to be location specific. In addition, costs such as taxes, insurance, incentives on EVs, etc., are all applied to the vehicle purchase cost which varies for each location.[50] The purchase cost from the vehicle showroom varies too in the same way depending on the location where it is being purchased. Thus, all these costs need to be considered for the life cycle costing, by which a customer can make its decision as to which vehicle will fit based on its budget. Different ways for life cycle costing of passenger cars and city buses are shown below in Figure 1–16.

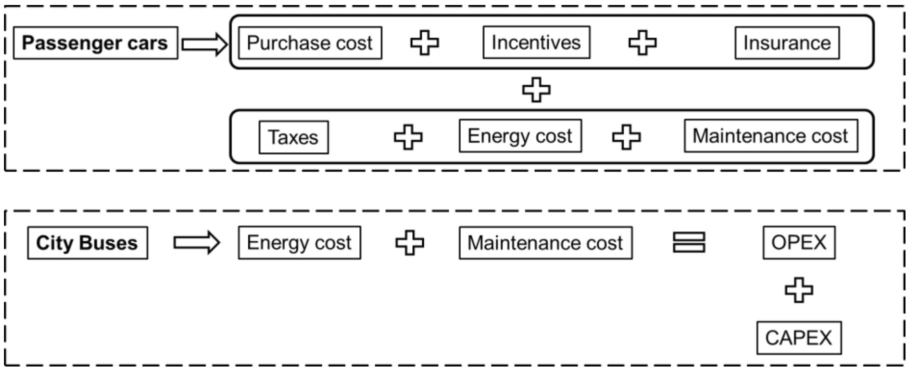


Figure 1–16: Major components of the life cycle costing for vehicles.

As shown in Figure 1–16 above it can be observed that the total cost of ownership is a suitable way for personal vehicles like passenger cars, but not for vehicles like buses which are operated by the government. This is because several government related costs are waived off and the purchase costs vary depending on the quantity of vehicles purchased as the orders are generally made in bulk.[55] Hence, although the price of a bus can be higher for a private bus operator company, it will be different for a government bus transit company due to subsidies and tax waivers. Hence, for such evaluations the approach of Capital expenses (CAPEX) and Operational expenses (OPEX) can be a better choice. Where, the CAPEX can be calculated by dividing the total amount for which the order is made by the total number of buses.[56] In this way the CAPEX for each bus can be calculated. Then for the OPEX the energy consumption and specific cost of energy can be used to get the cost related to the operation as well include cost for the maintenance depending on the type of buses. Such approaches have been used in this thesis later for evaluating sport utility vehicles and city buses individually which is discussed later in dedicated chapters.

1.4 Document content and structure

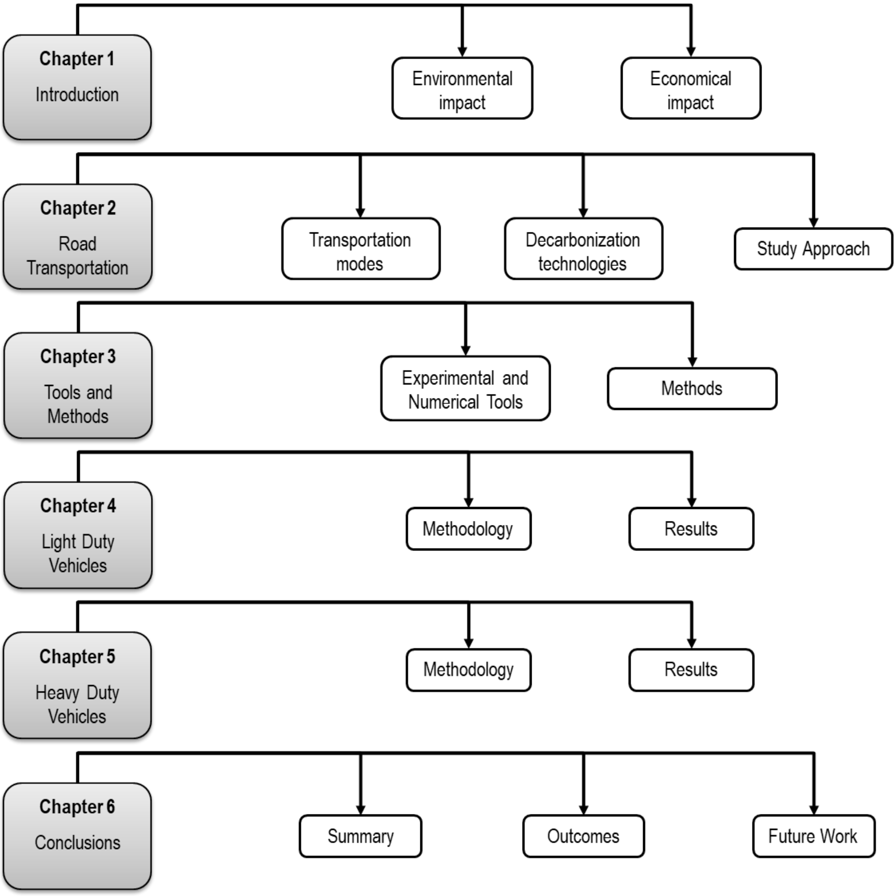


Figure 1–17: Structure of the thesis with the major contents of each chapter.

Chapter 2

Road Transportation

Content

2.1 Introduction

The transportation sector is mainly classified into three separate groups based on the type of transportation, which are, Air, Marine and Ground transport. While the emissions from the air and marine transport sector are as impactful to the environment as from the ground or road transport sector, the damage to human health is relatively higher from the road transportation. This is due to the presence of human population on the grounds or land, where the road transportation is operational. Thus, the road transportation has been heavily scrutinised for its emissions specifically from passenger cars.[57] It is also a fact that the passenger cars are the most sold type of transportation vehicle, which makes it the largest contributor for transportation emissions. The urban transportation is even higher impactful to the human life as it includes movements and pollution from the vehicles within the cities or areas habited by the human population.[58] Therefore, it is important to investigate different ways to reduce the impact of these vehicles on the eco-system of our planet.

Moreover, the road transportation comprises of several different types of vehicles based on the type of transportation intended with it. Hence, their impact on the environment is also variable which must be kept in mind while investigating the different solutions for decarbonising it.[32] Another important constraint in investigating the right solution for decarbonising is the applicability of it into the respective vehicle segment due to profitability and scalability.[59] Several investigations have been done in the past related to this but there is a lot of gaps and bias observed in the available literature.[60] Hence, this study is done to fill those knowledge gaps which are mentioned in the present chapter by highlighting the research framework followed to carry out this evaluation. Thus, this chapter highlights the different vehicle technologies considered as a potent alternative for the decarbonisation of different vehicle segments following a holistic approach to bring the real-world picture of the decarbonisation capability of each.

2.2 Transportation modes

The transport sector consists of different modes which is based on the type of mobility it is used across. This primarily includes marine transportation for water-based mobility, air transportation for air borne mobility and ground transportation for land-based mobility. In terms of emissions the road transportation is the largest contributor as it is the most sold vehicle segment across the world.[5] Also, the road transportation, more specifically the urban road one, poses a great impact on human health as it operates in areas of intensive human populations.[61] Hence, although the decarbonisation of all the transportation sectors is required for lower environmental impact and a sustainable ecosystem for the future, the decarbonisation of road transportation has been the highest priority due to its direct effect on human health.[62] The Figure 2–1 below shows the different modes of transportation available for easy mobility.

Figure 2–1: Different modes of Transportation. (Adapted from [63]*)*

Figure 2–1 illustrates the different modes of transportation and that the road transportation is made up of different types of vehicles. This is due to the varying needs of the human population for which based on the type of mobility needed, different vehicle segments have been developed and are used for transportation purposes. In other words, it can be understood that based on the type of commodity to be mobilised, different vehicle types are used for road-based transportation. For example, passenger cars are used for personal transport, buses are used for mass public transport, trucks are used for goods transport, etc. Thus, the specifications of all these vehicles are quite different from each other with respect to size, powertrain capacity, payload capacity, etc.[32] Hence, the road transportation vehicles are sub-divided into several categories based on different parameters.

One such parameter is the number of wheels, as there are two wheeled vehicles like motorcycles, three wheeled vehicles like motor-rickshaws (primarily in Asian countries), four wheeled vehicles like passenger cars, and so on. However, the global share of contribution of emissions from two and three wheelers is less than 5%, which means that vehicles with four wheels and above are the main problem.[64] This is true as out of the total emissions from the transportation sector, about 75% of the emissions comes from these types of vehicles. This includes vehicles like passenger cars, Medium and heavy-duty trucks, buses and minibuses as well as light commercial vehicles. The distribution of global CO_2 emissions from the transport sector by each different sub-sector is shown below in Figure 2–2 for better understanding.

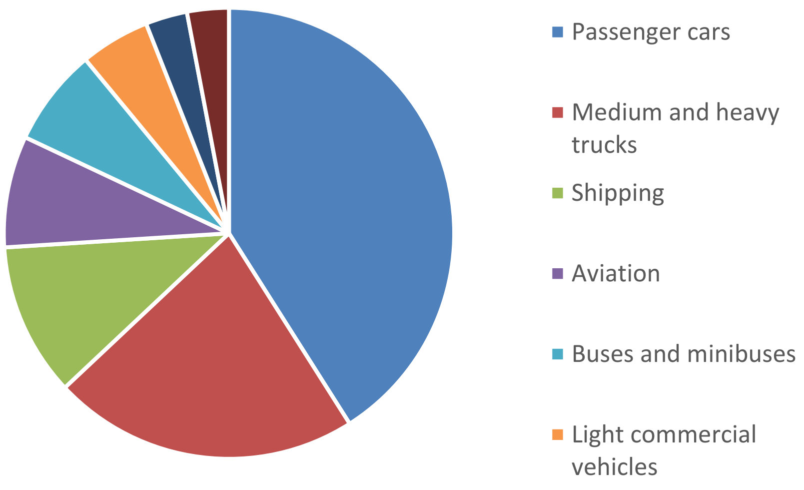


Figure 2–2: Global GHG emissions distribution of the transportation sector among the different sub-sectors. [64]

It can be seen above in Figure 2–2 that there are several vehicle segments within each sub-sector as well. This is due to the different weight classes in which these vehicles fall due to the purpose for which it is built. To categorise these vehicles properly, the Federal Highway Administration (FHWA) in the United States of America has come up with its definition of these vehicles based on the gross vehicle weight of each of the vehicle manufactured.[65] Mainly, these vehicles are divided into three categories, i.e., light duty vehicles, medium duty vehicles and heavy-duty vehicles. However, even within these vehicle segment there are further sub-categories based on the vehicle gross weight. Each of these vehicle's segments are explained in further detail in dedicated sub-sections below for an in-depth description and understanding.

2.2.1 Light duty vehicles

The light duty vehicle segment as per the name comprises of light weight vehicles mainly under 10,000 lbs. Thus, these vehicle segment includes vehicles such as hatchbacks, sedans, SUVs, vans, pickup trucks etc. As these vehicles are the most sold vehicle types that operates on the road it can be easily understood that they also contribute to the highest level of pollution and emissions to the environment.[66] Moreover, these vehicles are generally bought for private ownership for personal use, so it is very important to investigate this type of vehicles so that the best possible technology is applied and used on the roads. Further, these vehicles are even into two distinctive classes based on the vehicle weight.[65] This includes class 1 vehicles whose weight is below 6,000 lbs and class 2 vehicles with weight between 6,000 to 10,000 lbs. This categorisation is shown below in Figure 2–3 as defined by the Federal Highway Administration under the law enforcement vehicle identification guidelines.

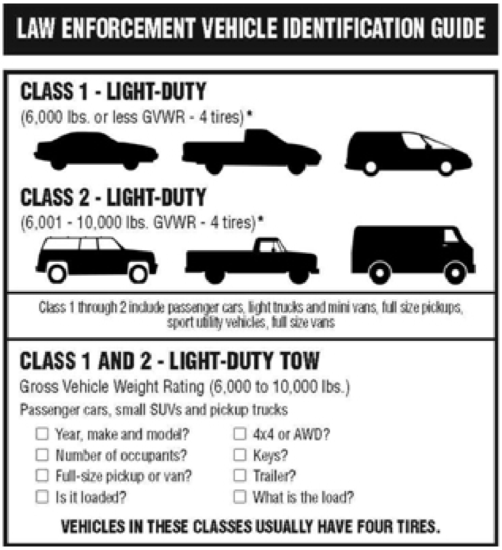


Figure 2–3: Different classes of vehicles within the light-duty segment. (Adapted from [65]*)*

In the Figure 2–3 above, based on the gross vehicle weight the gross vehicle weight rating is given to the vehicles. For the light duty segment there are two classes, i.e., class 1 vehicles with less than 6,000 lbs of weight and class 2 vehicles with a weight between 6,000 to 10,000 lbs. It can be understood that due to the varied vehicle weight the payload capacity and the powertrain capacity will also vary within this vehicle segment. In fact, it will also vary between the different classes of light duty vehicles.[66] Hence, it important to investigate which technology makes sense to decarbonise each of these vehicle classes and types individually. Due to the variations in the vehicle specifications, there might be several different constraints. These constraints or limitations need to be kept into account while investigating or proposing a decarbonisation solution for it.

2.2.2 Medium duty vehicles

The medium duty vehicles contain several different types of unconventional vehicles that are used for dedicated purposes, mainly for goods transportation.[67] They range from a wide range of weight varying from 10,000 lbs to 26,000 lbs and containing 4 different vehicle classes as per the Gross vehicle weight rating.[68] The different kind of vehicles that consists in this segment includes minibuses, delivery trucks, school bus, fire-fighter trucks, landscape utility vehicles, etc. Although this category of vehicles is not the most selling and most running vehicle segment on the roads, they include several different vehicle types that are used for special purpose transportation.[69] The Figure 2–4 below shows the composition of this vehicle segment as defined by the Federal Highway Administration under the law enforcement vehicle identification guidelines so that the officers can identify the vehicle type correctly.

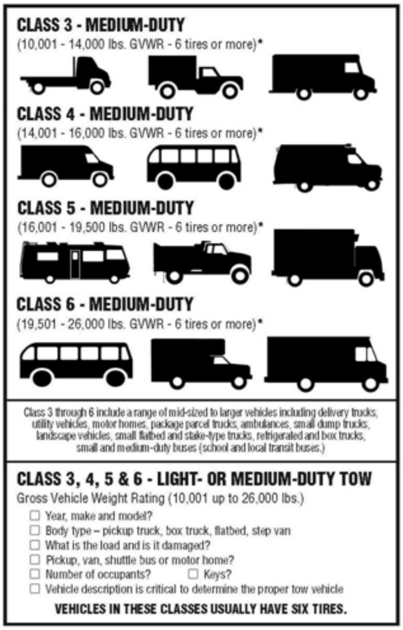


Figure 2–4: Different classes of vehicles within the medium-duty segment. (Adapted from [65]*)*

From the Figure 2–4 above it can be said that the vehicles that falls under the medium duty segment, are specially built for special purposes only that makes it a very low selling segment globally. Although these vehicles are available globally, its number is not as high as that of light duty vehicles. Moreover, due to its less presence in the total global vehicle fleet its contribution towards emissions is also not very high. Thus, although its decarbonisation is also important for a future sustainable environment, it is not an urgency to be addressed. This is because by finding a decarbonisation option for vehicles such as that of the light duty segment which is the largest contributor towards transportation emissions will be more impactful. Hence, more focus needs to be given to investigate about emission reduction options for the vehicle segment that have higher contribution towards the total emissions from the transportation sector.

2.2.3 Heavy duty vehicles

The third and the last segment of vehicles for road transportation are the heavy-duty vehicles that mainly includes all the vehicles that have weight more than 26,000 lbs.[70] These vehicles are an important part of the transportation as it mainly involves vehicles for heavy goods transportation as well as mass public transportation. These type of transportation enables the availability and reach of these things to all areas across the globe including several remote areas. The most important feature about these vehicle segments is that it is part of every industry of sector globally either directly or indirectly, as the goods transportation is needed in all types of industries or sectors. The most common types of vehicles of this segment are large delivery trucks, city transit buses, bus coaches, large trailer trucks, refuse trucks, construction vehicles, etc. To understand better the different classes of vehicles within this vehicle segment and the different types included, Figure 2–5 below shows the composition of different vehicles defined under it by the Federal Highway Administration.

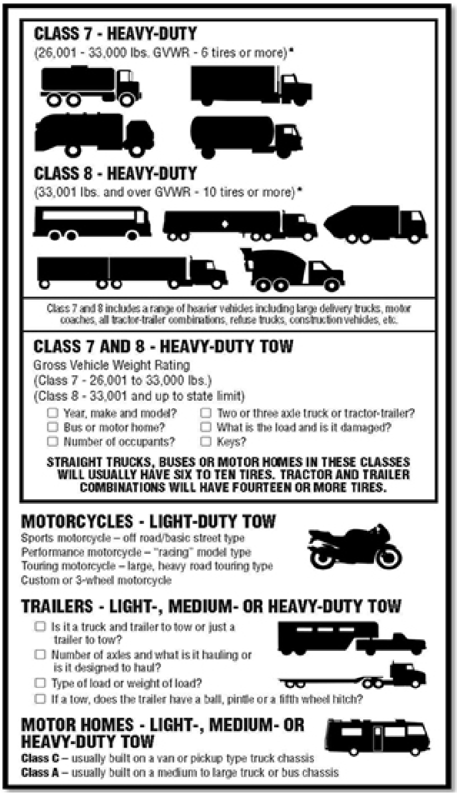


Figure 2–5: Different types of vehicles that are defined withing the heavy-duty vehicle segment. (Adapted from [65]*)*

From the Figure 2–5 above, it can be said that the heavy-duty vehicles are the next most vehicle types present in the global vehicle fleet after the light duty segment. Thus, it is also true that it is the second highest contributor towards the total emissions from the road transportation sector but also the overall transportation sector.[71] Hence, it is the second most important vehicle segment that needs to be decarbonised to have sustainable transportation in the future by adhering to the Paris agreement to become climate neutral by the year 2050. However, it is also important to realise that the solutions that makes sense for light-duty transportation might not always make sense for the heavy-duty transportation.[72] This is because while the light duty transportation is mainly intended for short haul urban transportation, the heavy-duty transportation is intended for long haul transportation. Moreover, the heavy duty involves high payload carrying capacity which must not be compromised while proposing a decarbonising technology for them. Hence, a dedicated evaluation of both vehicle segments needs to be done to obtain the most fitting technology for their decarbonisation by keeping into account all the bottlenecks for each of them.

Hence, for this thesis the light-duty vehicle segment and the heavy-duty segment is considered to assess which technology can be the most promising one for its decarbonisation. For which SUV vehicles are considered for the light duty segment while buses are evaluated for the heavy-duty segment. For the heavy-duty segment buses are considered as it is more used in city or urban areas and have higher impact on human health. Also, previously heavy-duty trucks have already been investigated in the research group in multiple doctoral research works. Hence, in the current research buses are considered to also focus on the mass transit system that involves heavy-duty transportation.

2.3 Decarbonisation technologies

This section focuses on the different technologies that can be considered as a possible way to lower the environmental impact of the different road transportation vehicles. They are primarily categorised under into three main vehicle segments. These include light duty, medium duty, and heavy-duty vehicles, out of which the top two are the largest contributors towards the total emissions from the transport sector. These are light and heavy-duty vehicle segments, as their combined emission share is about two-third of the total emissions among all the different transportation modes.[64] Thus, the decarbonisation of both these vehicle segments are focussed on this thesis by considering different solutions for each of them. Done by evaluating SUVs and buses for different powertrain and fuelling options, to find a solution to reduce the use phase emissions of these vehicle segments.

The need to reduce the use phase emissions is the biggest challenge to be addressed as its share is the highest for the conventional ICE vehicles.[73] Therefore, a reduction in the use phase emissions will have a significant impact on the reduction of the overall life cycle emissions. However, reduction in another phase that doesn't have a great contribution towards the total life cycle emissions will be not very helpful in the overall decarbonisation of the vehicle type. To do so the best possible approaches are:

- By enhancing the performance of the current ICE powertrains with higher efficiency, high capacity aftertreatment system, new advanced combustion concepts, etc.[74]
- By changing the fuel from the conventional gasoline and diesel to low carbon, carbon negative and carbon neutral fuels.[75]
- By electrification of the vehicle powertrain with partial electrification by hybrid systems or with a full electric powertrain.[76]

These three approaches involve several individual options which are discussed below in dedicated sections. This is done by explaining the technology in detail and then evaluating its advantages and disadvantages for both light duty and heavy-duty application purposes.

2.3.1 Conventional powertrain

The first and the most obvious solution for the decarbonisation of the transportation vehicles is to improve the current existing technology with the knowledge available and by developing more.[77] This can be done by improving several components that are currently used in ICE powered vehicles and by implying a new strategy of its operation as well. Figure 2–6 below shows the most common components that can be optimised for better performance of the current vehicle system.

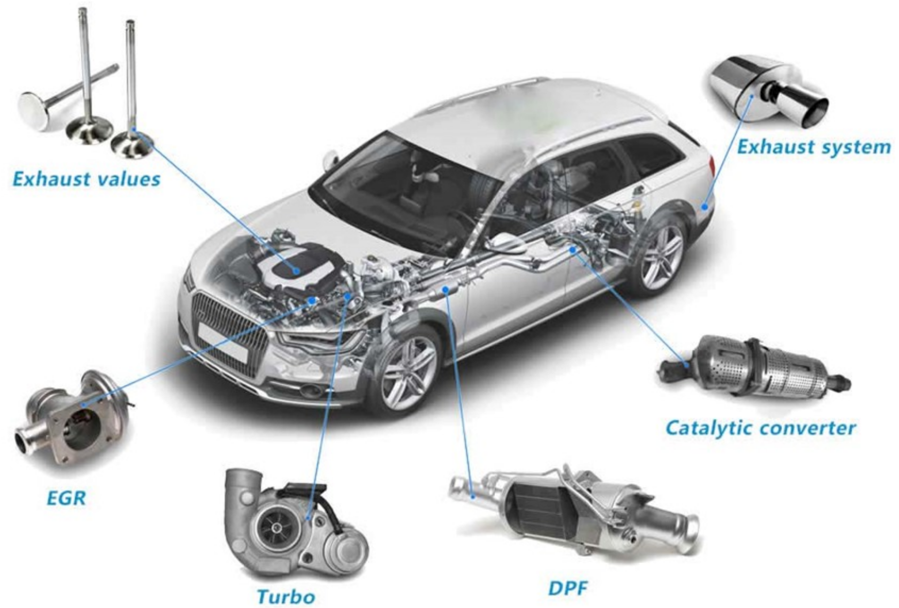


Figure 2–6: Important parts in ICE vehicles for emission reduction. (Adapted from [78]*)*

This can be done in several ways like:

1. By running the engine at lean conditions with excess air in the air-fuel mixture which lowers the fuel consumption of the engine.[79] Normally, the combustion in the engine is supposed to take place at the stoichiometric condition of an air/fuel ratio, by mass, of 14.7:1 for gasoline engines and 14.5:1 for diesel engines. This is because the three-way catalyst performs best only when the engine operates at stoichiometric conditions. Hence, although the fuel consumption may go down the emissions won't. Hence, it is important to design aftertreatment systems that can be efficient at non-stoichiometric conditions. Generally speaking, the

operation of the engine is limited for lean conditions and thus more research needs to be done to increase the lean operation limit of the engines.

2. By operating the engines at a higher compression ratio. By compressing the air-fuel mixture more we can get more power out of it, but this also increases the chances of knocking, where the combustion takes place at a time when it is not really needed. Therefore, fuels with high octane indices must be selected for operation in such kind of engine operating conditions as their auto-ignition will be delayed and will align with such high compression ratio engines.[80] Hence, this operation is highly dependent on the fuel under consideration. Variable compression ratio engines are also an option however, its control and application to multi-cylinder engines gets more and more complex and challenging with an increasing number of cylinders.

3. By new combustion cycles and new combustion concepts. Another way to reduce emissions is by applying a new combustion cycle such as the Atkinson cycle. In the cycle the compression ratio is made to be smaller than the expansion ratio, making the burnt gas cooler as it expands. This makes the cycle more efficient as we throw lesser heat out from the exhaust. Moreover, this can also be done by operating the engines in different modes such as, homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), reactivity-controlled compression ignition (RCCI), etc.[81] In fact, RCCI technology has been heavily investigated in the research group with major advancements and research made over the years by previous PhD students, Dr. Javier Monsalve Serrano[67], Dr. Rafel Lago Sari[62] and Dr. Santiago Matinez Boggio[82]. The RCCI concept, also referred as dual mode dual fuel (DMDF) engines required two different fuels as a high reactive and as a low reactive fuel. While,

the technology is highly efficient for NOx and soot reduction, carbon monoxide and unburned hydrocarbon emissions are quite high. However, with advanced aftertreatment systems this can be overcome as well and being a low temperature combustion mode, this can be a very potential way for reducing emissions specially for heavy-duty applications.[83] The reason behind these reduced emissions is the low temperature combustion but also the lower local equivalence ratio at which the combustion occurs.[84] Both these conditions help it to escape the NOx and Soot peninsulas as shown in the Figure 2–7 below.

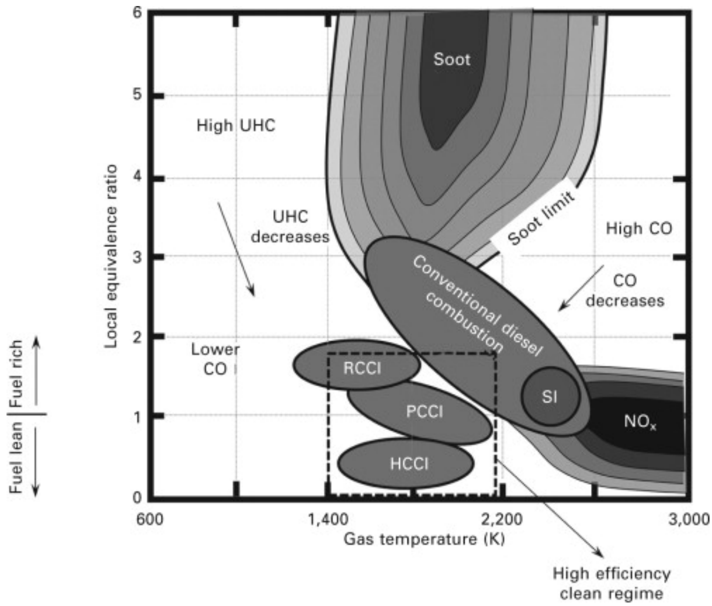


Figure 2–7: Different combustion modes and their characteristics. (Adapted from [85]*)*

The Figure 2–7 above compares the performance of RCCI, PCCI and HCCI combustion modes with the conventional gasoline spark ignition (SI) and diesel compression ignition (CI). It can thus be said that these new combustion concepts are capable to avoid both the NOx and the Soot peninsulas. As can be seen the NOx peninsula is characteristic of high temperature combustion, the soot peninsula is due to high local equivalence ratio or rich fuel air mixture. The decreasing soot formation with decreasing local equivalence ratio can be thus understood by the increasing amount of air/oxygen for cleaner combustion. Despite being cleaner in terms of NOx and soot, the emissions will still be there in terms of CO_2 which is the primary criteria for future emission targets. The presence of Carbon in any fuel will lead to the formation of CO_2 when it is combusted in the engines.[86] Hence, for the use of engines in futures, different alternative fuels must be investigated that can be low or zero carbon options. Or else finding a different powertrain concept will be needed.

2.3.2 Hybrid powertrain

The next possible way for emission reduction can be by adding some level of electrification into it. This can be done by adding the use of assist from electric machines that can be of different. The electric machine is powered by small battery packs which can be charged from time-to-time by the ICE itself.[87] Further, this electric machine can work as a motor as well as a generator, i.e., it can convert electric energy into mechanical energy to provide power for the wheels but also convert mechanical energy into electrical energy during braking.[88] This is termed as regenerative braking and makes the electric machine work as a generator to charge the battery packs. Hence, hybrid vehicles are capable of self-charging through two different pathways without being dependent on any external battery charging, except dedicated plug-in hybrid vehicles.[89] However, this may change based on the level of electrification integrated into the vehicle. To better understand the different levels of electrification, Figure 2–8 below is presented below.

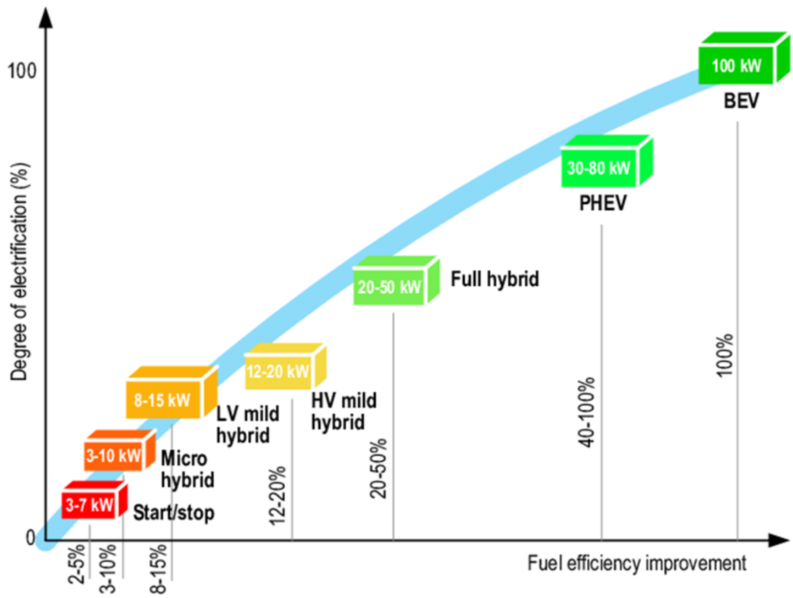


Figure 2–8: The different levels of electrification that can be integrated within automotive vehicles. (Adapted from [90]*)*

Figure 2–8 above shows the different types of hybrid vehicles that are commonly applied in vehicles ranging from 0 to 100% electrification. The conventional ICE powertrain can be considered at the origin with 0% electrification, while at 100% electrification is the battery electric vehicle. The relative fuel efficiency improvement can be seen on the X-axis for the corresponding level of electrification. By using a high voltage mild hybrid vehicle, a fuel efficiency improvement of 12-20% can be achieved, while with a low voltage mil hybrid system it can be of around 8-15%. This shows that by increasing the electric capacity of the system the fuel efficiency can be increased, which is directly related to the degree of assistance provided by the electric machine for the requirement of the power. The reason for this is the inefficiency of the engine compared to the electric machine, primarily due to engine friction by the presence of several rotating parts as well as due to excessive loss of energy as heat.[91]

Further, till the level of mild hybrid the primary source of power is the ICE which takes some level of assistance from the electric machine for things like engine start/stop, higher acceleration, higher traction, etc.[76] For the full hybrid though, the electric machine itself can power the vehicle alone while switching to the ICE completely or partly based on the driving condition.[92] However, beyond full hybrids, the primary powertrain option is the electric machine which drives the vehicle at all conditions. For a plug-in hybrid the engine is still present, but its use is to charge the battery in case it is going out of charge or provide some torque assist based on the driving condition. For the battery electric vehicle, of course there is the battery pack alone for meeting all the needs of the vehicle in terms or energy needs.[93] This also directly implies the increasing power capacity of the electric machine as its level assistance shift from partial to full. Moreover, the hybrid vehicles are also classified based on the location of application of the electric machine within the powertrain which is shown below in Figure 2–9.

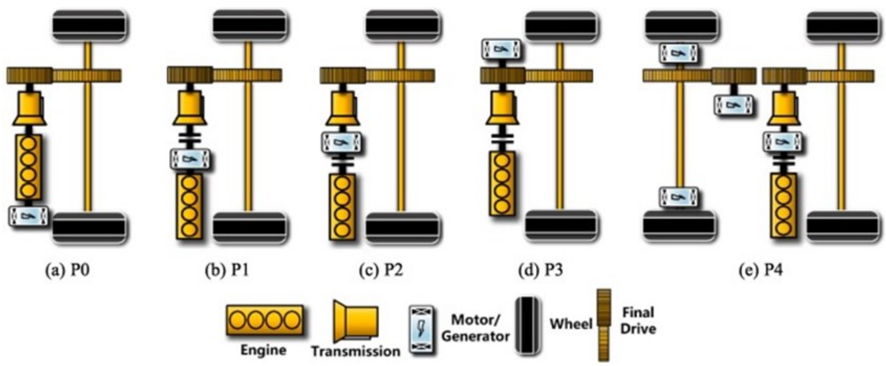


Figure 2–9: Different types of hybrid configurations based on powertrain architecture. (Adapted from [92]*)*

The Figure 2–9 shows different locations within the powertrain of the electric machines to power the vehicle which are mainly classified into five main types, such as, P0, P1, P2, P3 and P4. The P0 and P1 architecture are mainly used for small torque assist and the electric start/stop of the engine and therefore associated with micro and mild hybrid configurations.

The P2 configuration contains the electric machine between the engine and the transmission and is mostly used for full hybrids but also in some mild hybrid vehicles. While in P3, the electric machine is placed after the final drive while being connected to the drive shaft and is mostly found in full hybrid and mild hybrid vehicles as well. Finally, the P4 configuration is the one that contains several electric machines applied at multiple locations including at the axles of the wheels for higher recuperation from regenerative braking. This is mainly used mostly for plug-in electric vehicles and some full hybrid vehicles where the primary source of power is electric machine. Another way of categorising hybrid vehicles is by the energy or power flow in the vehicle powertrain by the engine and the electric machine as shown in the Figure 2–10 below.

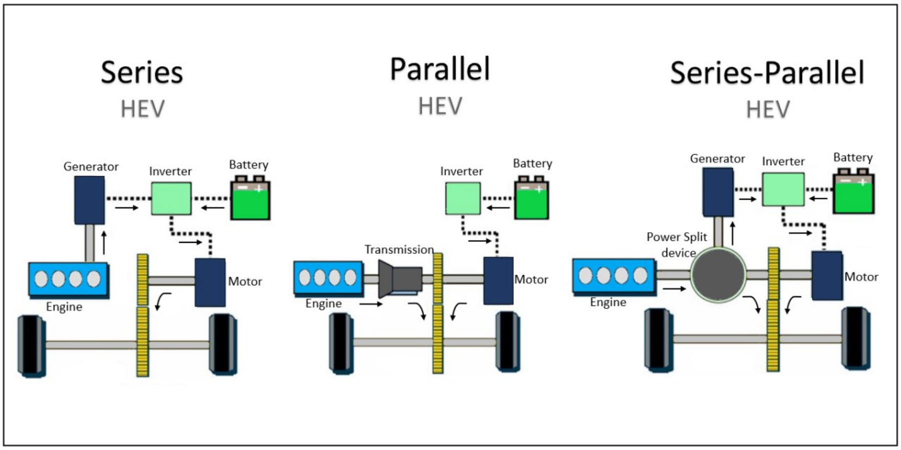


Figure 2–10: Hybrid classification by the type of power transfer by the electric machine and the ICE. (Adapted from [94]*)*

As shown in the Figure 2–10 above the three classifications are series, parallel and series-parallel hybrid electric vehicle configurations. The series hybrids are the ones where the primary energy generation is done by the engine-generator unit which is used to charge the battery and the battery then powers the electric machine which powers the vehicle. In parallel though the power can come from both the engine as well as electric machine to power the vehicle based on the requirements imposed by the driver or those driving conditions. Finally, there is a combination of series-parallel where the vehicle is operated in combination through a power-split device, where based on the need the engine and the electric machine power can be utilised individually as well as together simultaneously. Thus, based on the preference and the level of electrification needed the most appropriate hybrid vehicle configuration may be used. However, as the hybrid vehicles does involve the use of ICE there are going to be emissions from the tailpipe which may not satisfy the idea of zero emission vehicles.[95] But by an alternative fuel with low or no carbon content the vehicle can be fit to be a net zero emission vehicle.[96] Hence, it can be realised that the existence of ICEs in the long term will be based on the availability of alternative fuelling options that can lead to net zero emissions, which are discussed ahead in the following sub-sections.

2.3.3 Biofuels

As discussed previously, the primary cause of the emissions is the fuel that is used in the ICEs, the conventional gasoline and diesel. Apart from engine inefficiency, its emissions can be avoided by switching to cleaner fuels. One such type of fuels are biofuels, which can also be referred as renewable fuels as they come from bio-feedstocks and not fossil fuels. Unlike the fossil fuels which are limited in quantity, biofuels ae produced from biological sources which can be regrown and be produced again and again. This involves several chemical processes to convert the bio-feedstocks such as, wood, corn, bio-waste, etc., into usable fuels in engines for combustion. These fuels have lesser emission footprint as well due to its cleaner combustion related to added elements like oxygen in its composition.[97] Hence, its environmental impact can be quite low as compared to the traditional fossil-based gasoline and diesel fuels which are obtained from crude oil refining, that is a carbon intensive process. Figure 2–11 below shows a comparative image of the production pathway for the conventional fuels and biofuels.

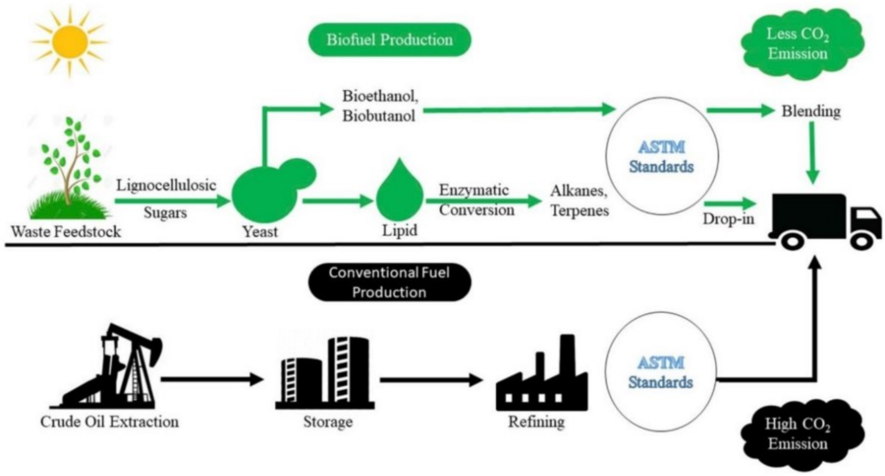


Figure 2–11: Comparison of production pathways for biofuels and conventional fuels. (Adapted from [98]*)*

It can be seen in the Figure 2–11 above that the source to produce the biofuels is the waste feedstock which is also a good way of waste management. Due to the demand of biofuel production more and more bio-based wastes will be used to generate something useful which is an energy carrier and used as a fuel for different applications to provide energy. Further, it shall be note that the main source for the generation of biofuels is the energy from the sun which is a renewable source of energy just like the renewable nature of bio waste. Hence, this is a renewable source of energy that is a sustainable solution for the future. However, as the biofuels are also carbon containing fuels its combustion too leads to emissions, but as the source of its carbon is the ones that were initially absorbed by the biological feedstock, like plants, it eventually offsets the emissions from its combustion.[77] Despite that it must be also realised that the scalability of biofuels can be an issue as to meet the demands we might be overconsuming our bio-resources and feedstocks.[98] Thus, a focus is now being given to develop alternative ways to generate biofuels from sources that are not much needed otherwise for human or ecological well-being.[99]

These developments are categorised into different generation of biofuels which is shown below in Figure 2–12.

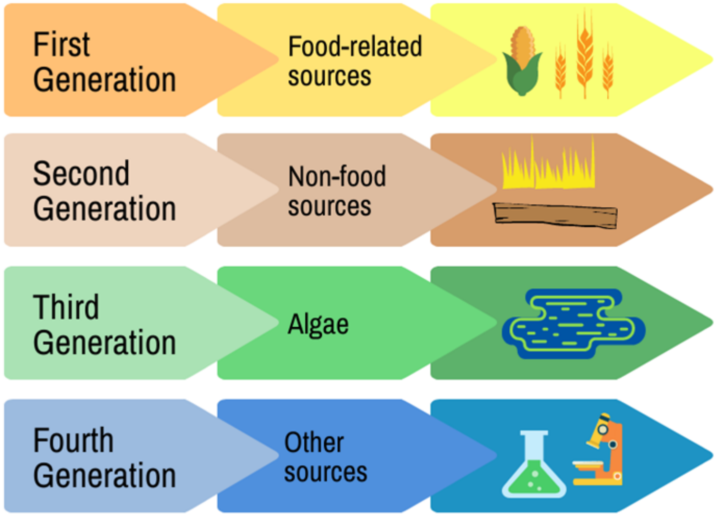


Figure 2–12: Different generations of Biofuels developed based on the type of source used. (Adapted from [100]*)*

As shown in the Figure 2–12 above, the first generation of biofuels mainly included food-based sources which may not be a good idea for large scale production. This is because the resources will be used for biofuel production instead of providing food to the living-beings for which it primarily grown in the eco-system.[101] Considering this, other sources have been and are being evaluated for biofuel production by keeping in mind the scalability factor. Thus, the second generation of biofuels came into the picture which included the use of non-food bio sources so that it doesn't affects the food consumption of the living beings.[67] Although it safeguards the food supply it can still affect the living beings by disturbing the ecological balance in the eco-system due to over utilisation of them. Thus, the need to explore more and more sources for biofuels were realised which led to the development of third as well as fourth generation of biofuels. The third-generation biofuel includes development of algae-based biofuels, which are grown separately outside the marine ecosystem so that its usage doesn't cause an imbalance in the aquatic environment.[98] Also, other sources such as some genomically prepared microorganisms like bacteria are being evaluated and considered as the fourth generation of biofuels.

Although biofuels are cleaner and more efficient fuel for sustainable transportation its usage is limited by the fact that it can't be used as a direct drop-in fuel in several cases. In fact, the ones that are more sustainable are the ones that can't directly replace of the conventional gasoline and diesel for its use in the engines. This is due to several chemical characteristics that are different from the traditional fuels even after extreme processing and treatment. Therefore, additional modifications such as different types of the injectors, compression ratio change, cylinder wall treatment, etc. are needed for operation of engines with 100% biofuels. Despite these modifications some biofuels will still need some blending of the conventional fuel to be used in engines, which makes the use of conventional fuels still relevant. Although some biofuels such as ethanol can be used neat in engines with very minimal changes in the engine system, its scalability to meet entire transportation demand is a big question. Thus, a drop-in solution needs to investigate that can be a direct alternative to the engines used in the current vehicles as a global solution. One such drop-in alternative is explained in the following sub-section that is referred as synthetic or e-fuels.

2.3.4 E-fuels

The e-fuels are synthetic lab made fuels which are supposed to be produced using renewable electricity for it to have the minimal possible emissions.[102] These fuels are an artificially produced cleaner version of the conventionally used fuels such as gasoline, diesel, kerosene, ammonia, etc. The main input for these fuels is hydrogen, produced as green hydrogen using renewable electricity or as blue hydrogen with natural gas reforming coupled with carbon capture systems (CCS) such as direct air capture or point source systems.[103] Also, carbon dioxide emissions can be used to catch CO_2 via direct air capture or point source systems to combine it chemically with hydrogen (green or blue) to obtain hydrocarbon fuels. These fuels are subjected to several processes and treatment to obtain the final product as e-gasoline, e-diesel, e-kerosene, etc. Also, e-ammonia can be produced by using the green or blue hydrogen and combining it with nitrogen that can be obtained from air separation units.[104] The Figure 2–13 below shows in detail the different ways through with some most common e-fuels can be obtained.

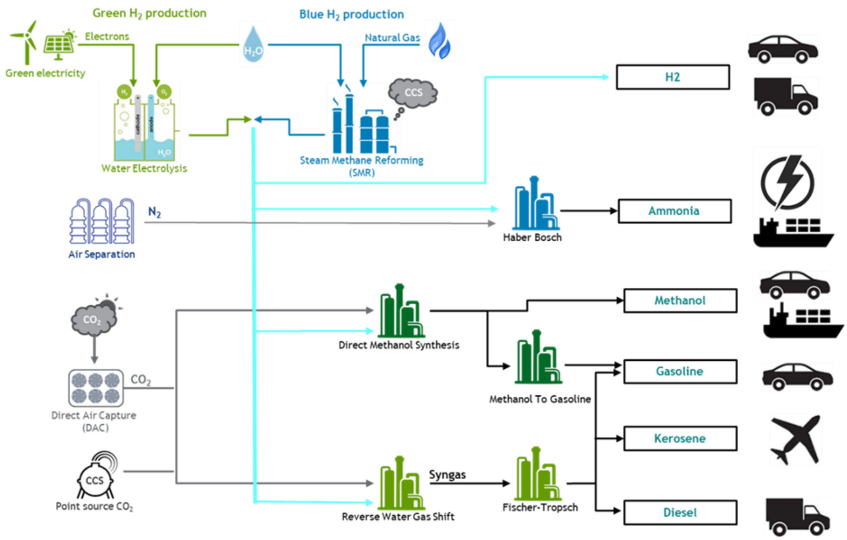


Figure 2–13: Production pathways for different common e-fuels. (Adapted from PhD thesis of Dr. Rafael Lago Sari-2021)

From the Figure 2–13 above, it can be said that the e-fuels have very clean production pathways and thus, have close to zero environmental impact. Further, when produced using CCS it in fact helps in removing the environmental CO_2 emissions and will be a carbon negative fuel.[105] Moreover, these fuels are a direct solution for the decarbonization of the ICE fleet as they can be used in the same engine without any modifications. This makes them a drop-in solution as it acts as a direct replacement for traditional fuels in the fuel tank. Moreover, its application covers the entire transportation sector including road, marine and air transportation and thus can be a very beneficial pathway for the decarbonization of the whole transportation sector. In case of using the e-fuels produced at a location which is immensely rich of renewable energy it can be a great way to convert that renewable energy and store into these e-fuels that can be then transported across the world to meet the energy demands.[84]

However, it is still a challenge to mass produce these fuels due to lack of investment from the governments globally as well as the scalability of it to meet the entire transportation sector's demands can be an important bottleneck.[103] Thanks to the partnership between Siemens and Porsche, they have now developed world's first large scale e-fuel production facility in Chile, a country that is highly rich of renewable energy sources such as solar and wind energy.[106] Moreover, companies like Audi in Germany have been long interested in e-fuels and have done extreme studies in the feasibility and technology development primarily for e-diesel production.[107] In fact, it is using e-fuels for its motorsports division and participated in 2023 Dakar rally by using e-fuels.[108] Moreover, formula 1, the pinnacle of motorsports, have also made a resolution to use 100% renewable fuels from 2026.[109] Thus, investments and initiatives like these are going to help the future development and adoption of e-fuels worldwide. The Figure 2–14 below shows the plan of the large-scale e-fuel production by the Siemens and Porsche led consortium in Chile.

Figure 2–14: E-fuel large scale production plant plan in Chile. (Adapted from [106]*)*

2.3.5 Full electric powertrain

As explained previously in the hybrid powertrain sub-section, the full electrification of the powertrain means that the electric machine is the only contributor to meet the power demand to the wheels of the vehicle.[110] This electric machine relies entirely on the battery packs which are on-board the vehicle. They must be capable of supplying the vehicle with enough electrical energy on board to cover a long range of distance once charged completely. As there is no IC engine on board this type of vehicle, there will be a different kind of weigh distribution and the wheels as the weight of the battery packs are now to be carried. Moreover, unlike the ICE which is normally placed in the front or back hood of the vehicles, in electric vehicles the battery is placed at the floor of the vehicle and the rest of the components are placed above it.[111] This type of arrangement is also known as skateboard architecture or platform, as it looks like the same. Other than the battery the next important components are the electric machine, inverter, and the battery management system. To understand the battery electric powertrain architecture Figure 2–15 is shown below.

Figure 2–15: Battery electric vehicle skateboard architecture. (Adapted from [111]*)*

As it can be seen in the Figure 2–15 above, the battery pack covers a large amount of area and requires proper insulation so that it is not damaged by any force from above or under. It is important to understand that large batteries that have large amounts of energy stored can be dangerous in case of fires or accidents.[112] One such common incident that occurs to the battery packs is the thermal runaway phenomenon that occurs in the batteries which is a chain reaction within a battery cell that is very tough to be stopped.[113] During this reaction lots of heat is released together with the emission of several gases which gets ignited and burns the complete battery pack. The main reasons for these battery thermal runaway or fire incidents that occurs is due to mechanical, electrical, or thermal.[114] To avoid thermal runaway several research is being done across the world to provide cooling and controlling the battery temperature rise to make sure it doesn't go into the state of thermal runaway chain reaction. Also, different chemical composition of the batteries as well as its packing strategies are also being investigated to have less possibilities of thermal runaway occurrence. To understand the causes behind the thermal runaway phenomenon and how it occurs, Figure 2–16 is shown below.

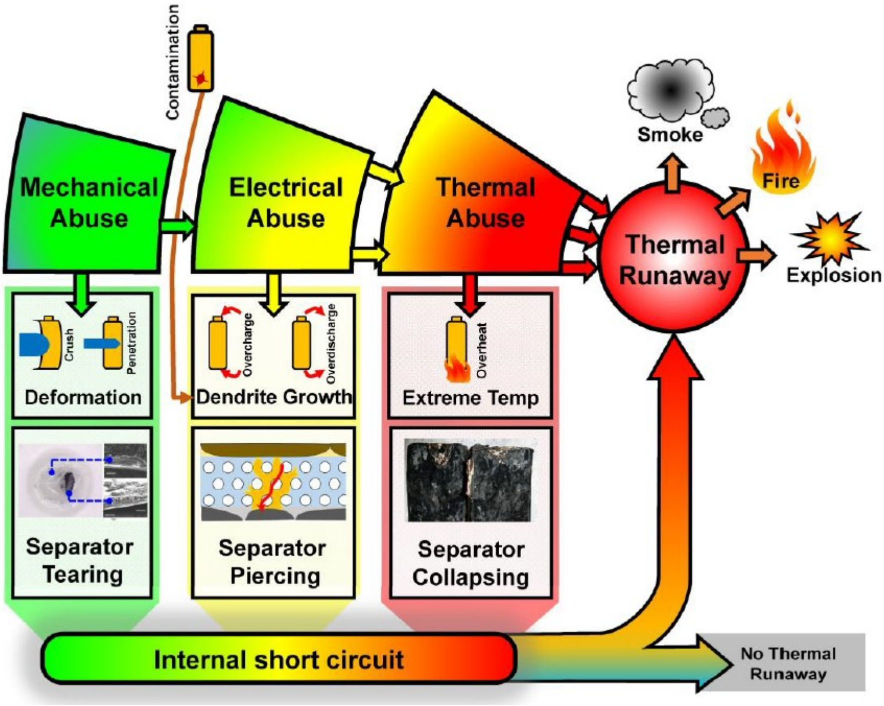


Figure 2–16: Summary of the thermal runaway phenomenon. (Adapted from [112]*)*

It can be seen in Figure 2–16 above that the thermal runaway is a multi-stage process that may occur due to several different reasons. Also, it must be realized that the higher the energy capacity of each cell is, higher is the amount of energy released if it goes into thermal runaway condition. Further, if this energy or heat release is high it will spread much more quickly and propagate across the entire battery pack and destroy not just it but the entire vehicle. Thus, the battery cell capacity and the separator or insulator between each of them, in a battery pack, must be calibrated and designed accordingly.[115] Although high energy capacity of a battery pack may bring higher damage to the battery packs or the vehicles, it is also required to have battery packs with higher specific energy and energy density. This means that for each kg or each liter of the battery pack it must have a higher amount of energy stored as this is where it lags the conventional liquid fuels. Despite the advancements in lithium-ion batteries over the years its energy density is still very low as compared to liquid fuels which is a very important feature for an energy carrier used for transportation. Figure 2–17 below shows the energy density of different energy carriers.

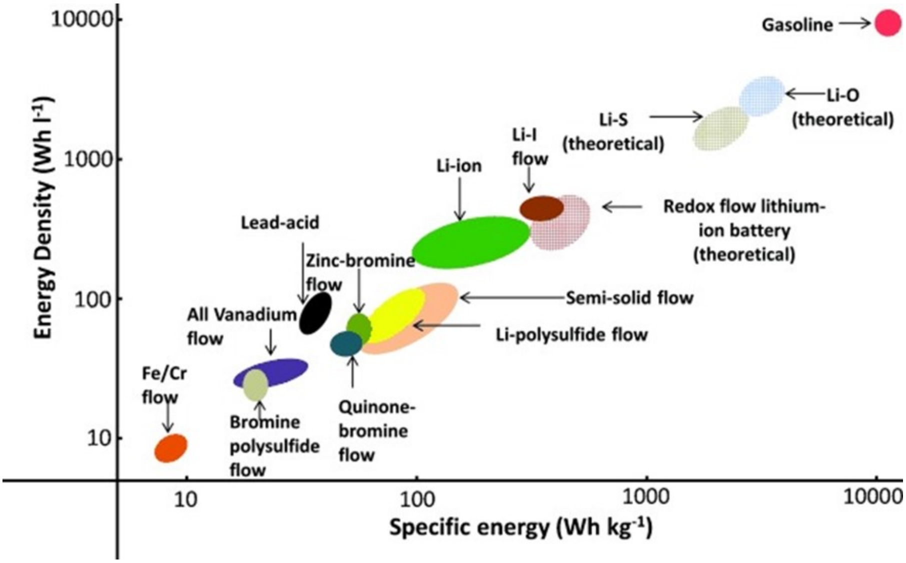


Figure 2–17: Specific energy vs Energy density of different energy carriers. (Adapted from [115]*)*

it can be seen from the Figure 2–17 that gasoline has about 10 times higher energy density than Li-ion batteries and even higher specific energy. Thus, storing energy in batteries will require a lot of space and weight on the vehicle which will limit the real purpose of the vehicles, which is to mobilize goods and public. Moreover, in case of adding a large battery pack to ensure lang range of driving, the emissions coming out from the manufacturing phase of such battery packs will also be very high. This will totally demean the real motivation of using battery electric powertrain for transportation which was to lower emissions coming out from the vehicles. Further, one major source that is the biggest concern for emissions is the source of energy or electricity for the operation of the battery electric vehicles. If the electricity to charge the battery comes from fossil-based sources, then there is not going to be any major change in the life cycle emissions of the vehicles as the emissions are not avoided but are just shifted upstream. Hence, it must be kept in mind that unless the electricity used to power the battery electric vehicles is not clean it won't be operating to its best potential for emission reduction. However, there are surely regions around the world that use very clean pathways for electricity generation, where these battery electric vehicles can be very useful in emission reduction. Though, the emissions related to its manufacturing (primarily battery packs) remain as an area to be addressed to make it a zero-emission vehicle.

2.3.6 Fuel cell electric powertrain

Although the electric powertrain is highly efficient and consumes much less energy, the low energy density of batteries limits it use for long range driving. This problem can be solved by using fuel cell systems on-board that can act as an energy generator and power either the electric machine directly or charge the batteries for powering the vehicle's powertrain.[116] A fuel cell is a device that undergoes a reverse electrolysis process, i.e., instead of splitting water into hydrogen and oxygen, the two elements are combined to produce water during which electricity is generated.[117] For this, hydrogen is stored on-board in high pressure tanks and oxygen from the air is used to combine inside the fuel cell and generate electricity that is used for battery charging or to power the electric machine.[118] The only by-product or emission from this process is water and heat. Thus, this is a clean way generating electricity on-board instead of using an ICE engine which less efficient as well as generates high emissions if powered by conventional liquid fuels. The efficiency of fuel systems is evaluated to be around 40-60% during practical use.[119] In these vehicles the fuel cell system, including the hydrogen storage tanks, are additional components other than the ones that are in battery electric vehicles. Figure 2–18 below shows the major components of a typical fuel cell electric powertrain vehicle.

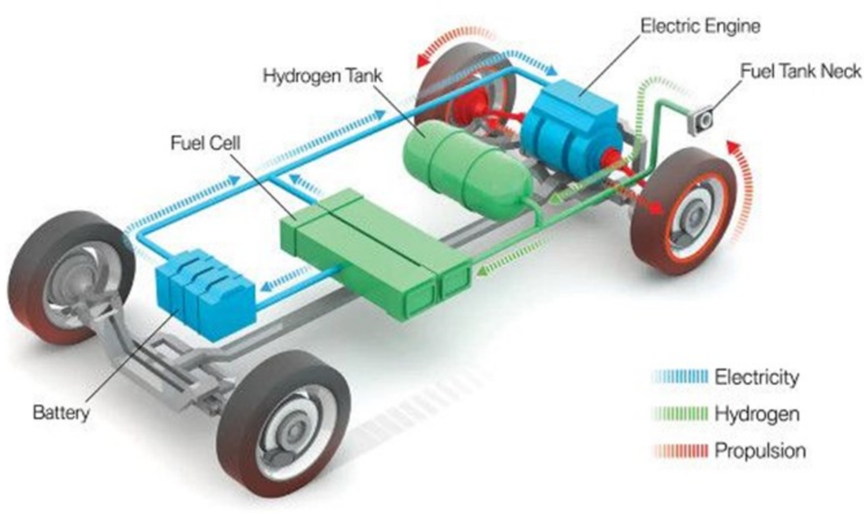


Figure 2–18: Typical configuration of a fuel cell electric powertrain. (Adapted from [120]*)*

A seen in the Figure 2–18 despite the presence of fuel cell a battery is also present to provide additional electricity demand from the electric machine. Further, in case of lower electricity demand by the electric machine the generated electricity from the fuel cell is directed to the battery to charge it. Hence, it can be understood that a fuel cell electric powertrain vehicle can be a nice way to apply electric powertrains for long haul transportation.[121] This been said, a lot depends on the type of hydrogen used in terms of emissions related to its production. Although compared to ICEVs the emission may still be lower even by using hydrogen produced from coal, but for it to be as clean as electric vehicles, the hydrogen production must be from a cleaner source.[122] For this, the development of hydrogen production ways for blue and green hydrogen are very important by ensuring that its cost is also affordable for the end users. This is one very important factor that has been the major barrier in the use of hydrogen-based transportation technologies over the years, be it in ICEs before or in fuel cells now.[123] Fortunately, a lot of push is being given by several regions globally towards green hydrogen production with forecasts to reach affordable prices soon which is a good sign for the application of fuel cell powertrains for transportation. However, that will be only possible in the future by 2030 or beyond till the hydrogen infrastructure has been fully nurtured and ready to be used.

2.4 Study approach

This section highlights the approach accounted in the present study. The focus is to present the reason why life cycle analysis has now become very important for the well-being of our environment and what are the challenges associated with the different emission reduction technologies. This starts by highlighting the motivation behind performing a life cycle analysis for the different transportation vehicle technologies. After which, the knowledge gap in the current literature or that has not yet been addressed for the life cycle analyses of transportation technologies, is discussed. The objectives that must be met in this thesis to address those knowledge gaps and to add additional value in the current research, are set. Finally, the research framework is developed and presented to provide an understanding of the steps and processes followed during this thesis.

2.4.1 Motivation

The primary motivation behind this thesis is to address the emissions coming from the transportation sector mainly due to the use of fossil fuels. In fact, the dependence of humankind on the fossil fuels started more than a century ago soon after the invention of gasoline engines.[2] It is important to understand that technical advancements such as the gasoline engines have eased the human way of living at a cost of increase energy consumption. One of the cheapest sources to meet the energy demand has been the fossil-based fuels, such as gasoline and diesel for the transportation sector.[57] As these fuels are used in the IC engines, where it is burned, it leads to the formation of several polluting gases. One major gas emitted is carbon dioxide, a greenhouse gas that heavily contributes towards global warming and climate change.[124] To reduce the emissions coming out from the fossil fuel combustion several alternatives have been explored over the years, but their implementation have not really happened at large scale and the use of fossil fuels have kept on increasing.[125] This has several harmful effects on the environment and therefore an alternative to replace them has become the topmost priority across the world.[126] Figure 2–19 below shows the timeline of energy production and increasing share of fossil fuels, highlighting the technological advancements till the 21st century era.

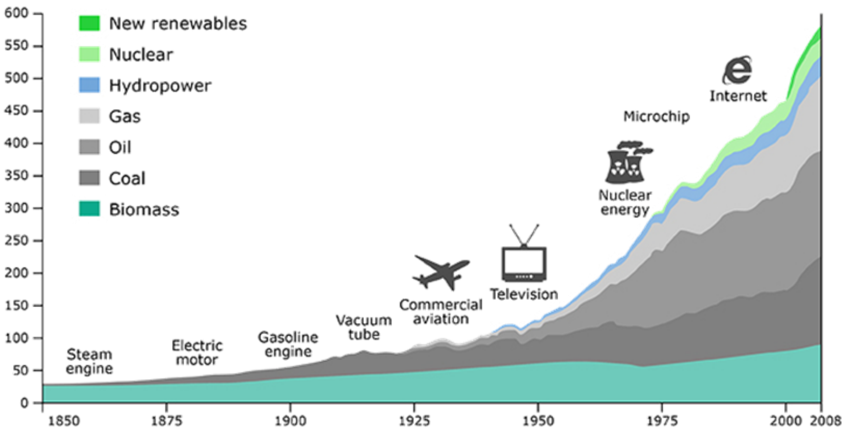


Figure 2–19: Evolution of the use of fossil fuels for energy production over the years based on different technological advancements over the years. (Adapted from [127]*)*

It can be seen in Figure 2–19 above that ever since the development of the steam engine, the global dependence on fossil fuels has started increasing. And since the invention of the gasoline engine and later aircraft, its growth rate has become exponential. While other energy options did come into picture, their deployment were not as high as the fossil fuels. This can be due to the strong power of the oil and gas industry lobby that keeps pressurizing the governments to force it to rely on fossil-based fuels for its primary energy demands. However, now as the world has finally come into its consciousness the need to switch towards renewable sources has been realized and efforts are being made to replace fossil fuels with cleaner renewable sources.[128] This is very important for the decarbonization of the transportation sector, as even electric vehicles can act as a low emitting vehicle if they are powered by a clean source of energy.[129] Unfortunately, this is not being considered and Electric Vehicles are being referred as zero emission vehicles around the world, irrespective of the emissions coming from the electricity generation to power it.[59] This is the primary motivation for this research, i.e., to evaluate how variable the emissions from the electric vehicles can be around the world based on the electricity generation mix of different regions.

2.4.2 Knowledge gap

Upon an extensive literature review for the life cycle analyses done in transportation, several knowledge gaps were identified that have been overlooked or mistaken. The biggest one is found to be in the legislations and policies set by the government as they refer to EVs as zero emission vehicles focussing only on the tailpipe emissions.[16] This is a big error as the emissions from the tailpipe are not avoided but are rather shifted upstream to the electricity generation process.[6] This can also be referred as Well-to-Tank emissions just as in case of ICEVs, which is also involved in the total use phase or Well-to-Wheel emissions. Hence, before referring to any vehicle as a zero-emission vehicle, the total amount of emissions must be evaluated, at least on a Well-to-Wheel basis, if not life cycle basis. Further, on a life cycle basis, the emissions of the EVs from its production are even higher as it also involves the battery production emissions which are very carbon intensive to manufacture.[130] Even though it is accounted in some studies there is a big bias in considering the battery size.[48] Several studies on life cycle analysis have considered a large SUV ICE vehicle and compared its emissions with a compact electric SUV with a very small battery pack.[131] One such life cycle analysis study and their results are shown below in Figure 2–20.

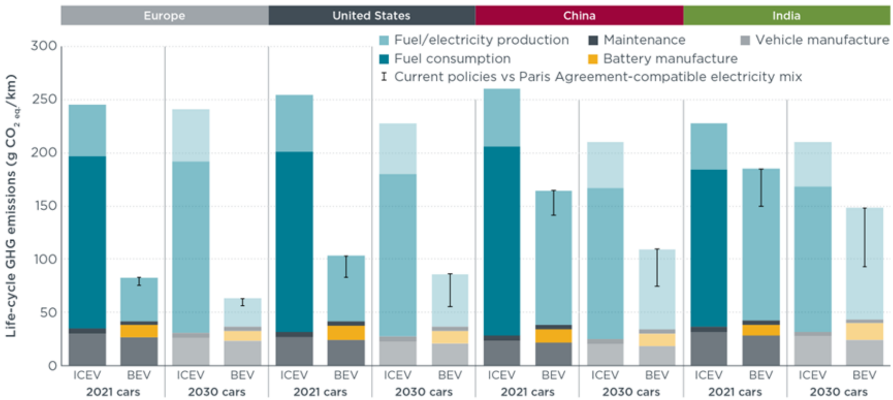


Figure ES.1. Life-cycle GHG emissions of average medium-size gasoline internal combustion engine (ICEVs) and battery electric vehicles (BEVs) registered in Europe, the United States, China, and India in 2021 and projected to be registered in 2030. The error bars indicate the difference between the development of the electricity mix according to stated policies (the higher values) and what is required to align with the Paris Agreement.

Figure 2–20: A biased life cycle analysis done comparing ICEVs with EVs. (Adapted from [131]*)*

In Figure 2–20 above, the emissions contribution from the battery production of the EVs are very less due to the small battery pack size considered in the study. Similar studies are done by several other research groups that consider EVs with very low battery capacity without mentioning the difference in the driving range due to such imbalance in the on-board energy in the vehicle.[132] Further, another aspect that has been missing is the inclusion of hybrid vehicles in these studies, which can be the best emission reduction option for countries that are heavily dependent on fossil fuels for its electricity production.[133] Also, hybrid vehicles cover a higher driving range than its equivalent ICEVs, and way higher than the EVs. Despite these advantages of hybrid vehicles, it is not included in the comparison in several studies for life cycle emissions comparison of different vehicle technologies.[134] One such study is shown below in Figure 2–21, where the effect of electricity mix of different European countries is considered for life cycle emissions of the EVs but is compared only with the ICEVs.

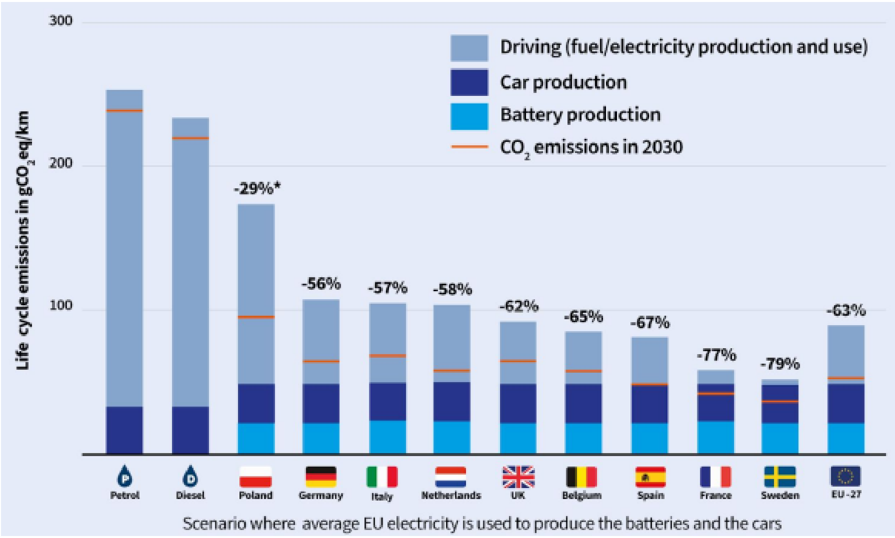


Figure 2–21: Life cycle emissions comparison of ICEVs with EVs powered by electricity in different European countries. (Adapted from [134]*)*

In Figure 2–21 above the effect of variable electricity mix among the European countries on the life cycle emissions of EVs are compared with that of the ICEVs. However, if hybrid vehicles could have been added in such studies it may be found that they are better in terms of emissions in a country with an electricity mix like Poland. Based on the driving conditions the emissions from a hybrid vehicle can change very much and can be less than 40% or even further when operated in city-based driving conditions.[89] However, in most of the research and governmental policies the emissions calculations for the use phase are done considering its operation on conventional homologation cycles. These driving cycles are not at all the correct representative of the emissions that a vehicle makes during its operation in real world scenarios. This is because the traffic in the real world can be highly variable and thus impact the performance of the powertrains, especially the ICE based powertrains. In such driving conditions with low-speed traffic, hybrid vehicles use the electric powertrain for propulsion and avoid the running of engines for propulsion.[27] This leads to fuel savings and thus, less emissions. Hence, hybrid vehicles can be as competitive as a full electric vehicle in terms of emission reduction in countries with high traffic congestion and high dependence on fossil fuels for electricity generation. Not including hybrid vehicles while comparing decarbonizing vehicle technologies can therefore be an incomplete and biased evaluation.

Also, for e-fuels there has been a very biased approach in several evaluations to create a false image of it and to not get supported for development.[135] It is important to understand two main things about e-fuels, it is intended to be produced from renewable electricity.[105] Secondly, although it does have emissions from tailpipe, it is produced using carbon capture systems making it have negative well-to-tank emissions.[136] These two important features of e-fuel have been ignored in a lot of studies carried out in the past by using the common electricity grid for its production and by comparing its emission reduction on a tank to wheel basis. Further, several studies claim that the energy efficiency of producing e-fuels and using it in ICEs is a very inefficient way of using renewable energy.[137] This is true but is applicable in countries where the renewable energy availability is very limited and so the produced electricity is better utilized by charging EVs. However, in several countries across the world renewable energy sources are abundant, such as Chile, Argentina, Morocco, Saudi Arabia, etc., and is even higher than what is required for its own energy requirement.[138] Such locations can be used for generating e-fuels as a more efficient way of its production. The e-fuels are easy to store and can be transported across the world from these production locations, just as gasoline and diesel are being transported currently.[139] One such non-holistic study of e-fuels and its results are shown below in Figure 2–22.

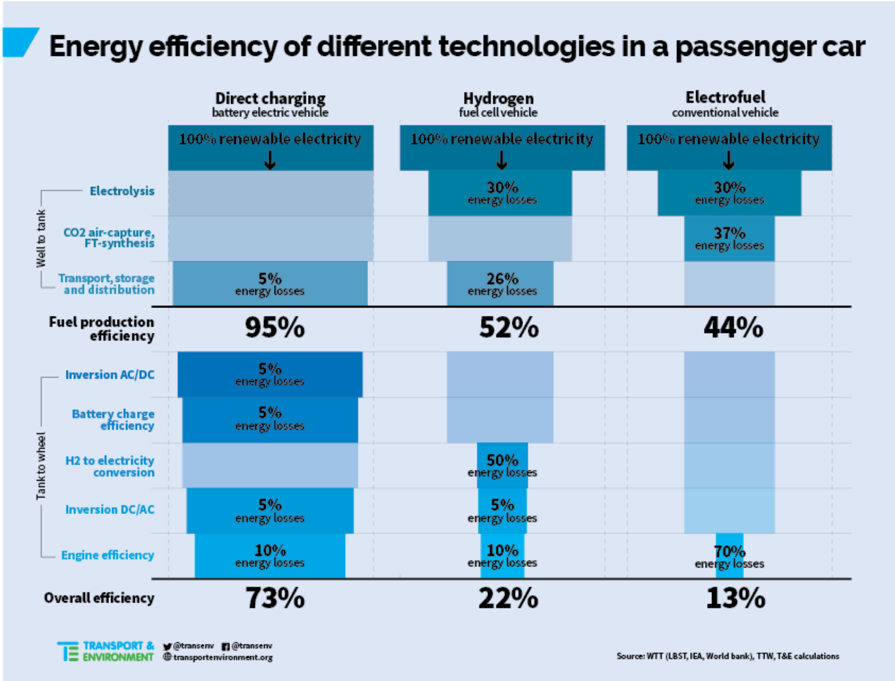


Figure 2–22: An evaluation of vehicle end efficiency for ICEVs with e-fuels and EVs, where the same location is used to produce electricity. (Adapted from [137]*)*

Finally, a lot of statements come from EV fanatics that the TCO of the EVs is lower than ICEVs, which when referred to the total cost of operation holds true as due to the highly efficient powertrain. However, in terms of total cost of ownership that is not the case most of the time.[140] This is because the purchase cost of an EV as compared to an equivalent ICEV is almost double. Therefore, even with lower operation cost, the time to offset the added purchase cost may be higher than an average vehicle's life cycle. Moreover, with the increasing cost of electricity, especially in Europe, the EVs may also lose the advantage of having lower costs of operation. This is what is not addressed in the literature and a lot of cost studies have been done without considering the variable cost of electricity. Further, for heavy duty transportation, especially buses, there aren't many evaluations done, which is actually a very important aspect for the bus operating companies. Also, in the case of e-fuels the claim is made that it is super cost inefficient due to its high cost per liter.[141] However, the fact that it can be used as a drop-in solution in the old existing vehicle is ignored. In such cases, there is no need to include the cost of new vehicles and only the cost of fuel can be considered during life cycle costing. However, for the EVs the cost of the vehicle purchase also needs to be accounted for as it is a new vehicle technology that needs to be bought and integrated into the current vehicle first. Hence, it was realized that there has been a lot of bias in the current literature and a holistic evaluation is very much required to have an apple-to-apple comparison to the most extent possible.

2.4.3 Objectives

Based on the motivation behind carrying out this study and after performing an extensive literature review to understand the knowledge gaps, the objectives for this study were set. These objectives are defined as follows:

1. Evaluate the different powertrain technologies on a life cycle basis by using real drive cycles and not just for homologation cycles to present the real on-road performance.

2. Have a country specific evaluation to see the variation of EVs decarbonization potential with respect to different countries electricity mix. And then pick the best technology for each country.

3. Evaluate the most suitable and feasible e-fuels for use in the road transportation sector by evaluating different production pathways and fuel types. As well as focusing on different locations for its production.

4. Extending the evaluation by bringing in cost evaluations to also consider which technology is financially efficient for the end user or also for the automaker.

The above objectives are the main targets that were set at the time of proposing the thesis that must be achieved by the end of the research period. These targets were set to address the knowledge gaps in life cycle analyses done for the road transportation systems but also add new dimensions and perspectives. Instead of focusing on the entire road transportation sector, the focus has been given to the light and medium duty sector as they are the most sold vehicle segments and are therefore the largest contributor towards emissions coming from entire transportation sector. In light duty segment SUVs are evaluated as they are the most sold vehicle segment currently across the world, while for heavy-duty, buses are evaluated as they operate within city areas and can affect human health immensely. Also, as buses help in mass public transport it is decarbonising way for transportation, however it should be further evaluated so as to find the best solution for its most efficient use.

The use of real drive cycles is a new way to evaluate transit buses on its dedicated routes by obtaining the vehicle speed data from the GPS. The main powertrains considered for this evaluation is the parallel hybrid vehicles and electric vehicles to compare its performance against the conventional ICE vehicles. Further, the country specific evaluations help to understand the right vehicle technology for each region considering the varying electricity mix in each of the locations. Also, the hybrid and ICE vehicles were also evaluated using poly-oxymethylene dimethyl ethers (OMEx), an e-fuel, as a decarbonising option to the conventional diesel. Moreover, the evaluations are supported by life cycle cost analyses to understand the cost efficiency of the different decarbonising options. As it is an important parameter that determines whether a product or technology will be accepted by the customers and penetrate the market.

2.4.4 Framework

To achieve the objectives, set for this thesis, the framework to carry out supporting research and investigation is drafted. The research framework is similar for both the light duty and heavy-duty vehicles however, based on the type of studies carried it varies and have been described further later in the corresponding chapters. Several evaluations have been done by using dedicated tools, which is also explained in detail in the next chapter, however, a lot of additional data have been collected through extensive literature survey. These data types vary based on the scope of different evaluations performed individually for both the light duty vehicles and the heavy-duty vehicles. Although the thesis includes several kinds of evaluations and assessments done to highlight the real picture of life cycle emissions of different powertrain technologies, there is a common approach followed for both the light duty and heavy-duty vehicle segment's assessment. The adopted broad framework thesis is shown in Figure 2–23 for a clear description and understanding.

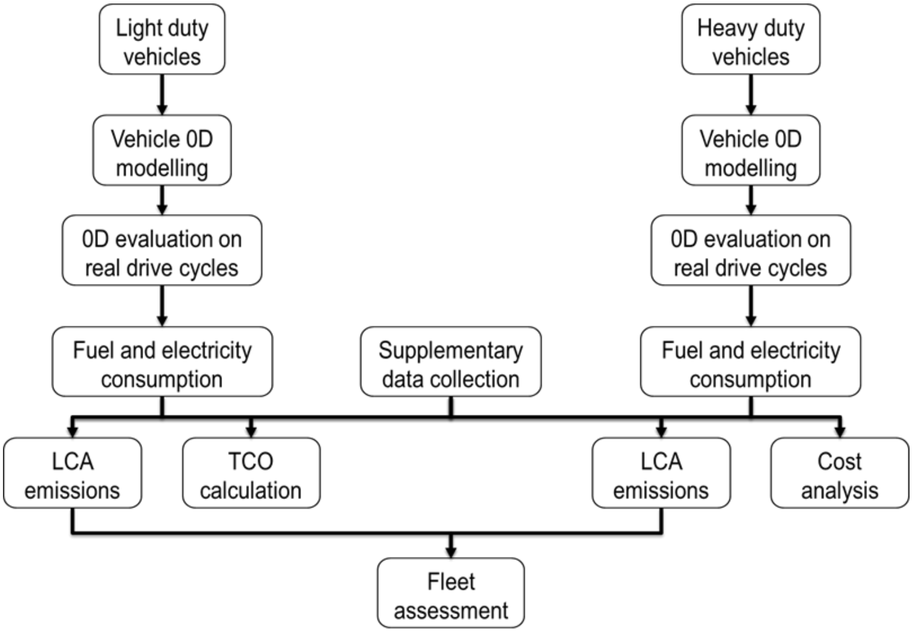


Figure 2–23: Broad research framework for this thesis.

Chapter 3

Tools and methodology

Content

3.1 Introduction

This chapter discusses how the research is carried out for this thesis. Starting off by discussing the engine set ups and facilities used to facilitate the numerical assessment done for this investigation. The different tools used to carry out the research involved for this investigation are then discussed. Different software and self-developed tools are used to perform the numerical assessment as per the scope of the research defined within the framework of this thesis. Details about these tools were presented to develop an understanding on how and what tools were used.

After highlighting the multiple tools used, each of the step performed to carry out the research objectives are explained separately in dedicated sub-sections. This is done in the same chronology in which they were performed during the PhD research. The different methods also explain the evolution of the process to cover the life cycle of the vehicles in terms of real-world emissions, cost involved as well as effect on the overall fleet. Finally, a summary highlighting the different tools and its involvement in the research methodology.

3.2 Experimental facilities

Over the years, the experimental facilities at CMT Motores Termicos, where this thesis has been developed, have become more and more advanced, especially in terms of engine and fuel testing.[142] Due to which the laboratories are equipped with several engines available for testing ranging from light duty to heavy-duty typically used for road transport vehicles or marine applications, like the Volvo Penta MD8.[143] The engines set ups comprise with advanced measuring systems to investigate on the different advanced combustion concepts and fuel combinations.[144] This helps the research group to carry out a wide range of research for different applications.[28] One of such engine test cell setup up for a light-duty engine is shown in Figure 3–1.

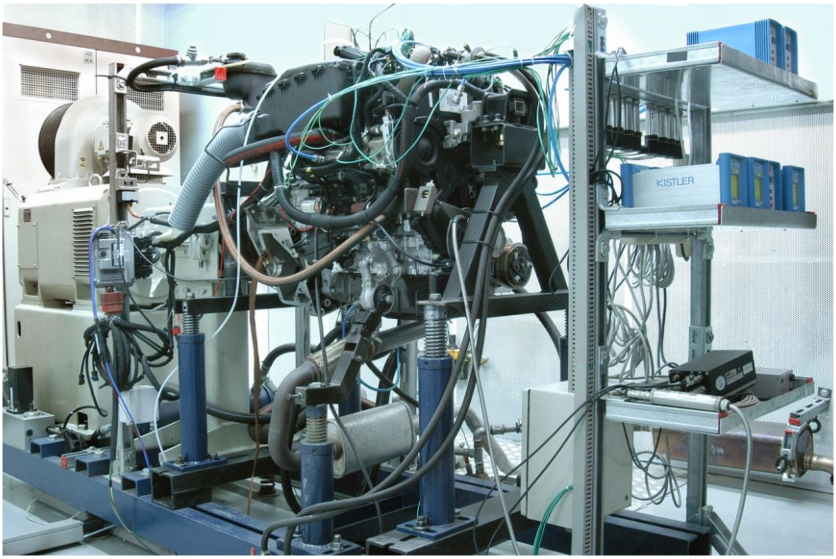
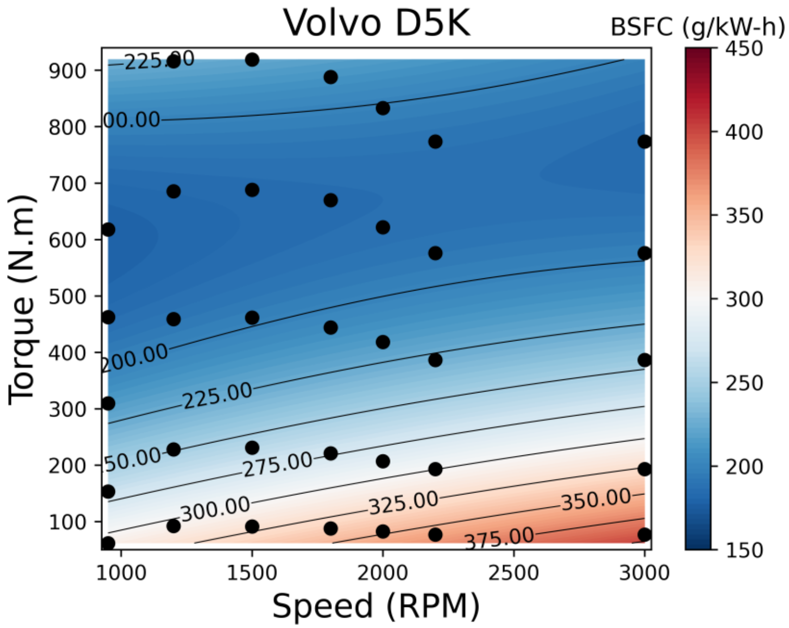


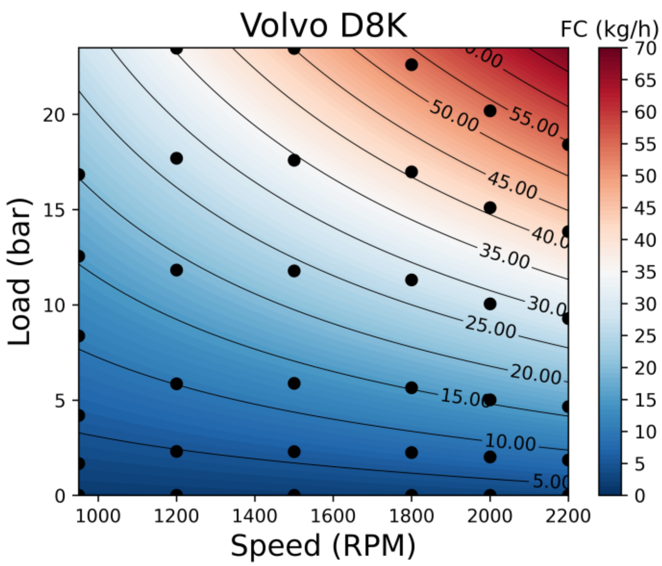
Figure 3–1: Engine test cell setup for a 1.6L Diesel engine.

The main idea is to test the engine with different advanced fuels (like methanol, OMEx, Fischer Tropsch diesel, etc.), covering the complete region of its operation to evaluate its performance. One main parameter that is used for this thesis is the Brake Specific Fuel Consumption (BSFC), which are obtained as a 3D map plots. This is obtained by testing the engine at multiple points covering the entire operational region by steady state condition testing at each of the points. These results obtained for each operating point are then used to generate engine BSFC maps through interpolation. Similar process is also done for other parameters such as Brake specific CO_2 emissions, Brake specific NO_x emissions, Brake specific Soot emissions, etc. Thanks to the advanced emission measurement devices with which the test cells are equipped like the Horiba© MEXA 7100 D-EGR. This helps in measuring the emissions of the engine setup as well as maintain the EGR supply by regulating the flow of exhaust gases with the engine test cell setup. Also, the Kistler© sensors by means of in-cylinder pressure acquisition, help in monitoring several other key performance indicators to ensure and enable a high-level engine combustion control. The maps are then used as input for transient evaluation for different vehicle types through zero-dimensional vehicle simulations.

The used engine maps are obtained through steady-state testing of the engine that matches the engine capacity for the specific vehicle type which needs to be evaluated. In this sense, three engine maps were obtained and used for the development of this thesis. Two heavy duty engines were used, Volvo© D5K for the hybrid bus assessment and D8K engine for the conventional Diesel bus. The Volvo © D8K engine is similar in specification and fuel consumption to the one used in the standard MAN© Lion City buses which is indeed considered for evaluation in this research. A third engine was used for passenger cars assessment which is a Nissan© 1.6 litre K9K engine. This engine is heavily used commercially for different vehicles by Nissan©, Renault© as well as Daimler©. Moreover, different vehicle segments such as hatchbacks, sedans as well as SUVs are all equipped with this engine. Hence, this same engine is used for evaluating both conventional diesel and hybrid passenger cars. The fuel consumption maps obtained for the three engines through steady state analysis at different operating points, are shown below in Figure 3–2.


Volvo D5K
BSFC (g/kW-h)
Torque (N.m)
Speed (RPM)
225.00
200.00
250.00
275.00
300.00
325.00
350.00
375.00
900
800
700
600
500
400
300
200
100
1000
1500
2000
2500
3000
450
400
350
300
250
200
150

(a)


Volvo D8K
FC (kg/h)
Load (bar)
Speed (RPM)
50.00
55.00
45.00
35.00
30.0
25.00
20.00
15.00
10.00
20
15
10
5
0
1000
1200
1400
1600
1800
2000
2200
70
65
60
55
50
45
40
35
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25
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15
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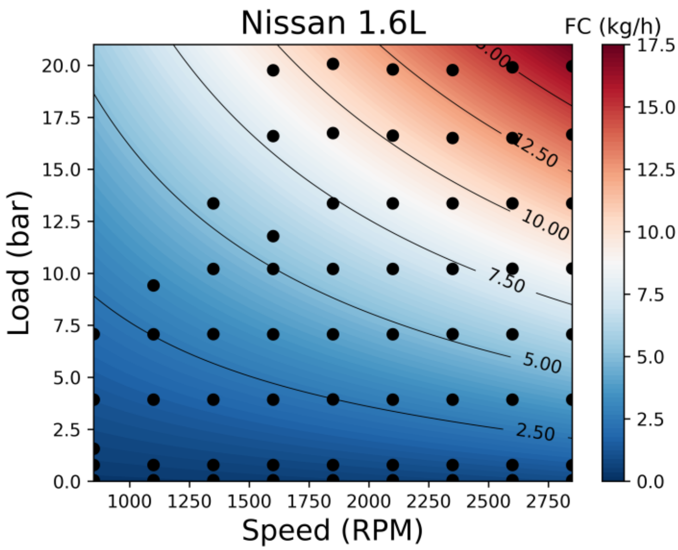
5
0

(b)



(c)

Figure 3–2: Fuel consumption maps obtained for the different engines used: (a) 5.1L Volvo D5K, (b) 7.7L Volvo D8K and 1.6L Nissan K9K.

The Figure 3–2 above shows the fuel consumption (FC) maps obtained through steady state evaluations at several operating points, highlighted as a scatter plot of black dots. While the BSFC maps are shown for the Volvo D5K engine, the FC map in kg/h is directly used for vehicle modelling for the Volvo D5K and Nissan K9K 1.6 L engines. Moreover, these maps can be obtained in several ways, one such variation is shown between the engine map of Volvo D5K and D8K, where the BSFC is obtained by varying load for D8K but for D8K it is presented as a function of Speed and Torque. Further, different other emission maps were also obtained, but was not the focus for this thesis, as the need for the engine test facilities was to get the BSFC maps to evaluate the fuel consumption that a vehicle can have when it is subjected to real drive conditions through the transient dynamic testing of the full vehicle through 0D simulations. It also important to note that at low speed the engine can operates at low load and thus these interpolated maps are limited to the maximum load reached at each speed during the testing. One such example can be seen below in Figure 3–3 for the 1.6 L diesel passenger car engine.

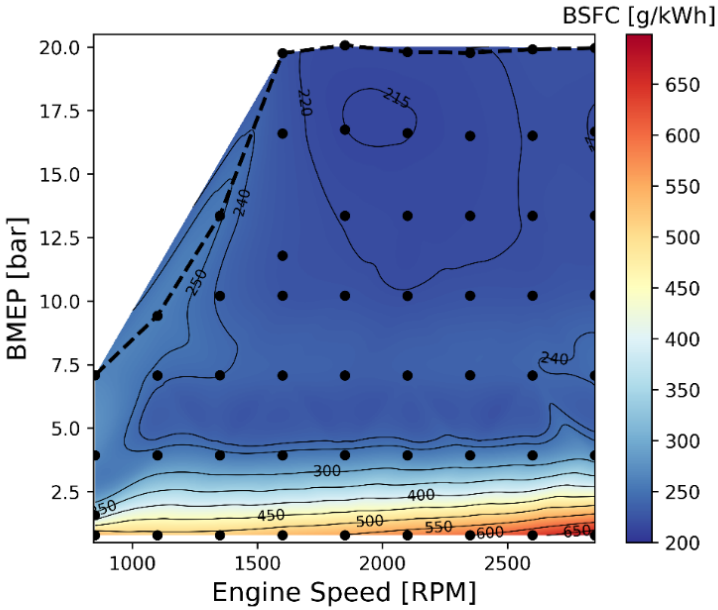


Figure 3–3: Limited map used for vehicle 0D modelling.

As it can be seen in Figure 3–3, a dotted black line indicates the maximum Brake Mean Effective Pressure (BMEP) value at each speed. For the vehicle modelling the interpolation of data is done only within this region to represent the engine capability most accurately. Based on these engine calibration maps, the vehicle performance is estimated by simulating its 0D models on real driving cycles. However, as there are more several components related to the vehicles, especially to the hybrid and full electric vehicles, related data is obtained numerically and is detailed in the following sections of this chapter.

3.3 Numerical Tools

This section discusses all the tools that were used to carry out the research work related to this thesis. After obtaining the engine maps from steady state testing, several numerical tools were used to build the models of each vehicle with specific powertrain configuration. This mainly included GT suite package by Gamma Technologies © for the 0D vehicle model development and its simulation using GT Integrated Simulation Environment (ISE), commonly known as GT Power. The GT suite package also recently launched the GT Real Drive which enables users to extract GPS based vehicle speed data for real world evaluations. This has been heavily used during the development of this thesis. The zero-dimensional modelling in GT also requires several other inputs such as electric machine's efficiency map, just as engine efficiency map for ICE based vehicles. To obtain it the JMAG software was examined to see its performance in obtaining right set of efficiency maps for the electric machines of different kind.

Further, after evaluation of the different vehicle models, its life cycle analysis is done, for which the GREET model, developed by the Argonne National Laboratory, is mostly used. The energy consumption values that were obtained from the 0D simulations were used together with the fuel cycle and vehicle cycle data in GREET to calculate the total emissions. Also, for optimal distribution of the buses a python code was developed to have the lowest emissions by operating the most appropriate bus type in each bus line. These tools are explained more in detail below in separate sub-sections to highlight how it was used in the study to achieve the objectives set for this thesis.

3.3.1 GT Suite

GT suite is a simulation package developed by Gamma Technologies ®, The industry's top simulation tool, GT-SUITE, has features and libraries geared for a wide range of applications and sectors. It provides engineers with features ranging from quick concept design to in-depth assessments of systems, subsystems, or components, design optimization, and root cause analysis. A flexible multi-physics platform for building models of general systems based on numerous underlying fundamental libraries serves as the basis of GT-SUITE:

- Library for flow (any fluid, gas or liquid or mixture)
- library for acoustics (both non-linear and linear)
- Thermal archive (all types of heat transfer)
- industrial library (kinematics, multi-body dynamics, frequency domain)
- Electromagnetic and electric library (circuits, electromechanical devices)
- Chemistry repository (chemical kinetics)
- Controls repository (signal processing)
- Integrated 3D CFD and 3D FE (thermal and structural)

GT-SUITE offers model resolution ranging from 0D to 3D calculations. Within a single model environment, a user can adjust the fidelity for any given task. An example could be using a lumped battery model for drive cycle analysis or a cell level model with 3D FE Thermal discretization to identify local hot spots during an acceleration event. The work packages consist of several tools to perform optimisation, machine learning and design of experiments, data analytics, CAS modelling and distributed computing. Some of its advanced features includes:

- Large-scale system simulations are made feasible by a quick solver.
- Computerized sharing.
- Optimization and Design of Experiments.
- 1D and 3D simulation combined in a single tool.
- Creates 1D and 3D models from imported solid CAD models.

- Embedded 3D CFD and 3D FE thermal/structural modelling is done with all boundary conditions supplied by the simulated surrounding full system.

Overall, GT suite is equipped with several applications for its enhanced simulation capabilities. These applications can be used based on the needs of the user depending on the scope of the research. It can be mainly categorised into six different applications for which they can be used, Battery, Thermal/fluid/HVAC, engine, rote/vehicle dynamics, mechanical/NVH and model automation. The apps corresponding to each of these applications are shown below in Figure 3–4.

Figure 3–4: Different apps within the GT suite package. (Adapted from [145]*)*

Out of the 10 different applications mentioned in the Figure 3–4, two applications are used mostly for the development of thesis, i.e., GT-Power-xRT and GT-RealDrive. These two applications are selected mainly as it supports engine and vehicle system level modelling and simulations, which is the focus for this research work. The GT-Power-xRT application enables to develop different 0D and 1D models of automotive vehicles and specific components. This helps to develop 0D longitudinal vehicle models of different vehicles for varied powertrain configurations, mainly, conventional ICEV, HEV and EV. Each specific component of the vehicle is fed with the data corresponding to the vehicle powertrain and dimensional specifications, as reported by the vehicle manufacturers. Thus, all the components of the vehicle are modelled to match the exact configuration of the one that is available currently in the automotive market. Further, to run the vehicles in the simulation environment, the control of the vehicle is also possible to model such as the electronic controller and the driver actions itself. This can be well seen in the Figure 3–5 below.

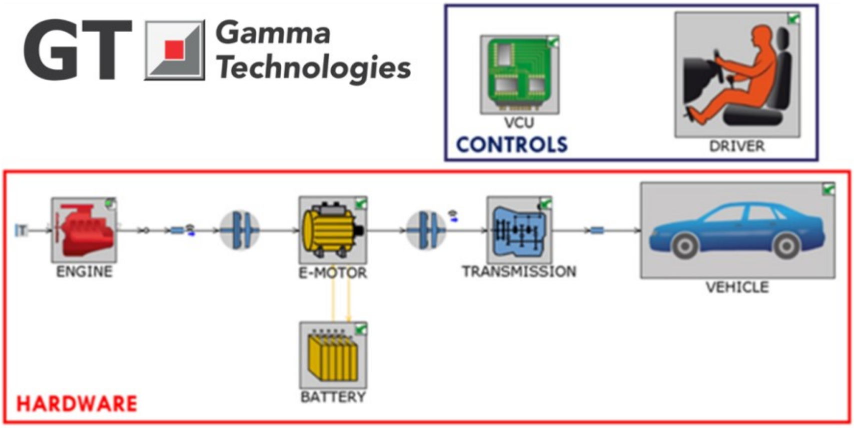


Figure 3–5: A GT Power model showing the capability of modelling the hardware and the controls for vehicle simulation. (Adapted from [146]*)*

Figure 3–5 represents that the GT Power application enables the user to evaluate the performance of a vehicle during its operation for a specified set of operating conditions. Thanks to these described capabilities this application is selected for the vehicle modelling as it can then be subjected to a drive cycle for its performance evaluation. To define a drive cycle which is most representative of the real-world scenario, the GT-RealDrive feature is also included in the research framework. This application is capable in providing vehicle speed data from the GPS for which the vehicle simulation needs to be carried out. The overall idea of using the GT suite package is to do the vehicle level evaluation in transient conditions.

As explained in the previous section, engine maps are obtained by steady state testing of the engine in test cells for several set of operating conditions. The obtained maps are used to make 0D vehicle models on GT Power, which can be then tested by specifying different drive cycles. These driving cycles are basically varying vehicle speed data over a course of time that a vehicle experiences when it moves from point A to point B. Based on the traffic conditions, a vehicle is subjected to acceleration and deacceleration when the accelerator and brake pedal are applied. Hence, to obtain this data the GT RealDrive enables the user to import it directly from the GPS by simply selecting the start and end position on the map. This is shown in detail in Figure 3–6 below for a drive cycle in Miami, USA.

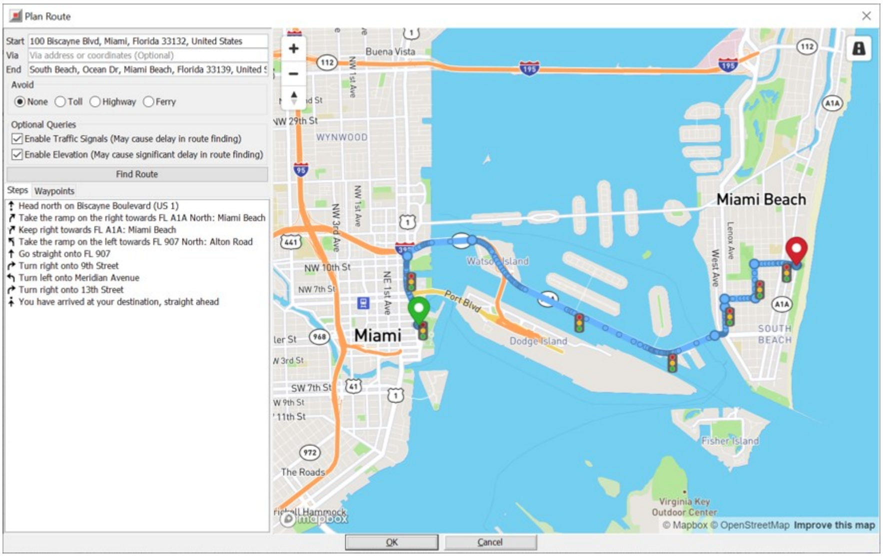


Figure 3–6: A typical GT RealDrive cycle to obtain vehicle speed evolution over time. (Adapted from [147]*)*

As shown in the Figure 3–6, the data specific to the route selected on the map can be obtained for the vehicle's position, speed, and elevation. This data is highly representative of the real-world performance of the vehicle as it considers the traffic congestion, traffic lights, road elevation, road quality, etc. Thus, to ensure a holistic evaluation in this research, real drive cycle data are obtained and used to carry out the vehicle performance evaluation. In the previous chapters it is already discussed why the homologation driving cycles are not the true representatives of the vehicle's true performance in the real world. More details on the methodology followed to perform the 0D modelling, drive cycle designing and the 0D simulation of the vehicle models on the drive cycles are shown later in the next section.

3.3.2 SUMO

SUMO is an open-source software that stands for Simulation of Urban mobility and is developed by the German Aerospace Centre (DLR). It is a multi-modal, open source, microscopic traffic simulation. It enables the simulation of the movement of a certain single-vehicle traffic demand along a particular road network. The simulation enables discussion of a wide range of traffic management issues. It is entirely microscopic: each vehicle is properly represented, has a unique route, and travels through the network separately. Although determinism is the default in simulations, randomization can be added in several ways. The Figure 3–7 below shows a table from the software's website highlighting the different applications within the software and its short descriptions.

Application Name	Short Description
sumo	The microscopic simulation with no visualization; command line application
sumo-gui	The microscopic simulation with a graphical user interface
netconvert	Network importer and generator; reads road networks from different formats and converts them into the SUMO-format
netedit	A graphical network editor.
netgenerate	Generates abstract networks for the SUMO-simulation
duarouter	Computes the fastest routes through the network, importing different types of demand description. Performs the DUA
jtrrouter	Computes routes using junction turning percentages
dfrouter	Computes routes from induction loop measurements
marouter	Performs macroscopic assignment
od2trips	Decomposes O/D-matrices into single vehicle trips
polyconvert	Imports points of interest and polygons from different formats and translates them into a description that may be visualized by sumo-gui
activitygen	Generates a demand based on mobility wishes of a modeled population
emissionsMap	Generates an emission map
emissionsDrivingCycle	Calculates emission values based on a given driving cycle
Additional Tools	There are some tasks for which writing a large application is not necessary. Several solutions for different problems may be covered by these tools.

Figure 3–7: List of applications and its description available in the SUMO software. (Adapted from [148]*)*

As shown in figure Figure 3–7, the software can do several things related to mobility simulations. However, one important feature is that it enables the user to select any location on the map and get the data for all the vehicle movements in the selected location from the GPS. The software tracks the movement of each vehicle that has travelled across the area selected on the map and gives the exact position and speed for each time step of 1 sec. In this way the vehicle speed evaluation during its operation within that area can be obtained. This feature of the software was very interesting as the GPS based drive cycle data can then be obtained from an open-source tool. However, it must be ensured that we must select the exact right area on the map, covering the entire drive cycle as planned or scheduled for a bus lines. For passenger cars it is easy to choose any of the vehicle that starts and stops within the selected or imported area. Thus, the tool was explore to see if it can be helpful in the current research. Figure 3–8 shows a sample area from New Delhi, India, imported from OpenStreetMap for its traffic data.

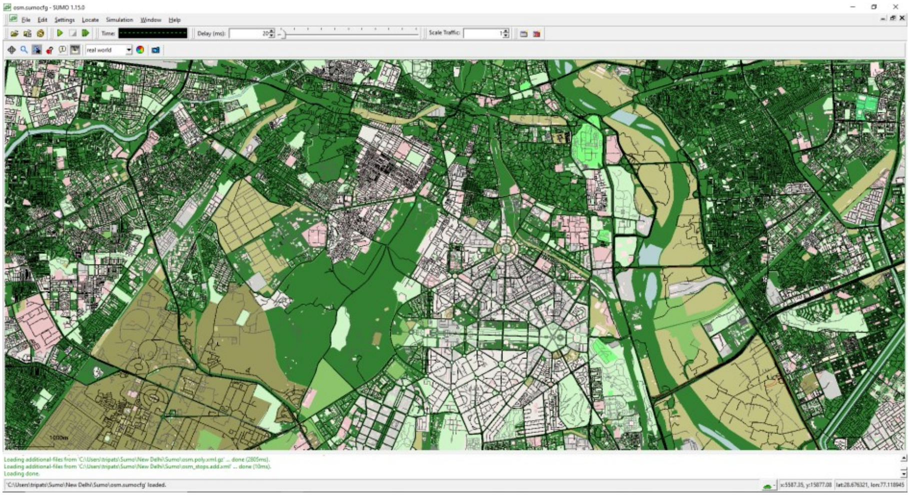


Figure 3–8: OSM file created by SUMO after importing the data from the map of New Delhi, India.

Figure 3–8 above shows the map of New Delhi for which the GPS data was imported from OpenStreetMap to obtain drive cycle data. Using some command line codes, the raw data for all the vehicles moving in the selected map region can be imported in .csv format. However, as the data for all the vehicles is imported it takes a lot of time and the final generated .csv file can be of a size of several gigabytes which is tough to access. Using tools like Notepad+, the files could be opened and the data for specific bus routes were exported in multiple steps of sorting and rearranging together with the help of MS excel. Unfortunately, the end data obtained for bus speed evolution for several buses were not as expected and in fact upon deep checking, various buses were tagged wrongly as their directions of the route were not as claimed by the bus transit company of the region. Similar issue was also encountered when evaluated for the buses in Barcelona, and so the research work was carried out by using the GT RealDrive application only.

3.3.3 JMAG

To ensure a robust model for the Electric Motor, the JMAG® software was explored for its capabilities and accuracy in obtaining the efficiency maps for the different electric machines. JMAG is a long-used software in the electric motor and vehicle industry for the assessments of the electric motors. The motivation behind exploring it was the fact that it could be coupled with the GT Power vehicle modelling interface and so could be easily used for vehicle performance assessments. In the motor sub-assembly of the 0D vehicle model in GT Power, the traction motor generator map can be replaced by the JMAG Motor generator map, shown below in Figure 3–9.

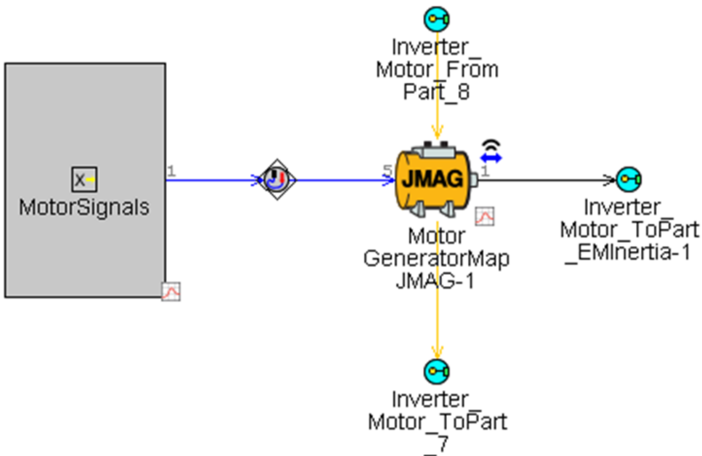


Figure 3–9: GT-JMAG coupling feature.

The Figure 3–9 shows the JMAG feature available in GT Power to generate efficiency maps and use it within the vehicle model to evaluate its performance. However, this feature can generate efficiency maps using very limited parameters. This may result in inaccuracy, as the full version, the

JMAG Designer, involves very detailed modelling of the rotor and the stator by asking for detailed values for several parameters. Thus, to evaluate the accuracy of the JMAG express tool, a comparison study with the obtained data sets available within the research group for different electric machines were done. The modelling methodology within the JMAG express tool is quite basic and mainly involves selecting the motor architecture, defining the motor and rotor geometry, and defining the Voltage and Torque requirements. Figure 3–10 highlights the main steps to obtain the electric machine's efficiency map.

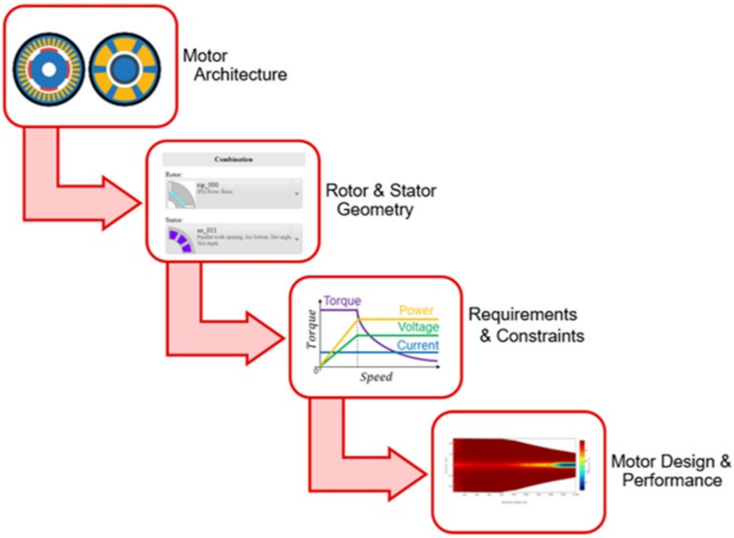
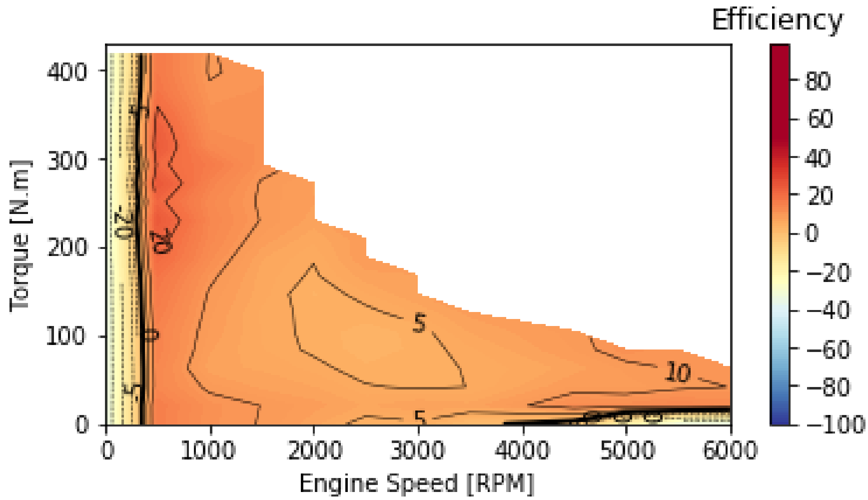
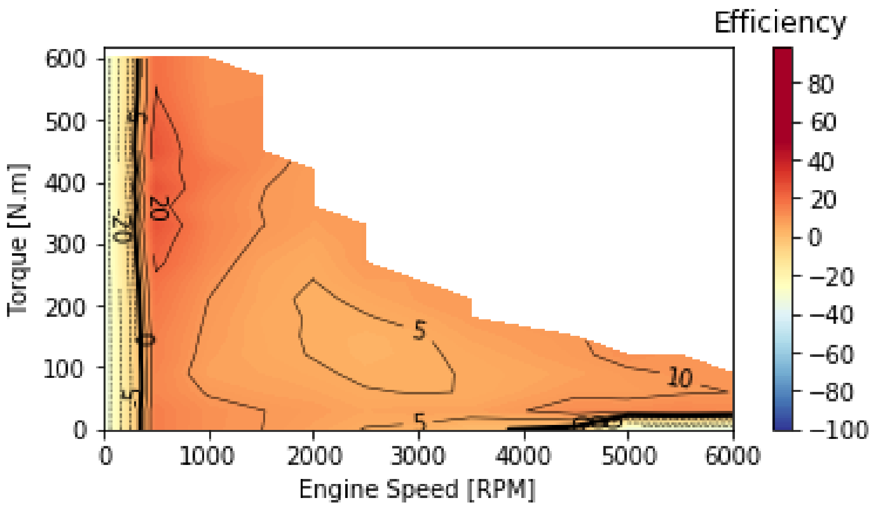


Figure 3–10: Steps to obtain efficiency map of an electric machine using the JMAG express tool within GT Power. (Adapted from [149]*)*

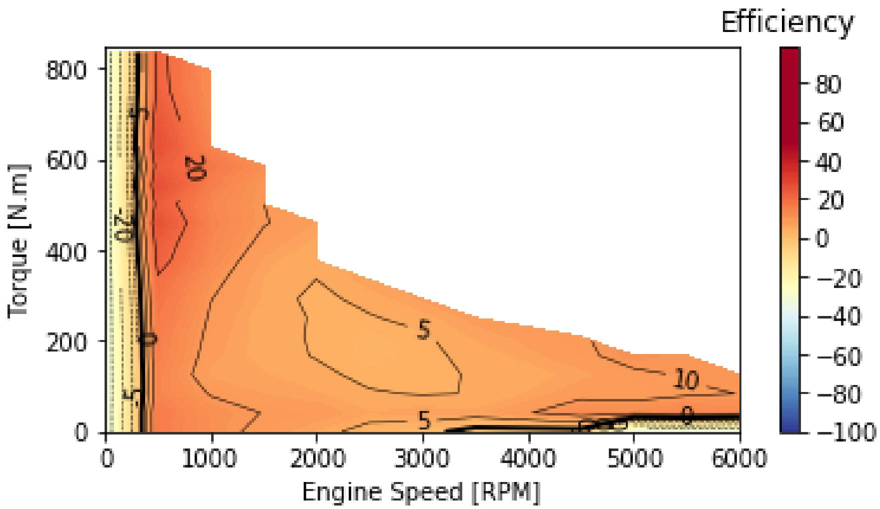
Figure 3–10 shows the step-by-step process to obtain the efficiency maps of the electric machines. The tool, however, was found to be incapable of accounting for losses which is normally the case in case of low speeds high torque region. This is primarily when also accounting the inverter losses because in JMAG, there is no possibility to model those losses. In GT Power the requirement is to input a Motor-Inverter efficiency map which couldn't be obtained using JMAG. To estimate the difference in the range of values, several motor inverter data obtained by the research group, were compared with the JMAG efficiency map results. The difference in the efficiency was found to be extremely high for the low-speed regions. The reference maps used in the research group comes from experimental data obtained for moto inverter setup for a 75-kW motor, which is then scaled for several other motor capacities. This difference in the efficiencies is shown in the Figure 3–11 below that shows up the comparison for different size of motors ranging from a 52 KW motor to a 208 KW motor.



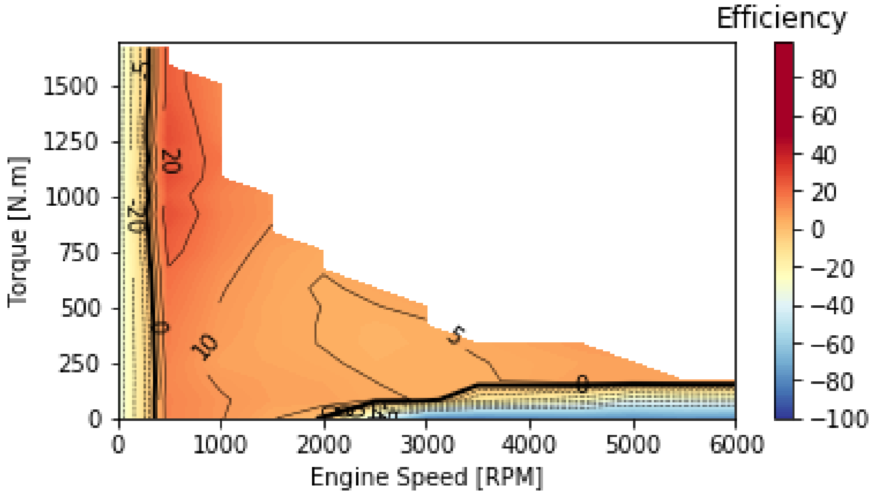
(a)


Efficiency
Torque [N.m]
Engine Speed [RPM]
600
500
400
300
200
100
0
0
1000
2000
3000
4000
5000
6000
80
60
40
20
0
−20
−40
−60
−80
−100
20
-20
5
10
5
0

(b)


Efficiency
Torque [N.m]
Engine Speed [RPM]
800
600
400
200
0
0
1000
2000
3000
4000
5000
6000
80
60
40
20
0
−20
−40
−60
−80
−100
20
-20
5
10
5
0

(c)



(d)

Figure 3–11: Efficiency map comparison (in %) between JMAG express and experimentally obtained results for (a) 52 kW, (b) 75 kW, (c) 104 KW and (d) 208 KW.

As it can be seen in the Figure 3–11 above that in the low-speed regions the difference in the efficiencies at the low speeds are up to 20% which makes the JMAG express tool not fit to be used in the GT Power. Similar, high difference in the efficiency is observed at the high-speed region as well for the two efficiency maps compared in the Figure 3–11 above. Hence, in this evaluation the experimentally obtained data, collected within the research group and published already, was used in the vehicle evaluations. This was found to be the best way to carry out the research for this thesis as the effect on the vehicle performance was found to be quite accurate when validated with the vehicle performance on homologation cycles as reported by the manufacturer itself. In this sense, this methodology had been historically used within the research group and the obtained results have been published in highly reputed journals already.

3.3.4 GREET

GREET© stands for Greenhouse gases, Regulated Emissions, and Energy use in Technologies model. The GREET is a dedicated model for simulating the energy use and emissions output of various vehicle and fuel combinations. It is developed by the energy systems and infrastructure analysis division of the Argonne National Laboratory. The development of the model has been sponsored by the US Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy. The model is available in two forms, the GREET.net model and the GREET Excel model for open access to the users. The modelling groups to have more than 45,000 registered users of the tool, globally. To cover more sectors, the model has been and is being extended to several other domains such as, Buildings, Aviation, Marine, etc.

The original GREET model is mainly divided into two separate parts, GREET1 and GREET2, where the GREET1 focuses on the fuel cycle while the GREET2 focuses on the vehicle cycle of the life cycle of automobiles. The Fuel cycle mainly represents all the processes involved in the Well to Wheel phase that includes both, the Well to Tank or Well to Pump phase but also Tank to Wheel or Pump to Wheel phase. The Well to Pump phase involves all the processes related to the extraction of the fuel from the crude oil refineries till the point when it is delivered at the refilling stations or pump. The Pump to Wheels cover the use of the fuels in the different vehicles during its operation which mainly is due to the powertrain efficiency of the vehicles with each different fuel considered for the operation or the use of the vehicle. The GREET2 focuses on the vehicle cycle which means the manufacturing and the end-of-life phases of it. The different phases covered by GREET are shown in the Figure 3–12 below for more details.

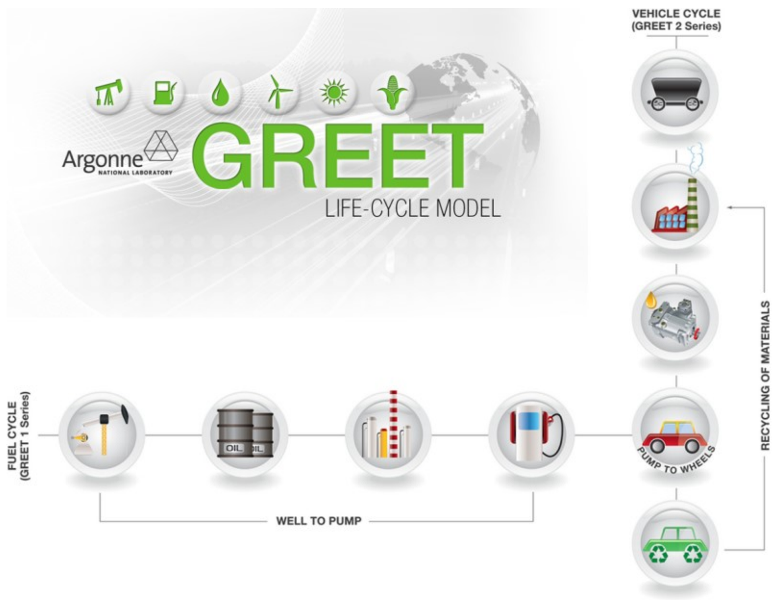
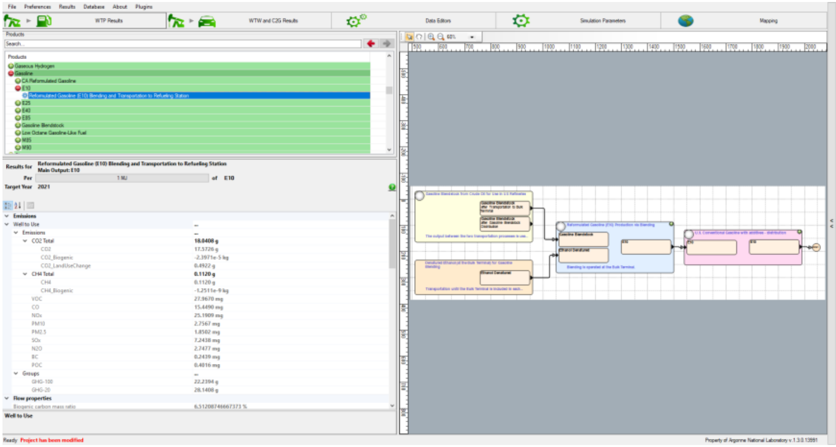
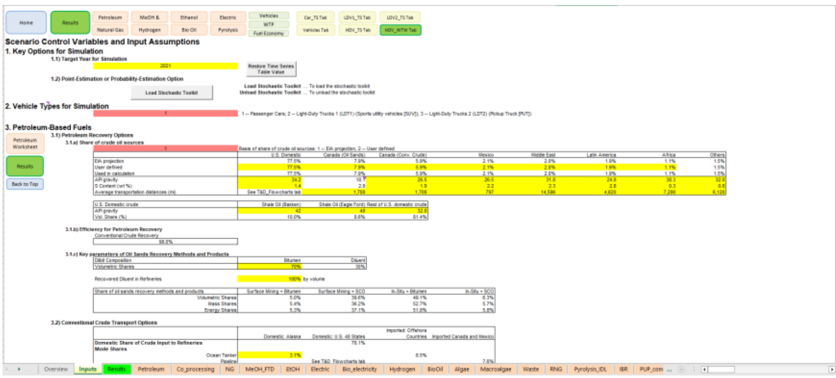


Figure 3–12: Details of the GREET model. (Adapted from [150]*)*

The GREET modelling group from time to time also conducts several workshops to keep the users informed with the new updates and features of their tool to ensure more acceptance within the life cycle analysis community. The tool is very well capable to provide a detailed set of data to carry out life cycle assessments of a wide range of vehicle technologies powered by several fuels. The analysis can be done by using both the .net version as well as the Excel based version of the software. With just a few clicks, the user may undertake life cycle analysis simulations of alternative transportation fuels and vehicle technologies using GREET.Net's user-friendly, completely graphical toolset. The tool contains data from the GREET Excel models' fuel-cycle and vehicle-cycle cycles. On the other hand, the well-known multidimensional spreadsheet model GREET Excel uses a life-cycle-based analysis to evaluate the energy consumption and emissions of traditional and cutting-edge vehicle technology. It consists of two sub-models, the Fuel-Cycle Model (GREET 1, which provides information on fuel cycles and vehicle operations) and the Vehicle-Cycle Model (GREET 2, which assesses the energy and emission impacts related to the recovery and production of vehicle materials, the fabrication of vehicle components, the assembly of vehicles, and vehicle disposal or recycling). While the Excel model provides separate versions for GREET1 and GREET2, the .Net version of the tool combines both into a single modelling environment. Both the versions are shown below in Figure 3–13.



(a)



(b)

Figure 3–13: GREET model in (a) .NET format and (b) Excel format. (Adapted from [151]*)*

In the framework of this thesis, the well to pump emissions and the vehicle cycle data are used from the GREET model and the pump to wheel emissions are calculated using the energy consumption data obtained from the 0D simulations sing the GT Power simulations. Thus, in this way the life cycle emissions estimation is done for carrying out the objectives of the research work. The software is however limited with data as any other software for life cycle analysis. One major issue is that the software is focussed for US and so most of the datasets considers the scenarios in the US only. Also, the electricity mix data in the software is limited and might not be available for several countries, which is an expected situation because the data is not openly available by all the countries. One significant drawback however is that the available electricity mix data is still quite outdated and is not updated with current values. To address these issues other life cycle tools and sources have been explored and used to meet the requirements for this research.

3.3.5 GaBi

Another software or tool investigated was GaBi®, which is a paid tool developed by Thinkstep® and owned by Sphera®. The software is highly used in the industry and requires additional purchase of databases that can be even more expensive. Though this software was used in the research group for an industrial project and was extensively used, the research findings were not allowed to be published by the industrial counterpart. The tool can also be used with an academic student license that the company provides to students, but the database available is very limited. Thus, the purchase of a dedicated database is a must, to use this software. The software is being used for future works related to the current research but hasn't been included in this thesis due to time related constraints. However, it is important to discuss the base of this software and its capabilities as it is a common tool to carry out life cycle studies, especially in the industry.

The working of this software is quite like GREET, but there is a flexibility for the user to define the process of its own by specifying the right processes and flows involved in the system which needs to be evaluated. The database to use the software must therefore be equipped with all these set of information to carry out a complete life cycle assessments with closed system boundaries. This needs to be done in a systematic way by creating a plan within the software, fill it with the right set of processes and then specifying the right set of flows within the processes. Upon completion of the plan the life cycle impacts can be calculated by an easy one click and the life cycle assessment will be carried out within the software. This can be understood better in the Figure 3–14 below that shows the structure of the software as well as a sample plan for a stainless-steel product.

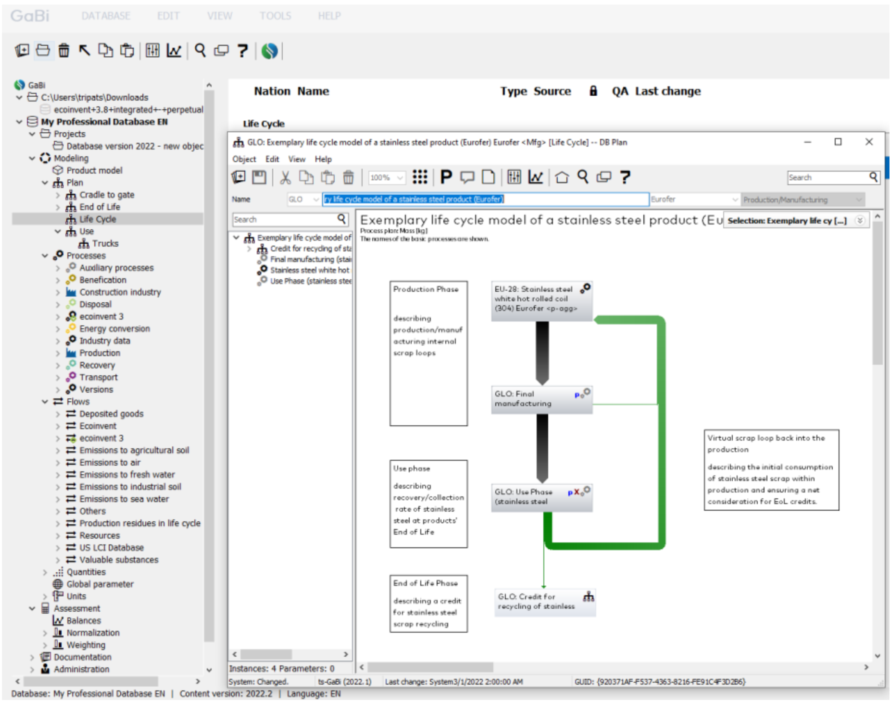


Figure 3–14: GaBi modelling for a stainless-steel product.[152]

In the Figure 3–14 above, in the toolbar on the left side, there are several Processes and Flows present under dedicated tabs. These tabs can be explored to get the right set of processes and flows to define the plan for the system that the user needs to evaluate. As a summary, it can be said that the processes are defined by the different flows, which are used to define the plan of the system. Interconnections are done within each to show the right inflow or outflow of the specific entity within the overall system. Finally, it can be said that the GaBi tool can be used to define one's own system for more specific evaluations, but it's possible only if the data required to define that process is within the available database. In all other cases specific databases needs to be explored and purchased. One good advantage though of the tool is that it does the calculation by itself to find the life cycle impacts by itself just by using the system definition by the user.

3.3.6 MATLAB and Python

It is well known that python and MATLAB environment are capable to do several statistical analysis and operations that enables the users to do several kinds of studies with the available data. Similarly, these two tools are used in the current research too for specific tasks that needed to be done for meeting the research requirements of this thesis. The MATLAB was used for the designing of the drive cycles of bus routes, to combine the data obtained between each bus stops to represent the overall bus route's forward or return journey. To do so, a MATLAB code was written to import the vehicle speed-time data as obtained from the GT Power simulations between each of the two stops. A 25 second stop time was added between each of these imported data files and was combined. This needed to be done as in the GT power modelling the drive cycles were only representing the vehicle's performance from Bus stop number A to B, B to C, and so on individually, without regarding the bus stopping time intervals. This can be understood better in Figure 3–15 relative to the M6 bus line of Barcelona.

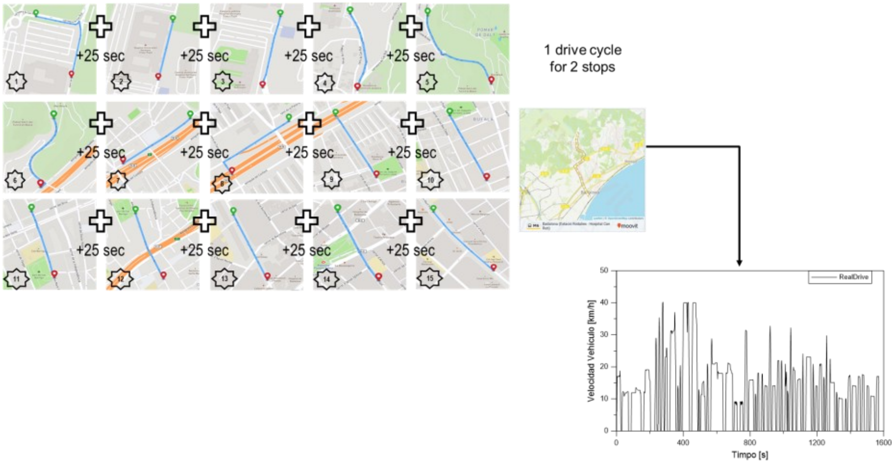


Figure 3–15: MATLAB usage to add 25 sec stop between each drive cycle obtained from GT RealDrive.

Further, Python was used to find the optimal number of buses that must be operated on the different routes for the lowest possible emissions values. This was done as the distribution of the buses, based on the types, operating in each of the bus route within the city of Valencia was not known. To do so an objective function was defined using the python language by specifying the emissions to be minimum as the main constraint. For this, the different emission values of all the bus routes with each of the bus types was given as an input to the python code. Also, it was assumed that 10 buses need to be operated in each of the bus lines. An initial value is added as an input for the distribution, which is optimised, and a new distribution is proposed by the code, the new distribution is then fed as a new input to get a more optimal solution. The process is optimised till the lowest possible emissions value is obtained and no further reduction is possible.

Other than these two tasks, MATLAB and Python were also used for other data analyses and plotting of the figures. Also, many calculations were performed in the python environment at the time of plotting the results to exploit the capabilities of it as much as possible. Several calculations are also done using MS Excel together with data analysis to carry out the research objectives set for this thesis on numerous occasions. Also, some exploration in SIMULINK was done for modelling inverters, R (a programming language for statistical computing and graphics) for some statistical calculations and analysis, as well as several in-house developed engine testing environments for engine calibration experiments.

3.4 Methods

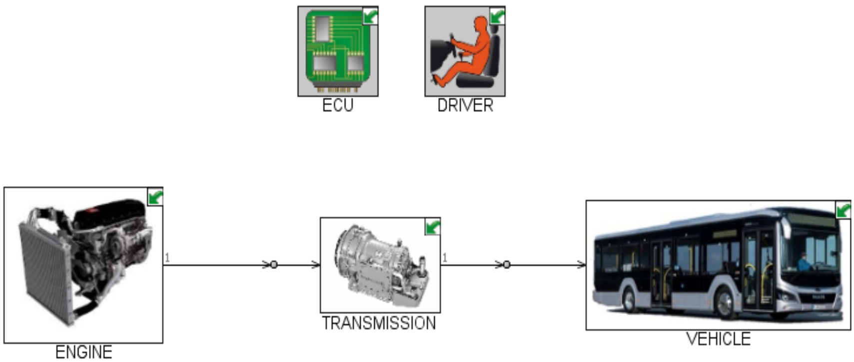
This section explains in detail and in a chronological way of how the tools and facilities, explained before, were used in carrying out the research for this thesis. The 0D modelling is first explained to understand the vehicle modelling process by highlighting how each of the vehicle type, and its corresponding components, are modelled to carry out their simulations on GT Power. Further, to have the evaluation of these vehicle models on real world cycles, the drive cycles are designed for GPS based drive cycles using the GT RealDrive application. Next, the life cycle analysis methodology is explained by highlighting the Well to Wheel evaluation methodology as well as the whole cradle-to-grave cycle. Later, the life cycle costing methodology is explained for both the light duty and the heavy-duty vehicle segments. Finally, the fleet assessment part is discussed for both the light duty and heavy-duty vehicles, as carried out for this research.

3.4.1 0D modelling

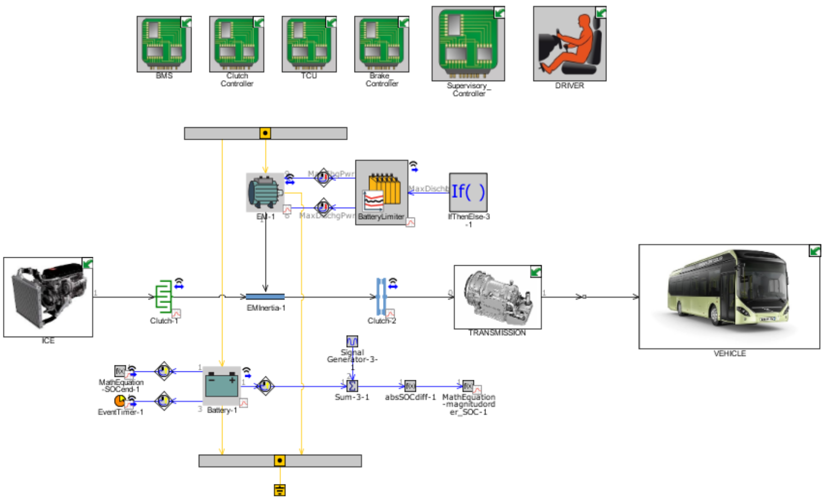
The 0D modelling of the different vehicles was carried out using the GT Power application of the GT suite package. The modelling is done for each of the vehicle by considering the specifications of most of the components as reported by manufacturers. The GT Power has in-built objects for most of the vehicle components that are part of a vehicle. GT Power by default has several vehicle models that are validated and can be used for assessments. To make the models more representative of the current vehicle model that needs to be assessed, the main components of the vehicle models can be edited for a much accurate evaluation. Each of these components are connected to show the transfer of power or signals in the form of inputs and outputs. These connections are mainly of two types, electrical connection, and mechanical connection, depending on the type of components used for each of the respective vehicle models.

To control the vehicle and the components several controllers can also be modelled such as battery management systems, clutch controller, brake controller, etc. To obtain specific values, the math equation object can be used to perform a user defined math operation and then get the result at the end of the simulation. Further, an output of one component can be used as an input for another by sending the value as a signal that can be sent wirelessly without making a physical connection in the model. Several types of limiters can also be used from the GT suite object library that can enable the user to limit the signal value being transferred as per the requirements. The different components can be modelled as a sub assembly too with several objects modelled within each sub assembly individually. Thus, depending on the complexity of the vehicle, several sub-assemblies are created to better integrate the vehicle level modelling. This is very much important for hybrid vehicles which contains both ICE system as well as electric propulsion system.

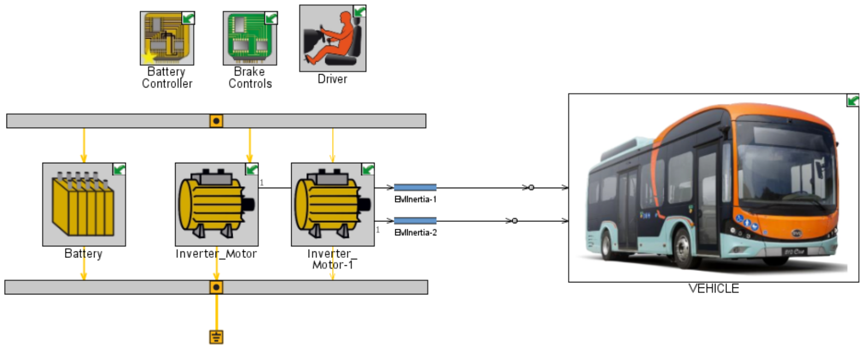
Thus, keeping the above information in mind, different 0D vehicles are modelled for this research, including five different bus models and 3 different passenger car types. The bus models are made to represent 5 specific bus variants that are commercially available and are used in the bus transit network of many cities. Thus, the vehicle powertrain as well as the aerodynamics structure of the vehicle is the same as claimed by the manufacturers of those bus models. However, for the passenger car, a commercial ICE SUV model, commonly sold, is considered with the same aerodynamics for three powertrain configurations. The powertrain of the vehicle is modelled individually by considering its impact on the weight of the three SUV models. The shape of the vehicle is however considered to be the same as to make sure that the comparison is a holistic evaluation for the powertrain's ability. This is because a vehicle shape can have a big impact on the overall performance and several car manufacturers are using a very aerodynamic design for its EV to have better range but not evaluating it with an ICE powertrain to see what the improvement in its performance will be as well. The different 0D models are shown below for the different bus and SUV models in the Figure 3–16.



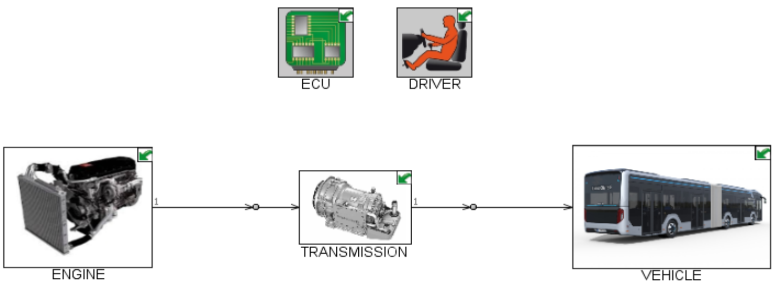
(a)



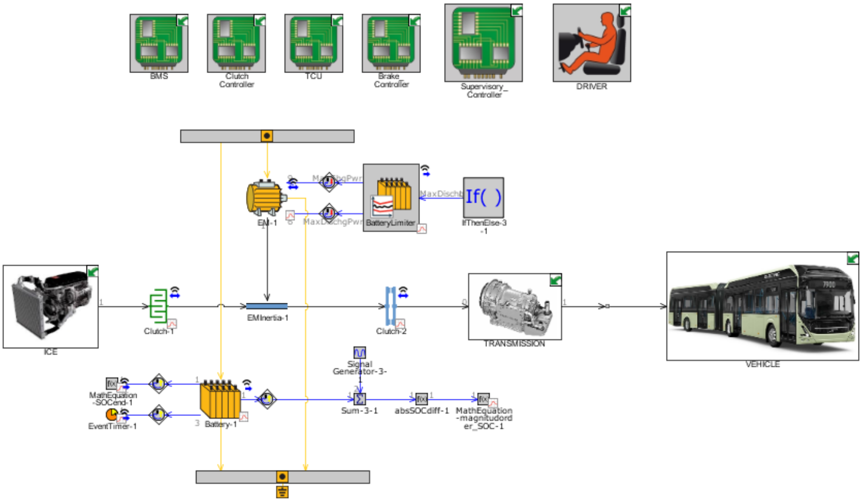
(b)


Battery
Controller
Brake
Controls
Driver
Battery
Inverter_Motor
Inverter_
Motor-1
VEHICLE

(c)


ECU
DRIVER
ENGINE
TRANSMISSION
VEHICLE

(d)


BMS
Clutch Controller
TCU
Brake Controller
Supervisory_ Controller
DRIVER
EM-1
BatteryLimiter
IfThenElse-3 -1
ICE
Clutch-1
EMInertia-1
Clutch-2
TRANSMISSION
VEHICLE
Signal Generator-3-
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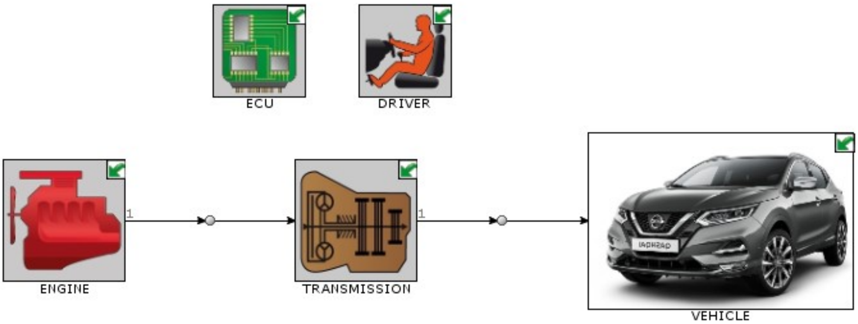
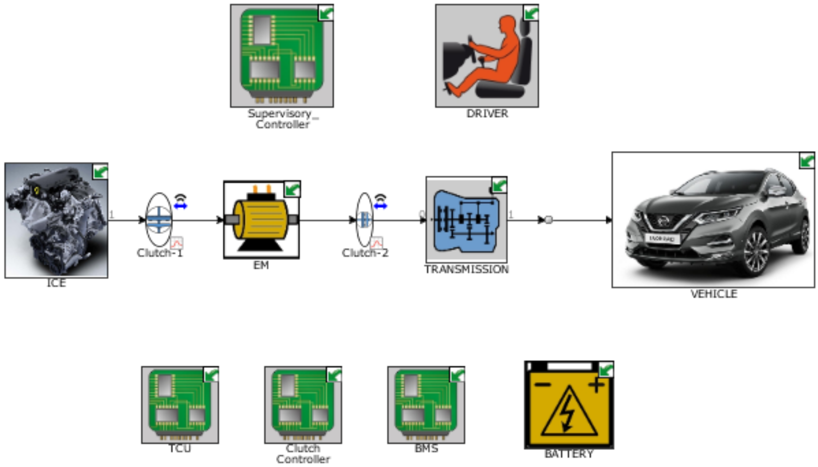
EventTimer-1
Battery-1
Sum-3-1
absSOCdiff-1
MathEquation -magnitudord er_SOC-1

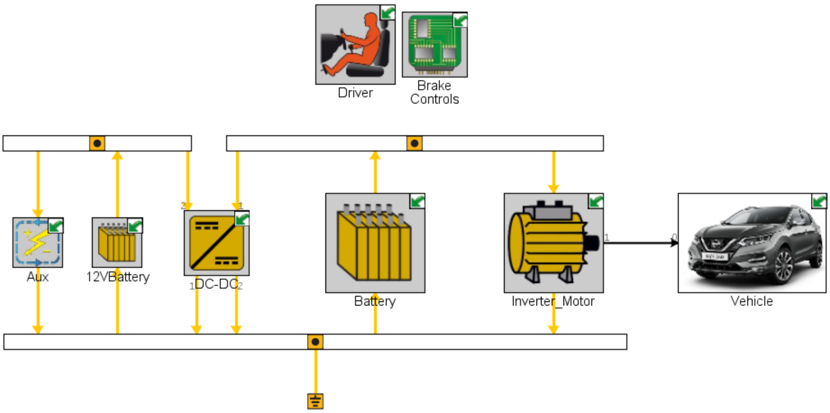
(e)


ECU
DRIVER
ENGINE
TRANSMISSION
VEHICLE

(f)



(g)



(h)

Figure 3–16: 0D GT Power model of: (a) 12m ICEB, (b) 12m HEB, (c) 12m EB, (d) 18m ICEB, (e) 18m HEB, (f) ICEV, (g) HEV and (h) EV. (Adapted from [21,153]

Among the eight different vehicles shown in Figure 3–16, it can be observed that the most complex modelling is for the parallel hybrid vehicles. This is due to the presence of thermal engine as well as an electric engine together with a Li-ion battery. The easiest modelling is for the EVs as the number of parts are the least like the ICE models. However, the ICE vehicles contain several other components which are not individually modelled in the 0D vehicle modelling as it doesn't have much impact on the vehicle overall energy consumption. As mentioned earlier, GT suite by default has several components modelled with acceptable input values that can be used for vehicle assessments. However, as in this study the focus is to evaluate the different vehicle types ranging from buses to passenger cars, the detailed modelling of the powertrain and vehicle dimensions is done. For the vehicle's size and shape the vehicle sub-assembly is defined which is fed with information specific to each of the vehicle. This can be seen in the Figure 3–17, which shows the vehicle sub-assembly of the bus models, highlighting the objects withing the sub-assembly to mimic the vehicle model most accurately in the software.

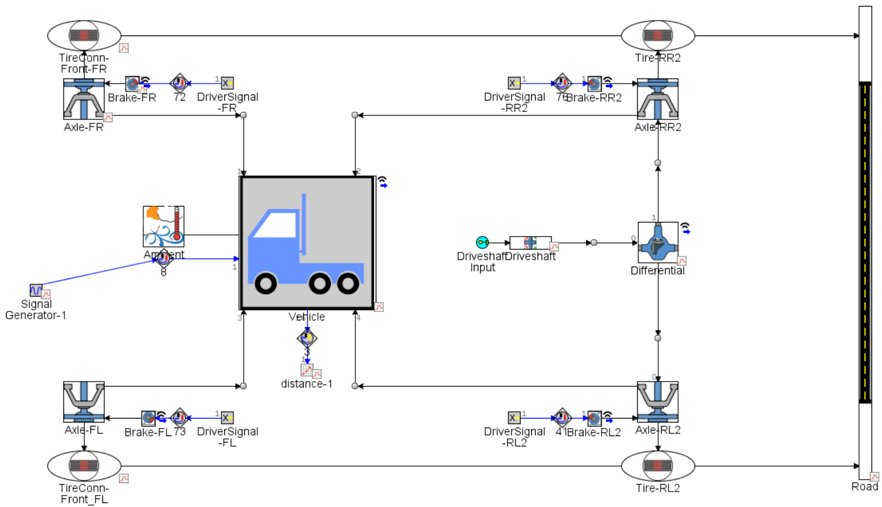


Figure 3–17: Vehicle sub-assembly within the GT power models for buses (heavy-duty segment).

Just as the vehicle sub-assembly all other sub-assemblies as seen in the 0D models for each vehicle type in Figure 3–16, are modelled. The most important sub-assemblies among all the 0D vehicle models for the vehicle powertrains are the engine, battery, and the electric motor. These subassemblies contain the secondary objects for the control of the component together with the primary object to define the component itself. The component object requires the performance efficiency of the dedicated components used in that specific vehicle, like the electric motor efficiency, engine fuel consumption, etc. For this current research three major components i.e., the engine, battery and electric motor are modelled individually with data obtained experimentally and from the literature that corresponds most accurately to the component specification by the manufacturer of individual vehicles. These are explained in detail below.

(a) Engine

The engine sub-assembly is used in the ICE vehicles and the Hybrid vehicles, for both the buses as well as the passenger cars. It contains mainly the engine object which uses the engine fuel consumption map as an input. These maps were obtained from the experimental tests of the different engine types as mentioned earlier in the Experimental facilities section of this chapter. In addition to the fuel consumption data, the engine details such as the displacement, operating speed, engine type (number of strokes), engine inertia as well as fuel used, are specified in it. This helps the software to make the calculation for the energy consumption of the powertrain for the vehicle's operation of the analysed drive. In addition to the fuel consumption map, the emissions map (obtained for steady state engine performance) may also be given as an input to the engine object for the emission estimation on the transient drive cycles. To get an insight of the engine sub-assembly, Figure 3–18 is shown below, highlighting the different objects included in the engine sub-assembly of the hybrid bus.

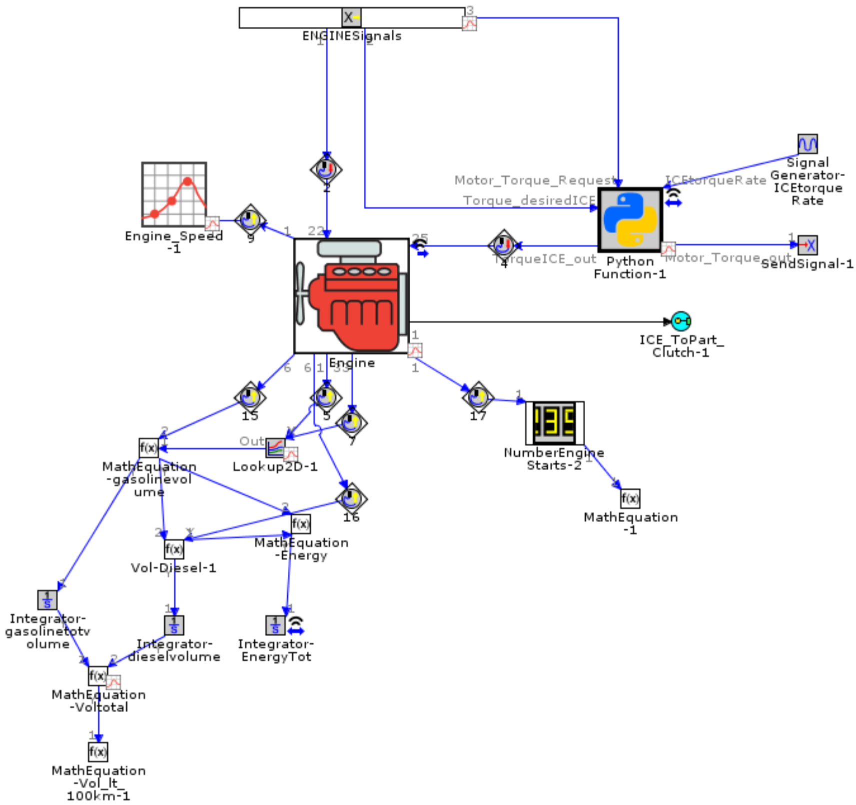
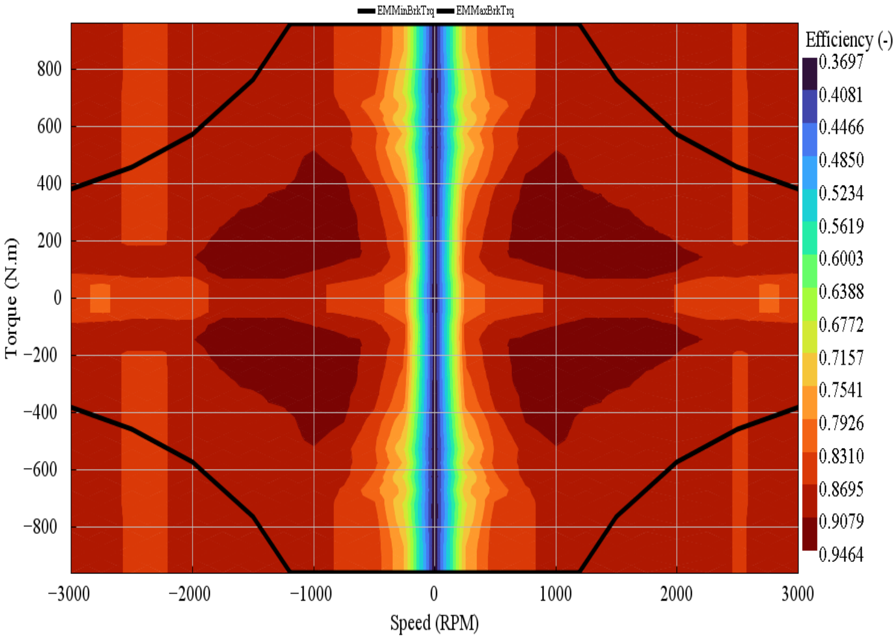


Figure 3–18: Engine sub-assembly of the 12m HEB.

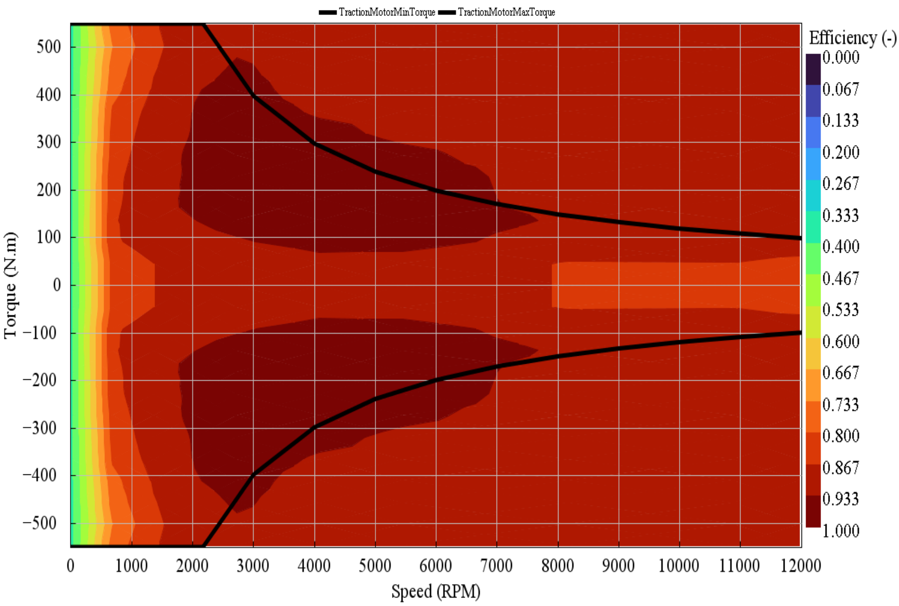
As shown in Figure 3–18 above, there are several other objects within the engine sub-assembly. These objects are even high for the hybrid vehicles as there is a very complex control system involved in such type of vehicles to have ensure smooth switch between the IC engine and the electric motor for propulsion. To do so, several control logics can also be prepared on python and linked into the GT model using the python object that can run independently using input from the GT model and giving pack the output to the GT power model as an input for the next connection which is made to the python object. This can be seen in the Figure 3–18 above. Moreover, there are several math equations that are used within the sub-assembly here to sense different engine parameters and obtain value that the user needs. In this study it was done to obtain the energy consumption value per 100 km of distance covered from the GT simulation. Similarly, depending on the vehicle and user needs, the sub-assemblies of each component can be customised.

(b) Electric motor

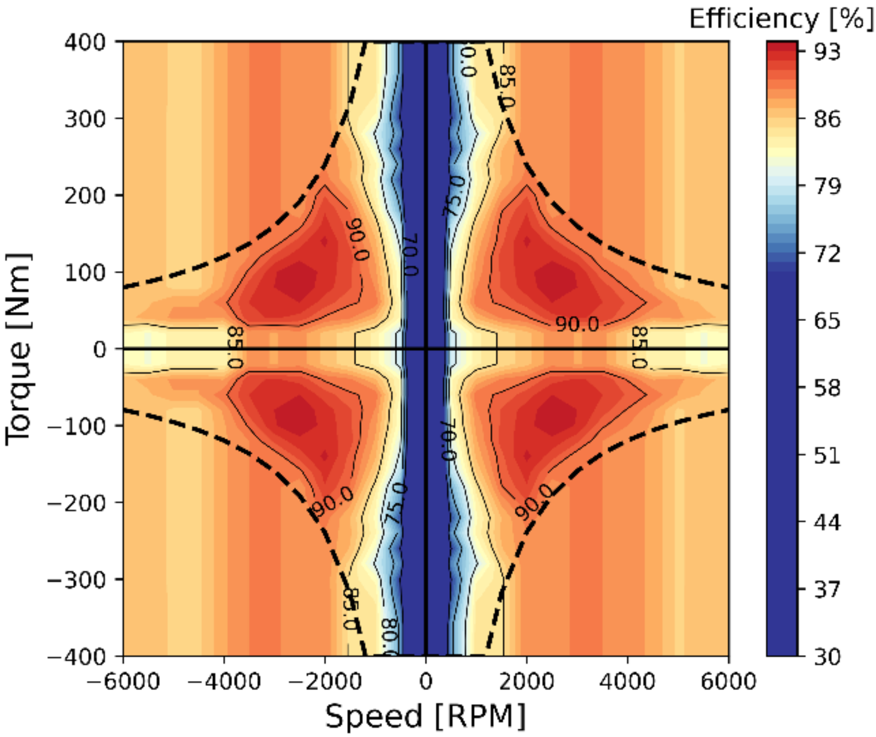
Like the engine, the electric motor sub-assembly is also made to distinguish the operations related to the electric motor for the hybrid and full electric vehicle types. The sub-assembly mainly contains the electric machine object to input the performance of it, both as a motor as well as generator. This can be fed to the model by using the electromechanical conversion efficiency map of the specific motor obtained experimentally. The maps can also be generated for a custom motor by length scaling the efficiency map obtained for another motor experimentally. Several works have been published for scaling of electric motors by showing very minimal change on the efficiencies that have an insignificant effect on the overall energy consumption of the vehicle. To carry out the current research different types of electric motors are used to power the hybrid and the electric models of the passenger cars and buses. Thus, using the scaling approach, the efficiency map of different motors is obtained and used for the zero-dimensional vehicle modelling. The efficiency maps of four different sized Permanent Magnet Synchronous Machines (PMSMs) are used in the scope of this study. The efficiency maps are shown below in Figure 3–19 for the four different electric motors to have the zero-dimensional analysis.


EMMinBrkTrq EMMaxBrkTrq
Efficiency (-)
0.3697
0.4081
0.4466
0.4850
0.5234
0.5619
0.6003
0.6388
0.6772
0.7157
0.7541
0.7926
0.8310
0.8695
0.9079
0.9464
Torque (N.m)
800
600
400
200
0
−200
−400
−600
−800
−3000
−2000
−1000
0
1000
2000
3000
Speed (RPM)

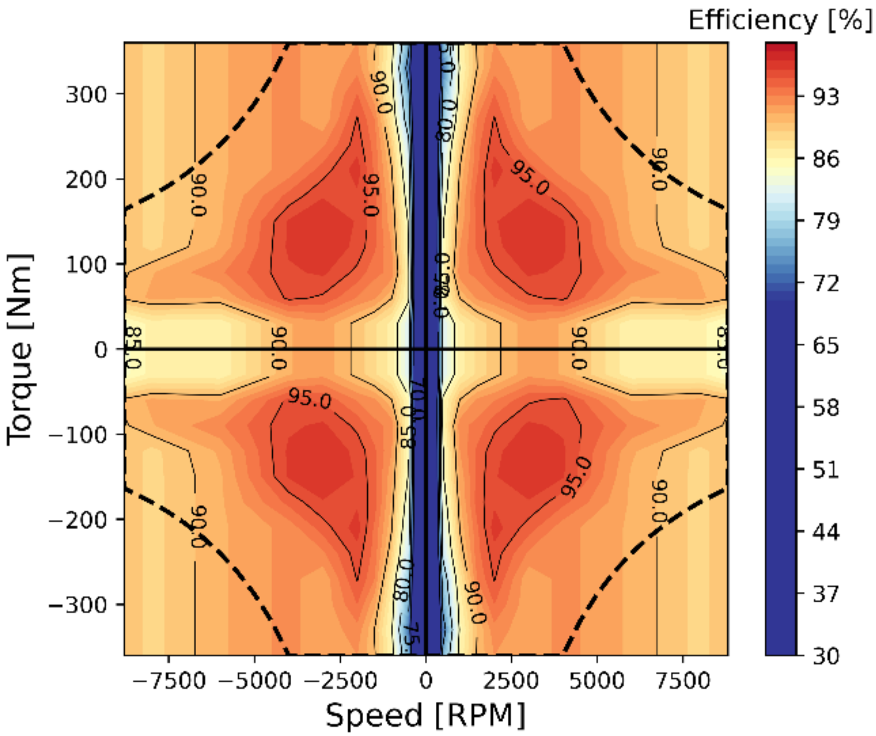
(a)


TractionMotorMinTorque TractionMotorMaxTorque
Efficiency (-)
0.000
0.067
0.133
0.200
0.267
0.333
0.400
0.467
0.533
0.600
0.667
0.733
0.800
0.867
0.933
1.000
Torque (N.m)
500
400
300
200
100
0
−100
−200
−300
−400
−500
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
Speed (RPM)

(b)


Efficiency [%]
93
86
79
72
65
58
51
44
37
30
400
300
200
100
0
−100
−200
−300
−400
Torque [Nm]
−6000
−4000
−2000
0
2000
4000
6000
Speed [RPM]
90.0
85.0
75.0
70.0
80.0

(c)



(d)

Figure 3–19: Efficiency maps of the four different PMSMs used in modelling for the (a) 12m & 18m HEB, (b) 12m EB, (c) EV and (d) HEV. (Adapted from [21])

In Figure 3–19 the interpolated efficiency maps of the different electric motors used for this research are shown. It is important to note that efficiency maps contain a black line (solid and dotted) to highlight the maximum and minimum operating limit of the electric machine for all the four quadrants of operation. These values in each quadrant show the maximum or minimum limit for electromechanical efficiency of the electric machine while converting electricity to mechanical energy as a motor and while converting mechanical to electrical energy as a generator. This helps in defining the range of operation for the electric machine during the zero-dimensional simulations of each vehicle type. The first two graphs for the efficiency map are plotted within the GT Post application, while the last two are plotted in python environment to understand that both this kind of representations shows the same thing. The second efficiency map for the 12m EB is shown by only two quadrant representation, while considering the same in the other quadrants as a mirror image along the Y-axis.

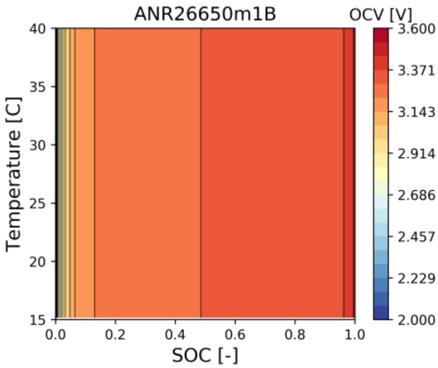
The scaling of maps is done by using the default electric motor maps within the GT power example models. These models are equipped with most of the components that are pre validated and trusted for their value. The specifications of the four different PMSMs and the vehicle types to which is applied are shown below in Table 3–1.

Table 3–1: Different motor specifications used for the 0D modelling.

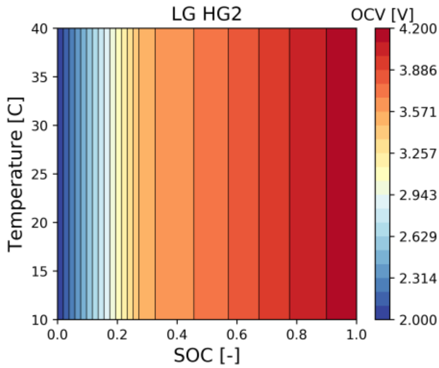
S.No.	Maximum Torque (N.m)	Rated Power (kW)	Vehicle type
1	1200	150	12 & 18m HEB
2	550	150	12m EB
3	400	90	HEV
4	360	270	EV

(c) Li-ion battery

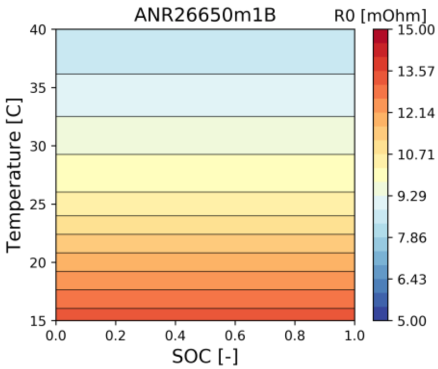
Like the electric machine the battery modelling is also done for the different type of battery chemistries separately. Based on the previous modelling and validation for batteries on GT AutoLion within the research group, the data is used for the NMC and LFP batteries. The difference in the battery chemistry results into different set of values for the open circuit voltage, internal resistance, capacitance, etc. against different state of charge. These values have been obtained for battery calibration by fellow colleagues within the research group and is shown below in Figure 3–20.


ANR26650m1B
OCV [V]
Temperature [C]
SOC [-]
3.600
3.371
3.143
2.914
2.686
2.457
2.229
2.000

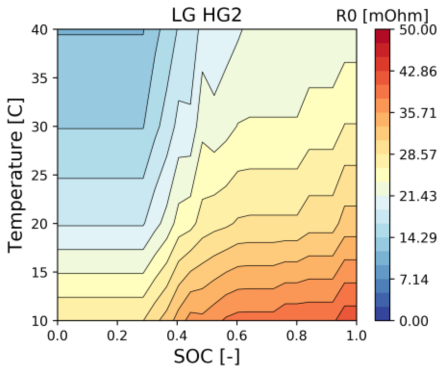
(a)


LG HG2
OCV [V]
Temperature [C]
SOC [-]
4.200
3.886
3.571
3.257
2.943
2.629
2.314
2.000

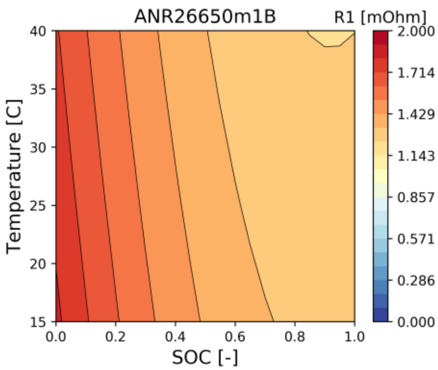
(b)


ANR26650m1B
R0 [mOhm]
Temperature [C]
SOC [-]
15.00
13.57
12.14
10.71
9.29
7.86
6.43
5.00

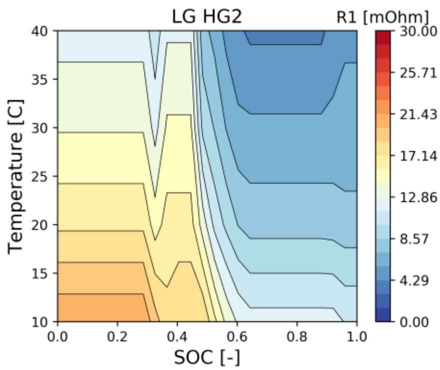
(c)


LG HG2
R0 [mOhm]
Temperature [C]
SOC [-]
50.00
42.86
35.71
28.57
21.43
14.29
7.14
0.00

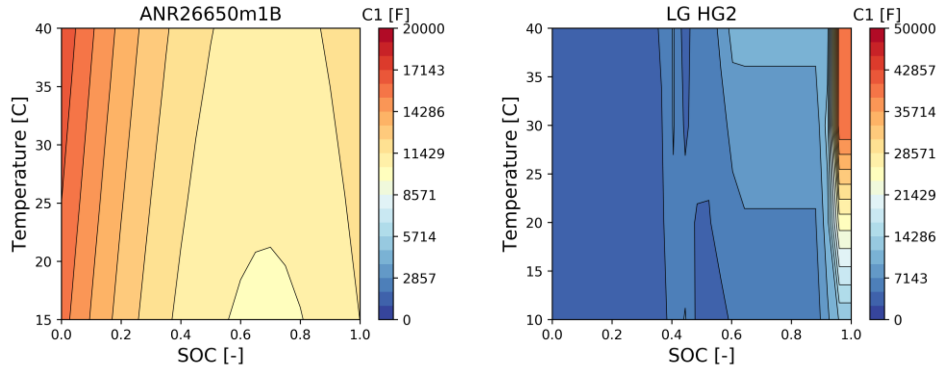
(d)


ANR26650m1B
R1 [mOhm]
Temperature [C]
SOC [-]
2.000
1.714
1.429
1.143
0.857
0.571
0.286
0.000

(e)


LG HG2
R1 [mOhm]
Temperature [C]
SOC [-]
30.00
25.71
21.43
17.14
12.86
8.57
4.29
0.00

(f)



(g) (h)

Figure 3–20: Electrochemical maps for OCV, Ro, R1, and C1 with respect to the battery state of charge (SOC) and surface temperature for (a), (c), (e), (g) LFP and (b), (d), (f), (h) NMC.

Based on the obtained electrochemical performance maps the battery modelling is done for each vehicle type that contains the Li-ion batteries. These cell data is used to define the properties or performance of the unit cell for the battery packs that are used in the different vehicles. To define the battery pack, the arrangement of these multiple cells is done in series and parallel to have the maximum packing efficiency to store the maximum amount of energy on-board the vehicle. However, the exact number of cells in series and parallel is not generally disclosed by several manufacturers for their vehicle's battery pack. Therefore, an iteration for the number of cells in parallel and series was done to get the battery energy capacity value as the same as reported by the vehicle manufacturers. The formula used to iterate the number of cells in series and parallel is represented by the equation 3.1 below.

$$Battery\ Energy = Number\ of\ cells\ in\ parallel * Number\ of\ cells\ in\ Series * Cell\ Capacity * Cell\ Voltage\ /\ 1000 \tag{3.1}$$

In the equation above, the cell capacity and cell voltage data are given as an input into the D models as shown in Figure 3–16. The number of cells in parallel and series are varied in an iterative manner to reach the exact battery capacity to match the specification mentioned by the manufacturer of each vehicle type. Due to the variation in the chemistry of the battery the number of cells in parallel or in series will also vary accordingly. For hybrid vehicles, the same data is used as in the default example in the GT suite library of example models. The details about the number of cells in parallel and series corresponding to the battery capacity and type for all other vehicle models are presented in Table 3–2 for a clear understanding of the battery modelling for the 0D evaluations.

Table 3–2: Battery pack details for the different vehicle models.

S.No.	Battery chemistry and capacity (kWh)	Cells in parallel	Cells in series	Vehicle type
1	8.9 NMC811	11	121	12 & 18m HEB
2	348 LFP	32	204	12m EB
4	90 LFP	3	160	EV

As seen in Table 3–2 the main details used for the battery modelling are presented for the different bus models and passenger cars are shown. For all the other components, default GT values and specifications are used. Further, as GT Power allows the users to specify several other parameters like the tire rim size, transmission type and gear ratio, etc., the values claimed by the vehicle manufacturers were used for it. In this way the zero-dimensional models are made to contain most of the data as of the target vehicle which is being modeled specially for the buses in this thesis, as the motivation is to evaluate the true emission from the buses running currently on the road and investigate options for its replacement by the bus options available currently in the automotive market.

3.4.2 Drive cycle designing

The drive cycle designing is done to make sure that the vehicle powertrain evaluations are performed on customized driving routes. This is done to have a real world like evaluation and not just having the assessment on homologation cycles, which are not a true representative of real-world driving scenarios. This was even more important for evaluating the performance of buses on dedicated bus routes as each bus route may encounter different driving conditions which can affect the vehicle performance significantly. Further, the area through which the vehicle is operating, if it is a city area or a suburbs area, affects the performance heavily of the vehicle powertrains. Thus, this is addressed by designing real drive cycles using the GT RealDrive application, within the GT suite package. Using this tool the location can be selected from the maps as the start and stop position and the driving route is calculated for that specific route.

The RealDrive application simulates this driving route based on some constraints that can be applied by the user and gives out the vehicle speed for the route from the data obtained through GPS. This enables a user to set the obtained vehicle speed as an input for the transient simulations of the zero-dimensional vehicle powertrain models developed using the GT Power application. Hence, the analysis of a vehicle powertrain model on such real driving cycles gives a more realistic set of values for its performance and highly resembles the real-world performance of them during the use of phase of its life cycle. The different constraints affect the speed obtained on a driving route which is the main parameter that influences the vehicle or powertrain performance in all the regions globally. Figure 3–21 shows the details for designing a drive cycle and GT RealDrive as used for this study.

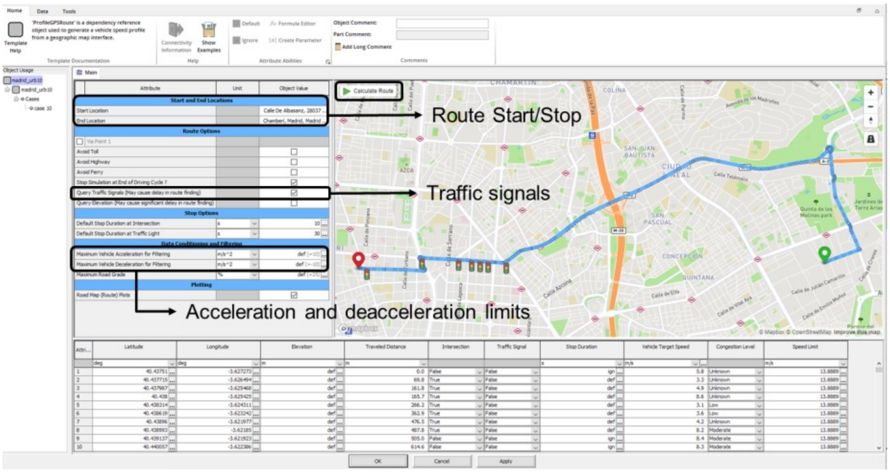


Figure 3–21: GT RealDrive used for drive cycle designing.

The different constraints that can be imposed while obtaining the drive cycle information are shown in Figure 3–21. These include start/stop locations, traffic signals inclusion, maximum acceleration, maximum deceleration, elevation, road grade, etc. After selecting the required set of constraints, the calculate route icon on the top left corner of the map must be clicked to get the route directions and all other related information such as the vehicle position, distance covered, speed, altitude, etc. Depending on the distance between the start and stop locations, the time for GT RealDrive to collect and show the information may differ. This approach is mainly followed for the evaluation of the passenger cars as they will be subjected to stopping due to the traffic, while going from point A to B. However, for the Buses, a stop time must also be included for the vehicle to be at idle condition at each bus stops. Moreover, if only the first stop and the last stop of a bus line is added, the resulting route obtained from RealDrive may not really represent the planned bus route for that line by the bus transit company, covering all its scheduled intermediate stops.

Hence, a different approach is applied, where each drive between two stops is considered separately as a single drive cycle. This means that for a bus line which has 20 bus stops, 19 individual drive cycles are designed on

GT RealDrive to cover each bus stop. In other words, if there are three bus stops, A, B and C, then there will be two drive cycles, one from A to B and another from B to C. To add the stop in between a MATLAB code was developed that adds the obtained vehicle speed from each of the drive cycles by adding a 25 second stop between each. There was an issue however in selecting the bus stops on the map as the location was not tagged correctly on the map or in fact some bus stops were not tagged at all. In this case the latitude and longitude of the exact location obtained from google maps were used to enter as start or stop location instead of using the name of the location. This approach helped in mimicking the exact route of the bus as claimed by the bus transit company of the city whose bus lines are being evaluated. One such line is shown below in Figure 3–22 with the map of the bus route and the names of the bus stops.

Figure 3–22: Bus route data of M6 line operating in Barcelona. (Adapted from [154]*)*

As seen in Figure 3–22, sometimes the location of the bus stops is shown on the opposite side of the road and the real drive app shows a long route with a U turn. To avoid this, a solution was explored, by keeping in mind that the data obtained from RealDrive is for specific positions or points across the route. Taking advantage of this, the extra path that shows up in the drive cycle were deleted manually to get only the path that represents or is equivalent to the planned route of each of the bus lines. Thus, it can be said that to design the driving cycles for the buses or to mimic the bus routes, the process was more complex. For passenger cars the drive cycle data were obtained by simply setting the start and stop location in GT RealDrive and the vehicle speed data was used as presented by the application itself without any significant changes.

3.4.3 Life cycle analysis

The life cycle analysis is mostly done using the GREET model available with open access and has been developed by the Argonne National Laboratory and funded by the United States Department of Energy. The model is equipped with an extensive database with values of the different components, phases and processes related to the life cycle of transportation vehicles. The model does have some gaps for heavy duty vehicle manufacturing and data related to the electricity mix of the country for which the data is used from other sources such as GaBi, climate transparency, etc. The life cycle analysis for each vehicle segment, light duty as well as heavy duty is explained in detail later in the respective chapters, however a brief and global description is provided in the present sub-section of the chapter. As in the model, this study uses similar approach by focussing on the four main phases of any vehicle, which are, Manufacturing, Use, Maintenance and End-of-life. These phases are explained in much more detail in the sections below:

(a) Manufacturing

As per the name, this phase comprises of all the emissions that are emitted during the manufacturing or production of the vehicles. This is calculated using the distribution of weight for the specific vehicle type as mentioned in the GREET model and through their published reports. The distribution of weight among the different components such as body, chassis, powertrain, transmission, motor, etc. are mentioned for the different vehicle powertrains ICEV, HEV and EV. This distribution doesn't contain the weight of the battery and tyres, thus, vehicle gross weight, as claimed by the manufacturer is subtracted with the weight of the battery pack (as applicable) and tyres.

The battery weight, it is calculated by considering the energy density of the NMC and LFP battery chemistries to be around 200 and 100 Wh/kg. Thus, considering the overall battery capacity in kWh, the weight of it is calculated and then subtracted from the gross vehicle weight. Similarly, depending on the number of tyres for the vehicle evaluated, its weight is subtracted too. The obtained weight of the vehicle is used to calculate the weight of each individual components by the distribution mentioned in the GREET model. Once the weight of each of these components are obtained, the GREET database for the emission footprints of the corresponding components in $kgCO_2$ per kg is used to evaluate the CO_2 emissions associated with the manufacturing of each of the component. The emissions from all the components are summed together to find the total emissions associated with the manufacturing of each specific vehicle type. In this way the manufacturing emissions for the different vehicles are calculated for this study. The main phases considered for the emissions from the manufacturing phase, are shown in Figure 3–23.

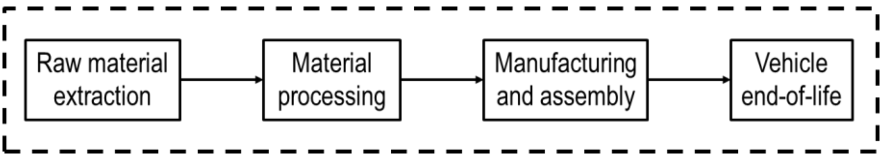


Figure 3–23: Processes considered for emissions within the manufacturing phase.

(b) Use

This phase accounts for all the emissions that are associated with the operation of the vehicle for its entire life cycle. The life cycle considered is

10 years for both passenger cars and buses, with 15,000 and 80,000 kilometers covered each year respectively. The data refer to the tailpipe emissions while the vehicle is in operation (tank to wheel) as well as the upstream emissions related to the production of the respective fuel consumed during the operation (well to tank). This Well-to-wheel approach considers the contribution of both to the greenhouse gas emissions. Therefore, it is important that the legislation set across the world must also consider both these types of emissions and not just focus on the tailpipe emissions. As even electric vehicles have emissions for the well-to-tank or well-to-pump phase, depending on the type of electricity used to power it.

Hence, it is important to keep a check on the WTW emissions to evaluate the real impact of a vehicle on the environment during its use phase. To calculate the tank to wheel emissions, the fuel consumed in kg/km is used to calculate the emissions from the combustion of that fuel by using the specific CO_2 emissions value for that specific fuel. For the well-to-tank phase the emissions are calculated by the emission footprint of the specific fuel during its production as obtained from the GREET model in kgCO_2 per kg of the fuel. These two emission types are added together to obtain the total well-to-wheel emissions in kg/km. Figure 3–24 shows the processes considered for the use phase in the GREET model and similarly in this study.

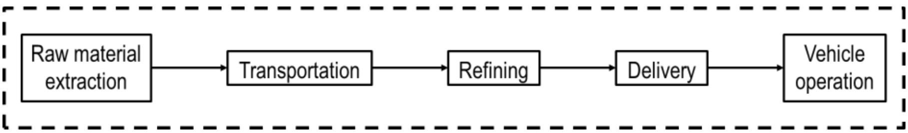


Figure 3–24: Emissions considered from the different processes related to the use phase.

(c) Maintenance

The maintenance phase in a vehicle's life cycle can be variable due to the kind of usage of it and if it encounters a severe breakdown due to an accident. It is tough to predict or account such accidents or unconventional scenarios, so the maintenance that is required under normal operation or the vehicle's life cycle is considered. This maintenance is required to enable the vehicle to be in operating condition with consistent performance during its entire life cycle. As the ICE powered vehicles have several parts which are mainly in contact due to mechanical power transfer, a lot of energy is lost to overcome the friction between the components. Further, the friction results in a high amount of wear and tear of the components which needs constant repair or maintenance. Due to this reason a vehicle is sent for servicing at service stations in a timely manner during which the lubricants, coolants and other components are replaced to ensure the smooth working of the vehicle system.

Thus, based on the life cycle kilometers of each of those components, its number of replacements are calculated by dividing the vehicle's life cycle kilometers with its. The obtained number of replacements is used to calculate the emissions that will happen in the production of those many components. Which is done by multiplying the weight of the component with the emission footprint of its production as mentioned in the GREET database. The obtained emission values of each component is multiplied with its respective number of replacements during the vehicle life cycle. The obtained values are added together and is referred as the total emissions from the maintenance phase. The major components considered for maintenance emissions are shown below in Table 3–3 as used in this research by mentioning its individual life cycle kilometers and the weight of each in kilograms.

Table 3–3: Component details considered for the maintenance phase of the vehicles.

Part	Life cycle (km)	Weight (kg)
Coolant	60000	5.5
Transmission fluid	150000	0.9
Windshield fluid	15000	0.5
Brake fluid	60000	0.6

Engine Oil	15000	2.5
Power steering fluid	150000	1
Tires	50000	28

(d) End of life

The end-of-life phase mainly involves the disposal and recycling of vehicles at the end of the life cycle period of 10 years. This is done by using the assembly, disposal and recycling (ADR) emissions footprint from the GREET database of each type of vehicle. This emission footprint is present in the unit kg CO_2 per kg of the vehicle and is calculated by multiplying it with the total weight of the vehicle excluding the battery. In this way, the emissions related to the vehicle's disposal and recycling out of the total ADR emissions, are considered as the emissions coming from the vehicle's end of life process. The battery recycling is not taken into account in this evaluation as it is considered that the batteries from the vehicle's must be subjected to a second life cycle upon its first life cycle.

In fact, recycling the batteries immediately after one cycle is sort of underutilizing the battery pack. The battery production itself required high amount of energy investment and so does it's recycling. So, it will be much smarter to increase the life span of the batteries by using it for a second least if not a third life. As battery manufacturing is already considered in this evaluation it is not considered that it will be recycled immediately after its first life as it can be used for other second life purposes. The vehicle disposal process modelling as considered in the GREET model and used in this study, is shown below in Figure 3–25.

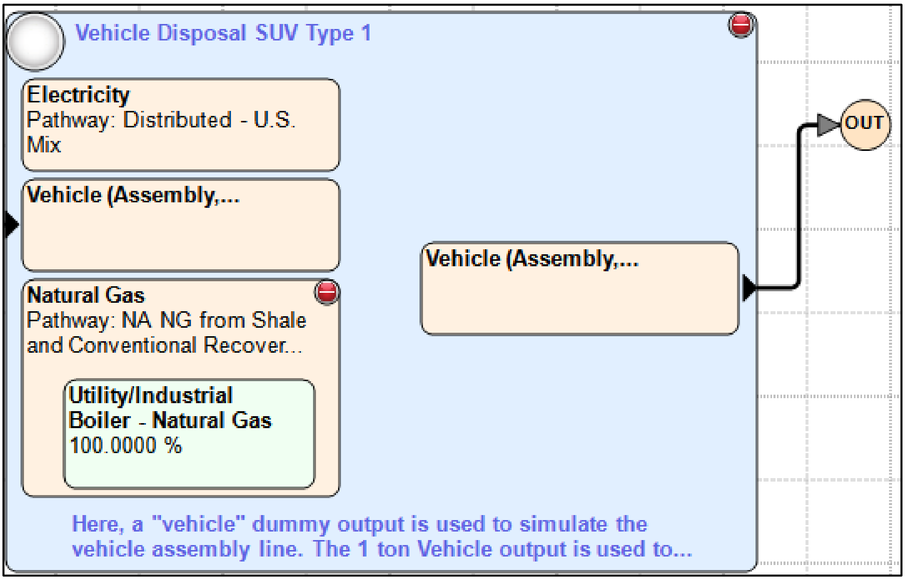


Figure 3–25: Vehicle disposal considered for a SUV vehicle in the GREET life cycle model. (Adapted from [155]*)*

3.4.4 Life cycle costing

The life cycle costing is done to evaluate the economic feasibility of each of the vehicle types in different scenarios and regions. This is mainly done to see which technology can be an optimal solution for decarbonisation in terms of cost. As this thesis covers passenger cars and buses, two different ways for the life cycle costing is used, one for each. For the passenger cars a total cost of ownership calculation is done by as it is needed to be owned by the customers and different types of costs are incurred for it like, insurance, taxes, etc. However, for the buses a more fundamental cost analysis is performed by considering the capital investments (CAPEX) and the operational costs (OPEX) for the bus transport companies which are mainly from the government of that region. Hence, the cost incurred for the bus companies will be different from those applicable to the car owners. The life cycle costing for both these vehicle segments are explained in detail in the dedicated chapters ahead, a brief overview is presented below separately.

(a) For passenger cars

The life cycle costing for the passenger cars, i.e., SUVs for this study, is done by calculating the Total Cost of Ownership (TCO) for the ICEV, HEV and EV. This is done to evaluate the cost these vehicles bring to the customer or the owner of the vehicles. It is important to study this aspect as the customer of the passenger cars are not mostly influenced by the emissions from their vehicles, but mainly influenced by the cost they must spend on its operation and procurement. Thus, this is calculated by considering the different costs needed to be paid by the vehicle owner before starting to its operational or use phase. As well as by including the cost of operation related to the energy cost associated with the fuel costs. It is important to consider all these costs because they have to be covered by the customer who owns the vehicle thought the period of its ownership, i.e., its life cycle in this study. The different cost considered for the total cost of ownership of the different SUVs are shown below in Figure 3–26 below.

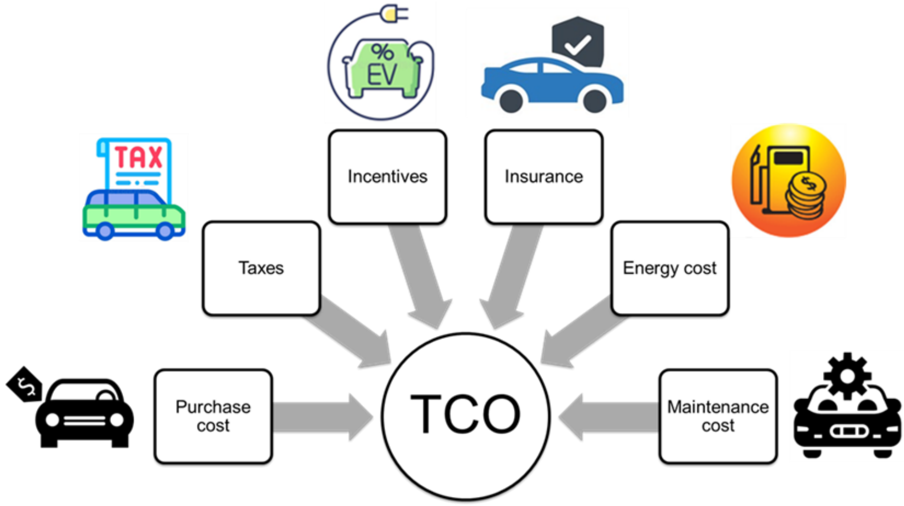


Figure 3–26: Different cost components considered for the total cost of ownership calculation of passenger cars. (Adapted from [21]*)*

The Figure 3–26 illustrates, the different component costs for the life cycle costing of the passenger cars. Based on the region as well as the type of vehicle being evaluated, these cost components vary. Thus, based on the region or country, the local values are used for these cost components for each type of vehicle. This can be best understood by taking the EV case as to promote its sales the governments in most of the regions impose zero tax for its procurement. Further, there are several additional incentives that are offered to the customers of these cars, which is surely not the case of the conventional ICEVs. The depreciation cost is not considered here as the goal is to have an evaluation for the duration like what has been used for the life cycle emissions calculation. This enables us to have a holistic cost analysis while evaluating the decarbonization potential of the different vehicle types on a life cycle basis.

(b) For buses

For the life cycle costing of buses, a different approach is applied, mainly because the owners of this vehicle segment are not the passengers but bus transit companies that work under the government. As these are government companies or subsidiaries, they don't need to pay taxes related costs which are to be paid by the customer who buys a passenger car for their private use. Also, as the customers are government companies with bulk orders, there are hidden subsidies or incentives given by the bus manufacturers which are not openly disclosed. Thus, using the commercial purchase cost of these buses for calculation will not be the best approach, that is offered to the private owners by the bus companies. So, for the life cycle costing of buses the capital expenses (CAPEX) and operational costs (OPEX) are directly calculated and considered. The different costs within these two categories are shown in detail below in Figure 3–27 for a clear understanding.

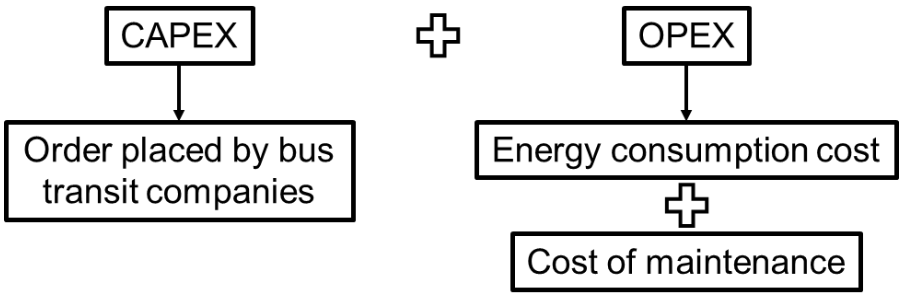


Figure 3–27: Cost components considered for life cycle costing of buses.

From the Figure 3–27 above, it can be observed that the CAPEX is calculated by considering the procurement orders placed by the bus transit companies of different cities. While, for the OPEX the energy consumption cost and the maintenance cost are calculated separately. For the CAPEX calculation the total cost of the order placed by the bus transit company is divided by the total number of buses included in that order. This way the CAPEX associated with the procurement of each single bus is calculated. While for the OPEX, the energy consumption cost is calculated by the energy consumption of a given type of bus multiplied with the specific energy cost (fuel or electricity) and the maintenance cost is calculated by the cost associated with the parts and components replaced during the maintenance phase as considered for the life cycle emissions assessment. Thus, by summing all these three major costs, the life cycle costing of the buses is performed in this research work.

3.4.5 Fleet assessment

The fleet assessment is also done for both the buses and the passenger cars to evaluate the effect on the total fleet emissions by integrating electric vehicles. The scope of the evaluation has been different for both these vehicle segments and is explained insightfully in dedicated sub-sections later in the chapters for both. However, for general understanding it can be said that for buses the fleet assessment has been done for the city of Valencia only. Which is done by evaluating the emissions for the 10 most used bus lines out of the total 50 bus lines. Also, the number of buses included for the assessment is taken to be 100 out of the total 491 buses operating in the year 2019. The main motivation for it was the decision of the municipal government of Valencia to renovate its bus fleet with 50% hybrid buses. In this sense, it was interesting to see if this decision could help in meeting future emission reduction target for the bus fleet operations in Valencia.[156] Thus, the fleet assessment is done by considering ICE and hybrid buses fuelled with diesel as well as e-fuel together with fully electric buses. To evaluate this a methodology is developed that can be used to evaluate the emissions from the bus fleet of any city, which is discussed in detail in Chapter 5 of this thesis.

Further, for the passenger cars the fleet assessment is done for the fleet emission reduction per vehicle for Europe and the United States of America by keeping into account the total vehicle fleet in both the regions. The motivation for this study is the legislations proposed in both these regions to enforce 100% sales of only zero tailpipe emission vehicles.[16] These kind of legislations puts an indirect ban on the sales of ICE powered vehicles and promotes the sale of only full electric or fuel cell electric vehicles by 2035 in Europe and by 2040 in the US. However, even though the sales might reach 100% by these years for zero tailpipe emission vehicles, there will be majority of vehicle in the total fleet which will be ICE powered and so solutions must be evaluated to decarbonise the total fleet. Also, these zero tailpipe emission vehicles do have emissions across its total life cycle and varies significantly based on the electricity source mix from which they are charged. Thus, a comparative assessment is done for passenger cars by evaluating the effect on the fleet emissions with increasing share of electric vehicles according to the proposed legislations and the sale of e-fuelled ICE vehicles for the same evolution as for the share of EVs. More detailed explanation is provided later in the next chapter about how it was done and the results that were obtained.

3.5 Summary and Conclusions

This chapter explains all the means or resources used to carry out the research to fulfil the objectives of this thesis. The main experimental facilities that primarily includes the calibration of the different engine sizes to obtain their fuel or energy efficiency, required for this research. The methodology is explained; the steady state tests of the engine at several operating points were used to obtain the overall efficiency map through interpolation to be used for zero-dimensional evaluation of the vehicle in the GT suite package. Further, different softwares, are also introduced including tools like SUMO, JMAG, GREET, GaBi, Python, MATLAB etc.

The use of different tools for the zero-dimensional vehicle modelling in GT Power application is explained. The modelling approach is highlighted for the different components associated with each of the vehicle type including the engine, battery and the electric machine. These zero-dimensional vehicle models are then simulated on real drive cycles which were obtained using the GT RealDrive application of the GT suite package. The obtained drive cycle data is GPS based and enables a real-world performance evaluation of the vehicle powertrains on a drive cycle that the user intend to choose based on its interest anywhere across the world. After obtaining the desired drive cycle vehicle speed data, the simulation is done to obtain the energy consumption of the different vehicle. These energy consumption data is then used for the life cycle analysis of emissions as well as cost for each of the vehicle type.

For the life cycle emissions calculation, the GREET model is mainly used and the four main phases of a vehicle's life is focussed, i.e., Manufacturing, Use, Maintenance and End-of-life. The manufacturing, maintenance and end-of-life emissions are calculated primarily using the GREET model by focusing on each of the vehicle's specifications and the different components associated with it. While, for the use phase, the energy consumption obtained from the 0D simulations are used. The emissions are calculated on a Well-to-Wheel basis using the energy consumption and the corresponding emission footprint for the fuel and electricity from the GREET database for per kg of fuel or per kWh of electricity. The emissions form all these phases are combined to get the total vehicle life cycle emissions. Similarly, for the life cycle costing the different types of costs associated with a vehicle life cycle are considered where the cost related to the energy consumption is calculated using the energy consumption values obtained from the 0D simulations and the specific energy cost of the fuel or electricity of the local region where the assessment is done.

Finally, the fleet assessment is discussed; in two separate ways for the buses and the passenger cars to see the effect of the emission reduction on the total fleet. This is done mainly to see how far or close the fleet emissions will be from the targets set by the governments across the world to estimate what mix of the fleet is required to really be low emitting and sustainable. The main purpose of this chapter is to highlight the tools and process needed to undergo such kind of evaluation covering both the technical as well as the economical aspect of decarbonisation of the road transportation sector. Thus, any area across the globe can be analysed for the decarbonisation potential of the different vehicle type to see which technology makes most sense for that region considering the variables that changes from location-to-location. The several results obtained from the performed study are presented and discussed in the next chapters.

Chapter 4

Light Duty Vehicles

Content

4.1 Introduction

The light duty transportation is the largest contributor for emissions in the transportation sector and thus the control strategies to reduce such emissions represent an important aspect. The total number of passenger cars in current global fleet is around 1000 million vehicles.[157] While as per the yearly vehicle sales data in the six largest automotive markets, a total of more than 50 million vehicles are bout every year. Thus, based on these data it can be understood that the vehicle emissions will have an immense impact on climate change due to the increasing GHG concentration in the environment.

The emissions values vary, based on the size of the vehicle and the powertrain. A small vehicle like a hatchback with smaller engine will lead to smaller emission values while a large vehicle like a Sport Utility Vehicle (SUV) with larger sized engines. Unfortunately, the most preferred vehicle segment around the world by customers is the SUV segment and thus the emissions will be even higher due to its sales and will have higher climate change impact on the environment from the light duty transportation sector.[158] Thus, it is important to estimate the real emissions coming from these vehicle segment and explore alternative ways to reduce emissions from the most selling vehicle segment of passenger cars.

The life cycle analysis of SUVs is done on real driving cycles in city-based routes for estimating the real world GHG emissions of it.[159] Three different vehicle types are considered: diesel, hybrid and electric. Also, oxymethylene dimethyl ethers (OMEx) are also considered as an alternative fuel for ICE based conventional and hybrid vehicles. The electricity mix is also varied for different countries within Europe and around the globe for a wider study.[21] Considering the energy crisis in Europe, future electricity mix are also considered with natural gas free scenario.[160] The results are also supported with assessment of total cost of ownership in each of the different regions with varying costs for the different input cost considered for the calculation.

The following sections provide a detailed explanation of the methodology and the results obtained from this study supported with valuable discussion and conclusions for highlighting the impact of the research.

4.2 Methodology

This section explains the methods and processes used to do this analysis by presenting the details of each part for a clear understanding. The research is carried out in three steps, firstly a techno-economic study is done for an ICEV, HEV and EV, to see the best option for emission reduction in the six largest automotive markets: China, United States of America, Europe, Japan, India and Brazil, in decreasing order of vehicle sales.[161] Dedicated study is devoted to the life cycle emissions and the total cost of ownership for each vehicle type in the six markets. This is done by means of the energy consumption of the vehicles in each of the country in the city driving conditions. The process of obtaining the real drive cycle data in each of the market for the different cities is shown below in Figure 4–1, where the route from Brooklyn to Queens is shown in New York City. Similarly, different routes are evaluated in the cities of the various region and a total of 10 routes are considered for the evaluation in each country.

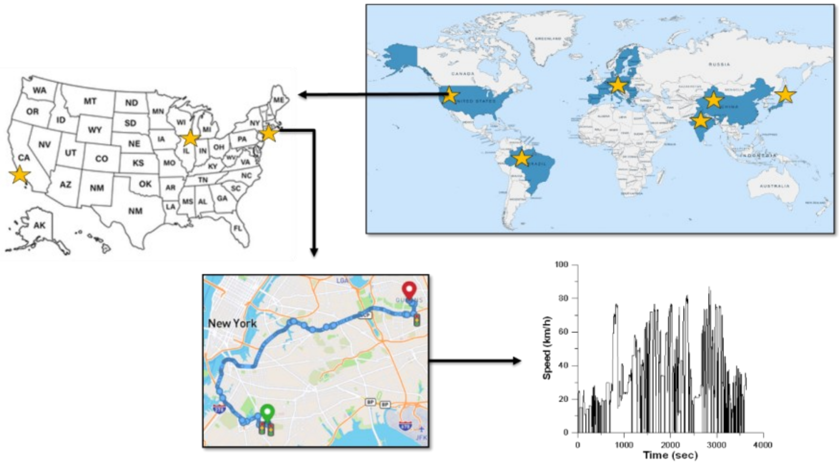


Figure 4–1: Techno-economic analysis carried in the six largest automotive markets. (Adapted from [21]*)*

Further, considering the energy crisis in Europe and the impact of gas supply cut from Russia, an assessment is done to see the impact of change in electricity grid emissions and cost on the life cycle GHG emissions and total cost of ownership of the vehicle. This effect is assessed for battery manufacturing and the use phase for the European average, Germany and Sweden.[160] The drive cycles used for the European average are obtained for Madrid, Berlin and Milan and not much variation was observed. A detailed flow of the process for evaluating the energy consumption is shown below in the Figure 4–2. Further the electricity mix considered for this study includes European average in 2020, European average in 2022, German mix in 2022 and Swedish mix in 2022 as it will be shown in Figure 4–8. The natural gas share for these countries and the average European region is calculated for year 2022 and is replaced in three ways for the study: (1) Coal, (2) Renewables and (3) 50% by coal and 50% by renewables. Thus, the results evaluate the best-case and the worst-case scenarios with an intermediate scenario.

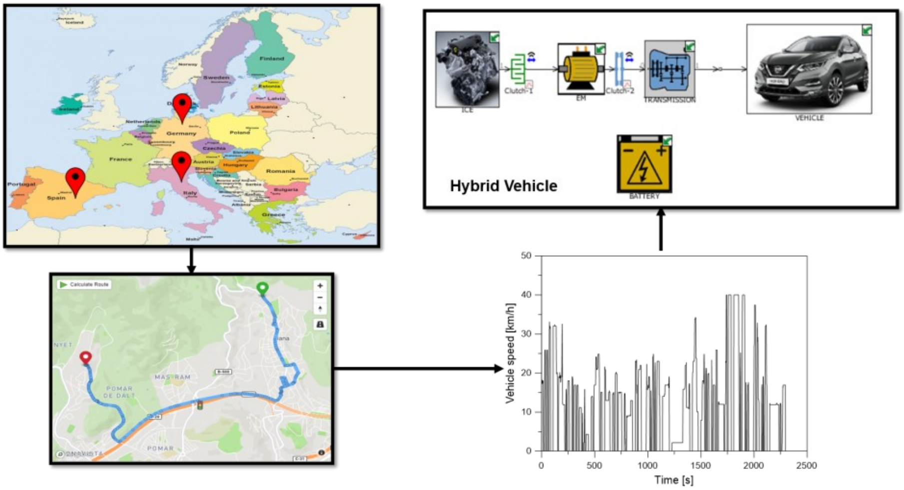


Figure 4–2: Evaluation methodology for energy consumption in the European region. (Adapted from [160]*)*

Finally, a study is done to evaluate the use of e-fuels in the ICE SUVs comparing the life cycle emissions with the full electric configuration.[162] This is also to see if the ban on ICE sales in the future really makes sense or is there any other option that can have similar life cycle emission reduction as an electric vehicle. Thus, for this real drive cycles of Europe and the United States of America separately, these two regions are considered for the evaluation as there has been a full ban on sales of EVs in the Europe for 2035 and a 50% sales target for EVs in the US. The research framework is shown more precisely in Figure 4–3 below. The obtained values are also used for a fleet emission reduction evaluation where both Well-to-wheel and life cycle GHG emissions are compared while using EVs and e-fuels.

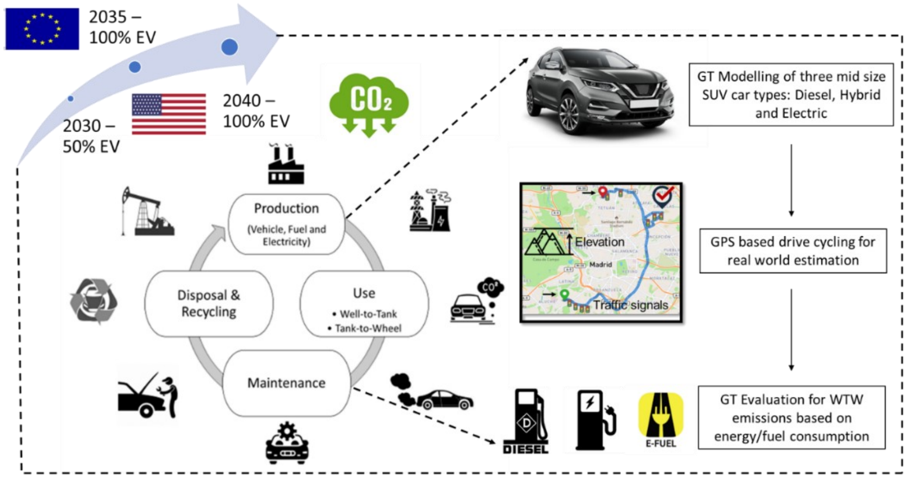


Figure 4–3: Research framework for comparing e-fuels and EVs in US and EU to meet future automotive legislations. (Adapted from [162]*)*

Thus, the research is carried out systematically to highlight the emission reductions possible by the different powertrains in the six automotive markets. This is followed by an evaluation to show the impact of the European energy crisis on the decarbonisation potential of EVs with the effect on its cost of operation and ownership. Finally, an evaluation is done to see if the ban on the sales of ICEVs really makes sense or if e-fuels can be a possible alternative to full vehicle electrification. The overall methodology followed to do the assessments can be divided into four separate sub-sections including: 0D modelling, Life cycle assessment, Total cost of ownership and Fleet assessment. Each of them is detailed individually below:

4.2.1. 0D Modelling

The zero-dimensional analysis was adopted to obtain the energy consumption values of the vehicles. This is done by creation of 0D models on GT Suite software for the SUV vehicle and running on real driving cycles using GPS based data to estimate the true emissions during its operation in different driving routes. The different powertrains, conventional diesel, hybrid and full electric are evaluated for the SUV model. Moreover, an estimation of using e-fuels as an alternative to diesel is done for the conventional and hybrid powertrain vehicles. This sub-section is thus divided into three parts: Vehicle types, Powertrain types and Drive cycles. These are explained below in the corresponding sections:

a) Vehicle type

The vehicle type selected for this evaluation is the Sports Utility Vehicle (SUV) as this is the most selling vehicle segment across the world over the years. In 2018 more than 35% of the total cars sold globally were of the SUV segment even though the emissions from it are the highest. Due to the presence of a large engine, bulky SUVs specially of type B, are having the worst impact on the environment due to the high tailpipe emissions coming from them. Thus, this research has been focussed to find alternative ways of emission reduction for this vehicle segment across six largest automotive markets across the globe. Also, the evaluation is done by keeping in mind the future ban on sales of ICE based vehicles for a zero-emission vehicle deployment. However, it is worth mentioning that vehicles such as an SUV needs to be equipped with large battery packs that is a source of large GHG emissions. Thus, it is important to assess different powertrain options for emission reductions in the most efficient way.

b) Powertrain type

To evaluate the emission reduction options for the SUVs three main vehicle powertrain architectures are considered, i.e., ICEV, HEV and EV. Also, an evaluation is done using e-fuels as an alternative drop-in fuel for the ICEVs and HEVs. The powertrain specifications of the vehicles are maintained to be as that of a commercially sold vehicle present in all the six automotive markets. This is done to have a real world like scenario for assessment of the powertrains including the motor capacity, battery capacity, engine size, etc. The details of the specifications for the three powertrains are summarised below in Table 4–1 as used for making the 0D models.

Table 4–1: Powertrain specifications of the SUV passenger car. (Adapted from [159]*)*

Parameter	**ICEV**	**HEV**	**EV**
Vehicle			
Engine Type	Nissan 1.6 L Diesel	Nissan 1.6 L Diesel and 90 kW e-motor	270 kW e-motor
Gross Weight (kg)	1750	1920	2230
Battery weight (kg)	-	65	450
Rated Power - Engine/Motor (kW)	85/0	85/90	0/270
Maximum Torque – Engine/Motor (Nm)	320/0	320/400	0/360
Battery Capacity (kWh)	-	13.5	90
Fuel Tank (L)	55	55	0
Vehicle frontal area (m^2)	2.2	2.2	2.2
Drag coefficient	0.31	0.31	0.31

The above Table 4–1 shows that the aerodynamics is considered the same and only the powertrain types are changed for the vehicle models. Further, as discussed, the evaluation is extended for e-fuels performance too by replacing diesel use in the ICEV and HEV. This assessment is done by assuming that the e-fuels is used as a drop-in solution and the engine operates with the same efficiency with this fuel. Thus, the energy balance is done using the lower heating value of the fuels to calculate the fuel consumption. The main fuel properties and characteristics used for this analysis are mentioned in Table 4–2.

Table 4–2: Liquid fuel properties. (Adapted from [159]*)*

Parameters	Diesel	OMEx
Lower Heating Value (MJ/Kg)	42.5	19.8
Density (kg/m3) @ 15 °C	850	1050
Viscosity (mm2/s) @ 40 °C		
Cetane number	55.7	72.9
TTW CO_2 emission potential (kg CO_2/ kg of diesel)	3.2	2.47
WTT CO_2 emission potential (g CO_2/ kg of diesel)	0.79	-0.53

c) Driving cycles

The research work is carried out to evaluate the performance of the vehicle powertrains on real drive cycles. This is done using the Real Drive feature of the GT suite software which gives GPS based information for the vehicle speed evaluation over time for the different driving routes. This data accounts the different traffic conditions of the region or location for which this evaluation is done. A total of ten driving cycles are selected to consider the variation of city driving conditions. Even for geographically large regions such as China, US, and Europe the cities are also varied to keep into account the variation among cities as well. The details about these driving cycles for the six largest global automotive markets are tabulated below in the Table 4–3 which was used for the Well to wheel energy consumption evaluation of the vehicles.

Table 4–3: Drive cycle information for the six largest automotive markets. (Adapted from [21]*)*

S. No.	Regions	Vehicles Sold (million per year)	City	No. of drive cycles
1	 China	21.09	Shanghai	5
			Beijing	5
2	 US	14.91	New York	4
			Chicago	4
			Los Angeles	2
3	 EU	11.77	Madrid	4
			Berlin	3
			Milan	3
4	 Japan	3.68	Tokyo	10
5	 India	3.08	New Delhi	10
6	 Brazil	1.98	Rio de Janeiro	10

4.2.2. Life cycle assessment

This section highlights the methodology used to calculate the emissions from all the life cycle phases of each vehicle. For the life cycle of the vehicles four main phases are considered in this research, i.e., Manufacturing, Use, Maintenance and End-of-life. The GREET database is used to do this assessment together with some additional data collected from other sources based on the scope of the analysis done. The master database of GHG emissions footprint for the different components or phases are shown below in Table 4–4.

Table 4–4: Database of CO_2 emission footprint for the life cycle assessment. (Adapted from [21])

Component (kg /kg)	ICEV	HEV	EV
Tire	3.14	3.14	3.14
Chassis	2.62	2.62	2.62
Transmission	3.17	3.17	3.17
Body	2.54	2.54	2.54
Powertrain	2.81	2.05	2.57
BMS	x	2.4	2.4
Electric Motor	x	2.51	2.51
Lithium-Ion Battery	x	9.7	10.6
Coolant	0.53	0.53	0.53
Transmission fluid	1.41	1.41	1.41
Windshield fluid	0.18	0.18	0.18
Brake fluid	1.41	1.41	1.41

Engine Oil	3.11	3.11	x
Power steering fluid	3.11	3.11	3.11
ADR	0.97	0.97	0.97
WTT (kg/kWh)	16.97	16.97	Variable
TTW	3.17	3.17	0

Using the dataset in Table 4–4 the life cycle assessment is done to evaluate the total GHG emissions from each vehicle during its entire life cycle. The calculations are performed separately for each phase of the vehicle's life cycle and then combining it to get the final life cycle emission values. The methodology to calculate the emissions from each of the phases are explained below in dedicated sub-sections in the same chronology to explain the entire cradle-to-grave approach followed for the evaluation.

a) Manufacturing

This sub section highlights the process followed to calculate the GHG emissions from the production or the manufacturing of the vehicle. This is done by using the approach used in the GREET models where the average distribution of weight for the vehicle is considered with respect to each component of the vehicle based on its type. This enables to estimate the weight of each component or part of the vehicle out of the total vehicle weight claimed by the manufacturer. The vehicle weight distribution for SUV type vehicles as obtained from the GREET model are shown below in Figure 4–4:

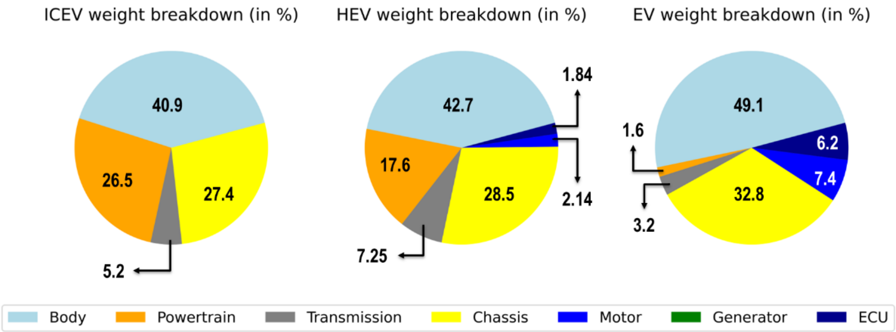


Figure 4–4: Weight distribution by components for a SUV type vehicle. (Adapted from [21]*)*

Upon obtaining the weight of the components its emissions can be calculated directly by multiplying it with its corresponding manufacturing GHG emission footprint listed in Table 4–4 above. This is a simple calculation due to the GHG emission footprint values being in kg CO_2 per kg of component. However, some normalisation must be done for the battery equipped vehicles as the above distribution doesn't accounts for its weight due to the varying battery capacity and chemistry for each different vehicle. Thus, before calculating the distribution of weight it is important to subtract the weight of the battery from the gross weight of the vehicle as reported by the manufacturer and use that for calculation of the weight distribution among the different components, using the equation 4.1 and 4.2 below.

$$VW_{\text{without battery}} = VW_{\text{gross}} - W_{\text{battery}} \tag{4.1}$$

$$W_{\text{component}} = \%\ Share_{\text{component}} * VW_{\text{without battery}} \tag{4.2}$$

Based on the weight of each component obtained from the vehicle's weight distribution, the total manufacturing emissions for each of the respective components are calculated. These emissions are then summed up together to get the total GHG emissions due to the vehicle manufacturing phase. This is calculated using the equation 4.3 shown below.

$$CO_{2\ manufacturing} = [\sum(F_{component} * W_{component})] + (F_{battery} * W_{battery}) \quad (4.3)$$

In case of battery manufacturing emissions, a special attention has been given to the electricity mix of the locations for battery pack manufacturing. To make sure that the GHG emissions of the battery manufacturing process are not very high, an evaluation is done using the average European electricity mix, German electricity mix and Swedish electricity mix. As reported in the literature, in 2020, 25% of the GHG emissions from manufacturing of a battery pack in Europe are due to the electricity mix emissions. Also, it is reported that producing 1 kWh of battery pack, 50 kWh of electricity can be consumed in year 2020 which is the best consumption efficiency as reported till now. The trend of reduction in the electricity consumption for battery manufacturing over the years is shown below in Figure 4–5.

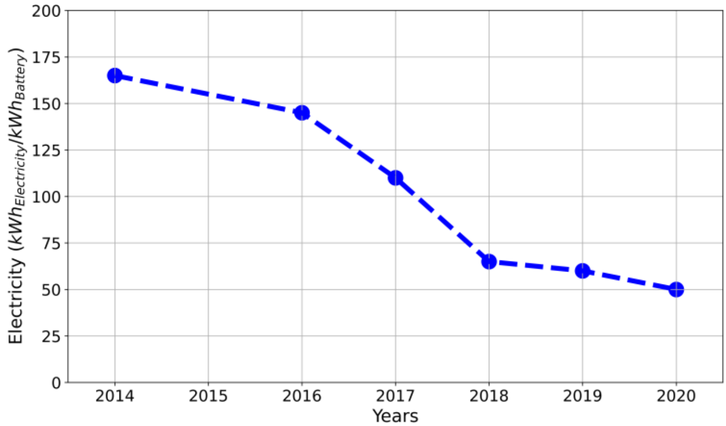


Figure 4–5: Evolution of electricity consumption reduction for manufacturing per kWh of battery packs. (Adapted from [12]*)*

Taking these values for the average European 2020 scenario as reference, the calculation for the change in the electricity grid emissions is done for future years for Europe but also for Sweden and Germany explained in the next sub-section. The reason behind selecting these two European countries is mainly to evaluate a best-case scenario with a worst-case scenario in terms of electricity grid GHG emissions. While the electricity mix of Sweden is one of the cleanest among the European countries, the one of Germany is among the most carbon intensive due to high use of fossil fuel-based energy generation. Moreover, for the battery production, two locations with the maximum number of gigafactories in the near future are Germany and Sweden. Thus, it can be said that the batteries used in the cars driven in Europe will majorly be manufactured in these two countries. Figure 4–6 below shows the distribution of gigafactories planned for 2035 in different European countries.

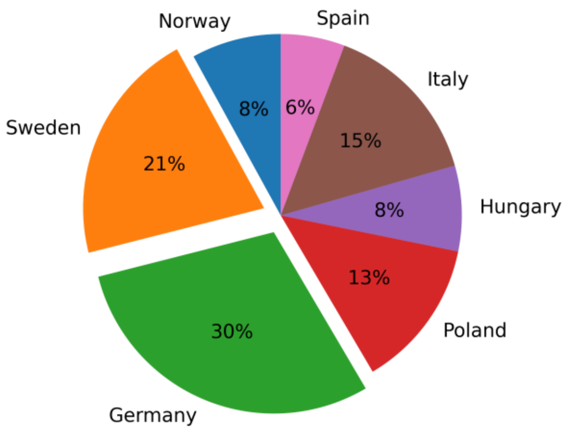


Figure 4–6: Share of battery manufacturing capacity as planned for 2025 by country in Europe. (Adapted from [163]*)*

b) Use

This sub section explains the well-to-wheel approach for the evaluation of the vehicles' use phase emissions while in operation. The well to wheel approach means, accounting the emissions from the tailpipe emissions as tank to wheel emissions but also well to tank phase due to fuel production and supply till it is filled into the vehicles' tank. This is done by using the energy consumption during the use phase on different real world drive cycles as mentioned in the previous section of 0D modelling. The 0D simulation of the different vehicles gives the energy consumption value which is used to calculate the WTT and TTW emissions using the GREET database. The WTT emission for diesel powered vehicles is calculated using the equation 4.4 below:

$$CO_{2\ WTT\ Fuel} = F_{WTT\ Fuel} * C_{Fuel} \tag{4.4}$$

In the equation 4.4, the $F_{WTT\ Fuel}$ refers to the CO2 emissions from the fuel production per kg, while C_{Fuel} is the consumption of fuel in kg per km. The calculations for the use of OMEx in diesel vehicles is done by calculating the energy consumption of the same engine operating with same efficiency using a fuel with lower LHV. Thus, by doing the energy balance using the LHV the total fuel consumption for OMEx was calculated. However, as the study is carried out for different regions and energy scenarios the electricity mix variation is used for the calculation of emissions. Figure 4–7 below shows the electricity mix emissions' variation among the six largest automotive markets.

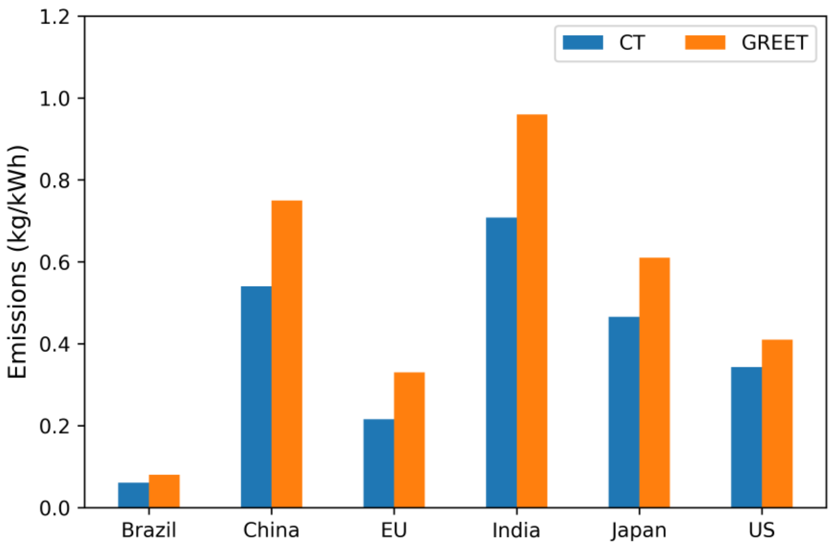


Figure 4–7: Electricity grid emissions used for WTT calculations for per kWh of electricity produced. (Adapted from [21]*)*

In the Figure 4–7 above, two different bars can be seen. This is because in GREET the electricity mix emissions of Brazil and India were not present. Thus, the data from climate transparency reports (in blue) for each of the region was used to get the data. The ratio for the four regions, except Brazil and India was calculated of these grid emission values. The average ratio obtained, was used to calculate the GREET equivalent emissions values using the climate transparency data. To maintain a homogeneity in data, the climate transparency values were converted to equivalent GREET values and used for the final calculations. Moreover, for Europe an extended study is done to see the variation within the region from 2020 to 2022 and comparing it with that for Germany and Sweden in 2022. This was done to see the change in the decarbonisation potential of electric vehicles due to the variation in the electricity grid and forecast future effect due to the current energy crisis in the region. This was done by including Germany and Sweden as a best case and worst-case scenarios in terms of electricity grid emission values. The respective electricity mixes emission values used for those related calculations are shown below in Figure 4–8.

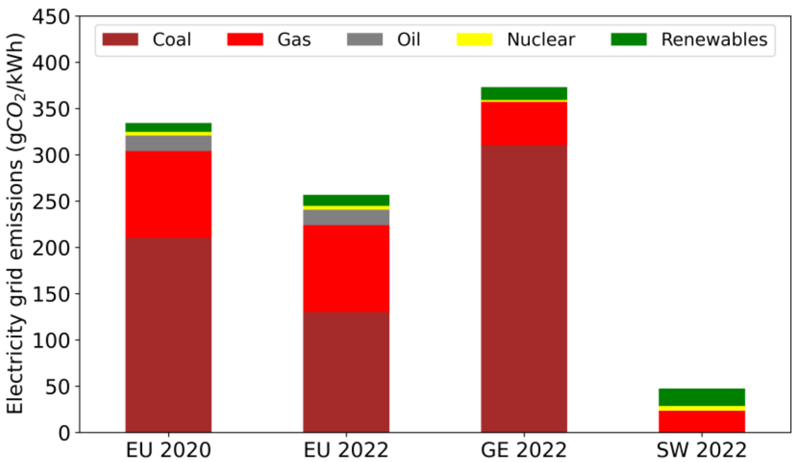


Figure 4–8: Electricity grid emissions of Europe in 2020 & 2022 and of Germany and Sweden in 2022. (Adapted from [160]*)*

The above Figure 4–8 shows the share of natural gas in 2022 for Europe, Germany and Sweden, whose supply was stopped by Russia due to the geopolitical tensions with Ukraine and the entire European Union. To add a futuristic dimension into this study the replacement of tis natural gas was evaluated for three scenarios:

1. Scenario 1: Replacement by Coal
2. Scenario 2: Replacement by Renewables
3. Scenario 3: Replacement by both Coal and Renewables (50-50)

The equivalent change in the electricity grid mix was assessed and the emissions value were calculated for the life cycle analysis later. It also needs to be mentioned that GREET doesn't have the emission value of the European, German and Swedish electricity grid for the year 2022. Thus, this as well as the emissions for the three scenarios is calculated by using the values mentioned below in Table 4–5. The table contains the emissions resulting from different electricity generation sources and its corresponding emission value is used based on the share of its presence in the total electricity grid of the specific country/region.

Table 4–5: Electricity mix information used for the assessment in Europe, Germany and Sweden. (Adapted from [160]*)*

Electricity source	EU 2020 (%)	2022 (%)			Emission intensity (kgCO2/kWh)
		Europe	Germany	Sweden	
Coal	21	13	31	-	1
Gas (Russian supply)	20 (8)	20 (8)	10 (5.5)	5 (5)	0.47
Oil	2	2	-	-	0.84
Nuclear	25	25	13	32	0.02
Renewables	32	40	46	63	0.03

The emissions values are calculated using the equation 4.5:

$$CO_{2\ \text{WTT Electricity}} = \frac{C_{\text{Electricity}} * F_{\text{WTT Electricity}}}{E_{\text{Charger}}} \tag{4.5}$$

The TTW emissions are only for the ICE powered vehicle types and thus are calculated using the equation 4.6:

$$CO_{2\ \text{TTW}} = F_{\text{TTW Fuel}} * C_{\text{Fuel}} \tag{4.6}$$

Finally, the WTW emissions are simply done adding both these two emission types as shown in the equation 4.7:

$$CO_{2\ \text{WTW}} = CO_{2\ \text{WTT}} + CO_{2\ \text{TTW}} \tag{4.7}$$

c) Maintenance

To make sure that the vehicle is in operable condition during its life cycle it needs to be maintained from time to time. Thus, it needs to be realised that the parts and materials needed during the maintenance of the vehicle also comes under the life cycle of the vehicle only. The emissions thus leading to the manufacturing as well supply with all such materials and components needs to be accounted as well. Moreover, there could be additional repairs or maintenance needed due to an extreme or unique situation due to accidents or mechanical breakdown. However, in this study only the normal maintenance is taken into account, considering the lifetime of components smaller than the vehicle and thus must be replaced. As regard to EVs, while the lifetime of the batteries was historically a concern, currently the batteries are capable to last more than the vehicle life cycle of 150000 kilometres, as considered for this study of passenger cars. The main components considered in this study as part of maintenance are shown below in Table 4–6, together with their life cycle kilometres and other details.

Table 4–6: Maintenance data considered for the different components. (Adapted from [21]*)*

Part	Life cycle (km)	Weight (kg)	Replacements
Coolant	60000	5.5	3
Transmission fluid	150000	0.9	1
Windshield fluid	15000	0.5	10
Brake fluid	60000	0.6	3
Engine Oil	15000	2.5	10
Power steering fluid	150000	1	1
Tires	50000	28	2

The number of replacements is calculated by using the equation 4.8, considering the components individual life cycle kilometres and the overall vehicles' life cycle kilometres.

$$N_{Replacement} = 150000 / LCK_{Component} \quad (4.8)$$

To get the total emissions from the maintenance phase for the life cycle of the vehicle the equation 4.9 is used, mentioned below:

$$CO_{2\ Maintenance} = F_{Component} * W_{Component} * N_{Replacement} \quad (4.9)$$

d) End of life

The last phase in the life cycle of the vehicles is at the end of its life which includes its disposal and recycling processes. In terms of the li-ion batteries, it is assumed to be subjected for a second life and thus its recycling is not really included here. For the remaining vehicle the disposal and recycling are considered for the entire vehicle using the GREET dataset value for assembly, disposal and recycling (ADR). From the name itself it can be understood that this phase or process happens only once in the entire life cycle of the vehicle. It is evaluated directly as a function of the vehicle total weight that is subjected to this process. The equation 4.10 below is used to calculate this emission associated with each vehicle type.

$$CO_{2\,ADR} = F_{ADR} * VW_{gross} \tag{4.10}$$

Hence, the total life cycle emissions calculation can be expressed as equation 4.11, below:

$$LCA = Production + Use + Maintenance + ADR \tag{4.11}$$

4.2.3. Total Cost of Ownership

This section highlights the methodology used to evaluate the cost efficiency of the vehicles in the different automotive markets. When assessing a technology's potential to take hold in the market, the economic factor is extremely important. Despite having technical benefits, if a technology is expensive, it will have a hard time competing in the market. In the same sense, the price of EVs is also substantially more than that of an equivalent ICEV or even a HEV, though they have no tailpipe emissions. For this, different costs that are associated with the vehicle for its entire life cycle are evaluated with a perspective of a first-hand vehicle owner. Thus, this includes the vehicle purchase, taxes, incentives, insurance, energy consumption and the maintenance cost. Hence the sum of all these costs is termed collectively as the total cost of ownership. The recycling cost is not considered as it's not something paid by the vehicle owners. Each of the accounted costs are explained separately in dedicated sub-sections below.

a) Purchase cost

The owner's purchase cost, which was incurred when the vehicle was bought, accounts for the largest portion of the TCO. The fact that this cost differs from nation to nation must be considered. As noted in the introduction, this study compares the powertrain capacity and driving range of an equivalent ICEV and HEV SUV with that of an EV SUV. Unfortunately, none of the currently available EVs can equal the ICEV's driving range due to the lower energy density of the battery packs. However, to provide the greatest feasible parity in terms of driving range with the ICEV, an EV SUV with a 90-kWh battery has been taken into consideration in this article. Thus, the purchase costs used in this study for the ICEV and EV SUVs in the six markets are shown below in Figure 4–9.

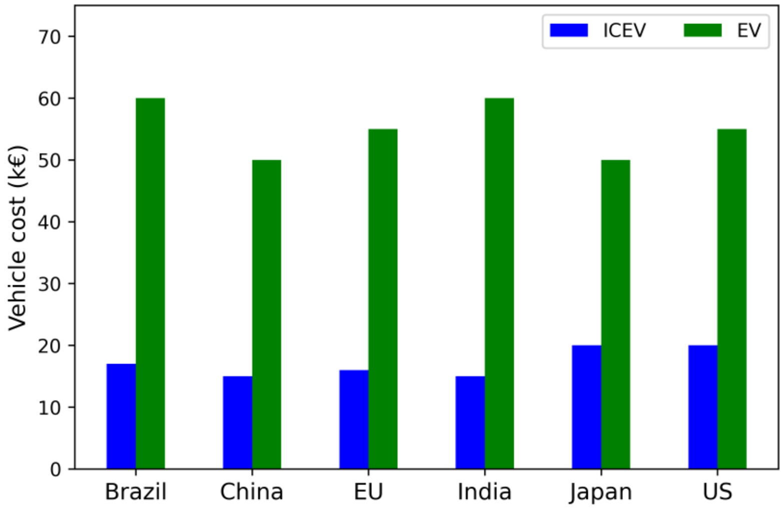


Figure 4–9: Purchase cost of the ICEV and EV in six largest global automotive markets. (Adapted from [21]*)*

Additionally, for the HEV SUV employed in this study, no commercially available model from the same automaker can be located based on the specifications in any of the six nations. As a result, its price is determined by simply sizing the vehicle according to its components. To establish their cost breakdown by component, the purchase expenses of the ICEV and EV are employed. This was accomplished with the aid of a prior study that looked at how much an ICEV and an EV cost separately. The percentage share of various parts in the overall cost of both cars' purchases is shown in Figure 4–10 for comparison.

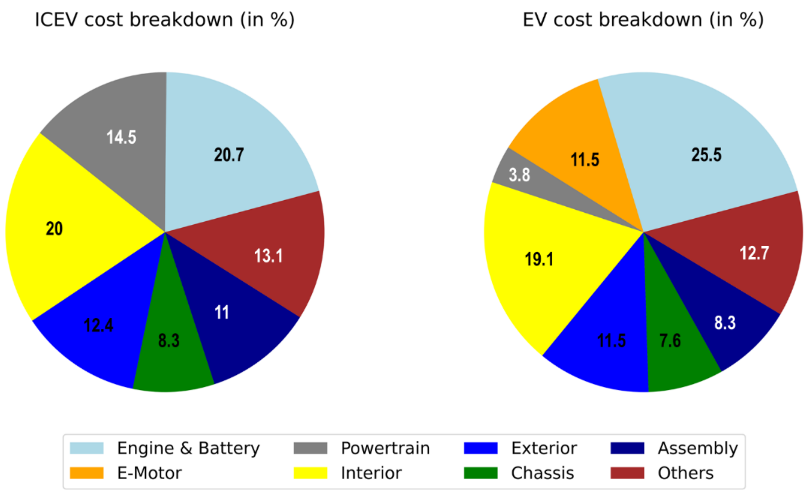


Figure 4–10: Distribution of the purchase cost by different components. (Adapted from [21]*)*

For the hybrid vehicle the price is calculated using the vehicle and the powertrain specifications, which is also similar with the ICEV in terms of interior, exterior, chassis and the powertrain. For the remaining parts the equation 4.12 to 4.15, shown below, are used to calculate the total vehicle purchase costs.

$$AC_{HEV} = AC_{ICEV} + [(AC_{EV} / VW_{EV}) * (VW_{HEV} - VW_{ICEV})] \quad (4.12)$$

$$EMC_{HEV} = (EMC_{EV} / EMP_{EV}) * EMP_{HEV} \quad (4.13)$$

$$EBC_{HEV} = EC_{ICEV} + [(BC_{EV} / BCap_{EV}) * BCap_{HEV}] \quad (4.14)$$

$$OC_{HEV} = OC_{ICEV} + [(OC_{EV} / VW_{EV}) * (VW_{HEV} - VW_{ICEV})] \quad (4.15)$$

The cost of the HEV components is evaluated using the above expressions by keeping in mind the following key assumptions:

1. The assembly costs of the HEV are higher than that of the ICEV as there are added number of parts due to the powertrain electrification. The difference in the vehicles' weight is considered for this calculation as the added weight of the components.
2. For the cost of the e-motor, it is calculated by evaluating the per kW cost of the motor using the value obtained for the electric vehicle. The cost per kW is then multiplied by the motor capacity of the HEV.
3. As the HEV is equipped with the same engine specification as the ICEV, same cost of the engine is taken into account. However, an additional cost of the battery is also involved in it which is calculated using the cost of the battery in the EV and obtaining the per kWh cost. Consecutively, the cost of the HEV battery is calculated.
4. Finally, for the auxiliary costs the calculation is made for the added components in the HEV as compared to the ICEV by considering the change in the weight.

Additionally, as for the emissions associated with the battery due to varying electricity mix, the cost of the electricity is also considered in the manufacturing process of the battery. As considered earlier, 25% of the emissions from the battery manufacturing in 2020 came from the use of electricity in Europe. Thus, for studying the effect of the energy crisis in Europe, this value is used to evaluate the effect on the battery production with the variation in the electricity cost as well. The electricity consumption is the same though and only the effect of changing price of the different scenarios is considered. The prices considered for the electricity in the different scenarios and regions are mentioned in the following sub-sections.

b) Taxes

At the time of procurement of the vehicle the owner must also pay for several taxes to purchase the vehicle and take it home or drive not the roads. These costs or taxes varies from region to region based on the policies and laws of the respective region or market. The costs even vary within a region as well, for example across European countries, the states in the US and India, etc. However, as the main motivation behind the study is to assess the largest market, the average taxes imposed in each of them are considered. Even while doing the dedicated study for Germany and Sweden, the average European values are used as it is not much different in the countries too. For the ICEVs and the HEVs the taxes imposed are similar while for the EVs it is waived off in most of the markets. The different values taken as taxes imposed in each of the evaluated automotive market is shown below in Figure 4–11.

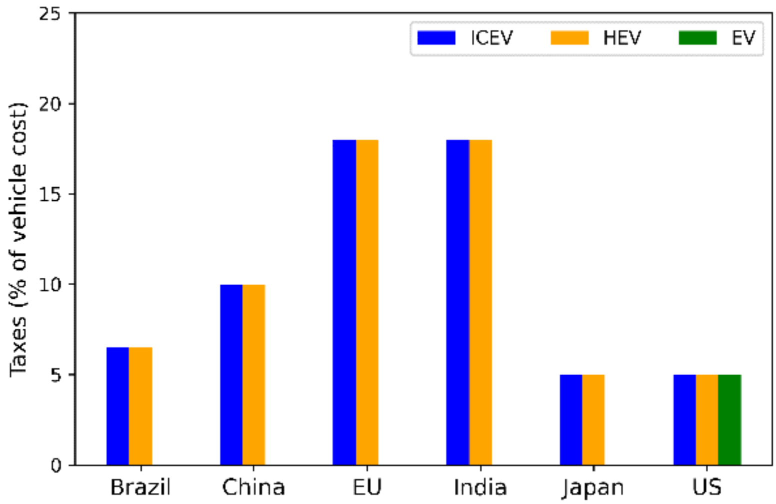


Figure 4–11: Taxes in the six different automotive markets in % of vehicle purchase cost. (Adapted from [21]*)*

c) Incentives

As could be seen in the Figure 4–9, the vehicle purchase cost for the EVs is much higher than that of ICEVs. Thus, to overcome the price difference several regions offer heavy incentives to the customer while buying an EV as an effort to promote them. Just as the taxes, the incentives are a government policy and is thus variable between them. While most of the country offers incentives by the vehicle type, in India the incentives are offered based on the battery size of the vehicle. Thus, as in this study, a 90-kWh battery pack is considered for the EV, the incentives offered for such a vehicle in India will be very high than offered in other regions or markets. Further, the incentives offered in Germany as well as in Sweden were found to be very much similar than the average European value and so the average value of incentives in Europe is used for Sweden and Germany as well for the evaluation study of the energy crisis within the European region. Moreover, no incentives were found to be offered by the government in Brazil. The dedicated values considered for the incentives in the six largest automotive markets are shown below in Figure 4–12.

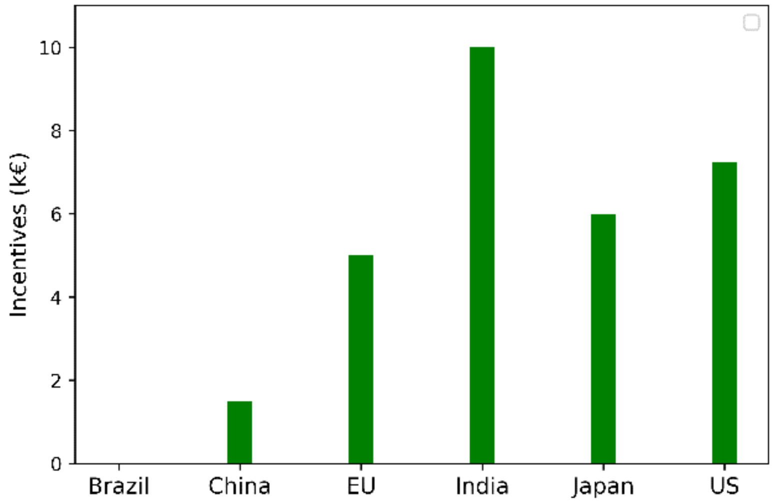


Figure 4–12: Incentives offered in the six largest automotive markets. (Adapted from [164–169]*)*

d) Insurance

To procure the vehicle, the final cost that needs to be paid by the customer to be the owner of the vehicle is insurance for the vehicle. This depends on the type of vehicle and on each specific region. For example, in the US, it is widely famous that the cost of vehicle insurance is very high. Also, due to the high cost of purchase of the electric vehicles, the insurance cost for them is also higher. The cost of insurance of the HEVs is like that of the ICEVs as there is not much difference in the purchase cost of them. The exact specific values used in this study to be considered as the insurance cost of the three vehicle types in the six different markets are shown below in Figure 4–13.

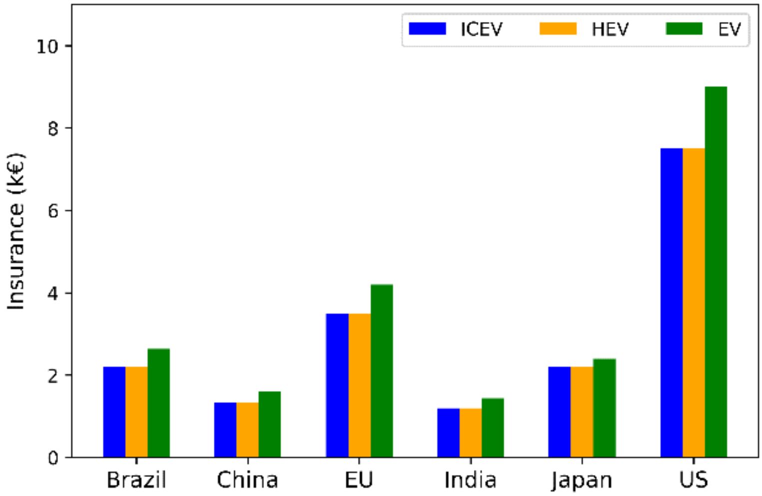


Figure 4–13: Insurance for different vehicle powertrains in the six largest automotive markets. (Adapted from [170–175]*)*

e) Energy cost

The second largest contributor towards the total cost of ownership is the cost coming due to the electricity consumption from the vehicles. This stands true for all the vehicle types including the electric vehicles despite their high efficiency, due to the significant cost of electricity all around the world. Based on the drive cycle the value of the energy consumption changes as so does the equivalent cost of the fuel energy consumption. Further, this also depends on the specific energy cost in each country or region considered for this study, i.e., for diesel in €/L and for electricity in €/kWh. The Table 4–7 below shows the cost considered for both these energy carriers in the six largest automotive market.

Table 4–7: Specific energy cost for diesel and electricity in the six largest automotive markets.[176]

Country	Fuel [€/L]	Electricity [€/kWh]
Brazil	1.217	0.137

China	1.147	0.079
EU	1.782	0.237
India	1.231	0.073
Japan	1.058	0.22
US	1.407	0.151

Additionally for the extended study of assessing the impact of the European energy crisis, the values for electricity and diesel are used as the same in the Table 4–7 above, Moreover, the prices are considered for the year 2022 as well as for 2023 by taking into account the possible variations in the price for the cost calculations. The yearly factor of increase in the winter season for Europe as well as Germany and Sweden are considered and the price of the electricity in 2022 currently at the beginning of winter is multiplied by it to get the probable value in 2023. These values as obtained and considered for the TCO calculation in this study are shown below in Figure 4–14.

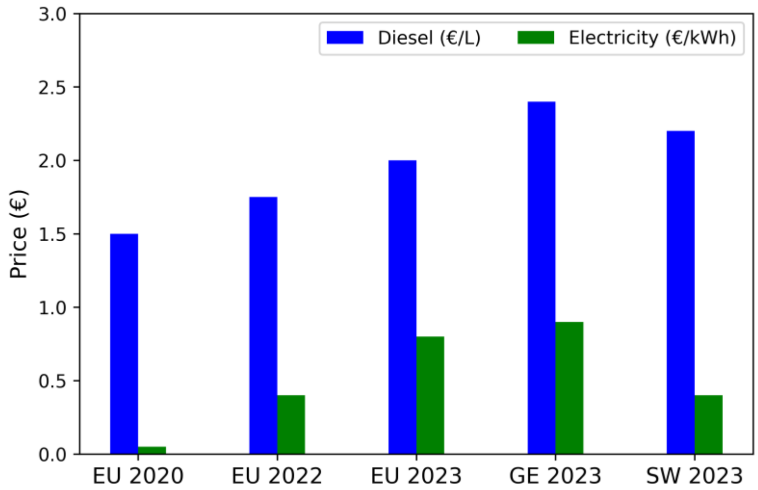


Figure 4–14: Electricity and diesel price in Europe, Germany and Sweden for different scenarios. (Adapted from [52,176,177]*)*

Finally, these energy costs are calculated using the equation 4.16 and 4.17 below for the diesel and electricity consumption.

$$\text{Cost}_{\text{Energy}} = \text{C}_{\text{Diesel}} * \text{Cost}_{\text{Diesel}} \tag{4.16}$$

$$\text{Cost}_{\text{Energy}} = \text{C}_{\text{Electricity}} * \text{Cost}_{\text{Electricity}} \tag{4.17}$$

f) Maintenance cost

The maintenance is the final cost to calculate the total cost of ownership of the different vehicle types. This cost takes care of all the investments needed to maintain the vehicle and keep it in running condition throughout the life cycle. Due to a large variation in the literature for this type of cost, for this study an average value is considered as percentage of total cost of ownership, reported in previous study. Since, this study is focussed on the world including Europe, Us and China the literature data used is for the regions as well. Below in Figure 4–15 a more detailed value for each vehicle type is shown as used for this study.

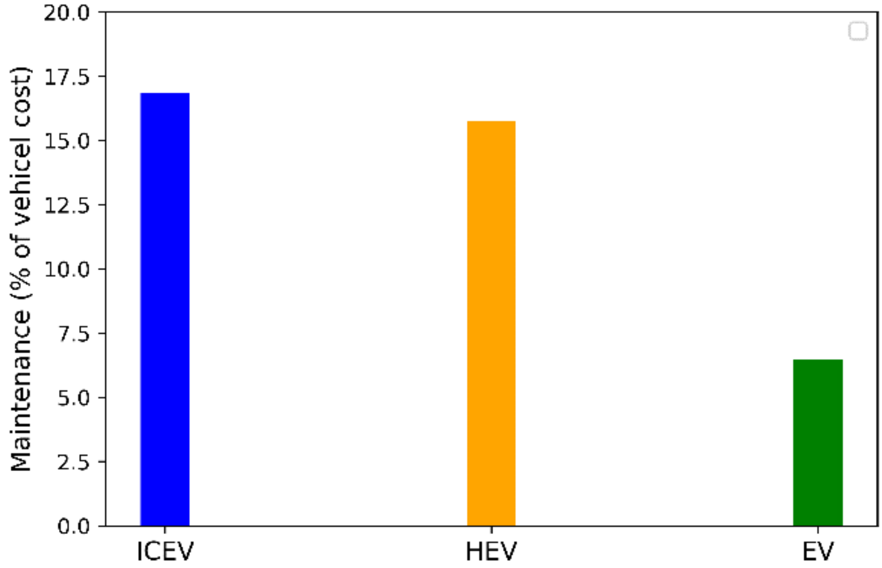


Figure 4–15: Vehicle maintenance cost considered as % of the TCO. (Adapted from [178]*)*

4.2.4. Fleet Assessment

Considering the target for future EV sales in the EU of 100% by 2035 and 50% in the US by 2030 a fleet assessment is done to see its impact on emission reduction of the total fleet. Also, for US the target of 100% EV sales is considered by 2040 keeping in mind the ambitions of car manufacturers as well as the current governments appeal. The results are further compared with the emission reductions possible by using e-fuels, such as OMEx, in the ICE based vehicles. The study is done for the well-to-wheel phase as well as the entire life cycle phase to highlight the bigger picture of the flaws in the laws being implemented in two regions. It needs to be understood that the use of electric vehicles is not the only way to decarbonise the fleet. Thus, the study is done to see what the effect on the fleet emissions will be if the sale of EVs is done to meet these targets and compare it with the use of e-fuels in the vehicles with the same rate as projected for EV sales in the two regions. The fleet distribution between ICEV and EVs for the two regions are done using Weibull functions to predict the fleet that will meet these targets. The expression used for the calculation of ICEV and BEV share in the fleet is shown below as equation 4.18.

$$Share\ (x, \alpha, \beta) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{4.18}$$

While x, is the initial number of vehicles, α and β are the coefficients used for the distribution curve. Different values are used for these coefficients to calculate the fleet distribution over the years for both the US and EU till the targets are met. The idea is to see the current share of vehicles for the two vehicle types in the two regions as well as the annual sale of vehicles to do a forecast of change in these numbers over the years. For US a single target for 100% EV sales is considered in 2035, for US 50% sales of EV s considered in 2030 and a 100% EV sales target is considered for 2035. The different parameters and values considered for the fleet assessment including the coefficients of α and β for fleet share calculation are shown below in Table 4–8.

Table 4–8: Data used for fleet assessment in Europe and the US. (Adapted from [159]*)*

Parameter	US	Europe
Total number of vehicles in 2021 (in million)	280	209
Number of ICEs in 2021 (in millions)	260	208
Number of BEVs in 2021 (in millions)	20	0.5
Total new car sales 2020 (in millions)	16.64	10
New ICEs' sales 2020 (in %)	99.4	96
New BEVs' sales 2020 (in %)	0.6	4
50% BEV sales target year	2035	-
100% BEV sales target year	2040	2035

α - ICE	3	3
α - EV	3.5	3
β - ICE	60	60
β - EV	36	70

4.3 Results and Discussion

This section discusses the main results obtained by following the methodology discussed in the previous section for light duty vehicles focussed on SUVs. The results refer each sub-sections as explained in the methodology namely: 0D simulations, Life cycle assessment, total cost of ownership and fleet assessment. The section contains the results for each of them with thorough discussions below.

4.3.1 0D simulations

This sub-section highlights the main findings obtained from the 0D modelling results through simulations on the GT suite software. This includes the drive cycle data obtained using GT Real Drive to see the average speeds of each drive cycle used in this study. Then the energy consumption of the vehicle powertrains in each of those drive cycles. And finally, the possible driving range of the vehicles for each of the drive cycles based on the energy stored on the vehicle on-board. These results are shown below in three different sections, namely: Speed variation, energy consumption and driving range.

a) Speed variation

The different drive cycles considered in this study for the six largest automotive market regions gave different data from the GPS based on the driving conditions associated with each of the driving cycle. These data vary a lot among itself due to several uncertainties such as traffic conditions, road quality, elevation, etc. Further, as the powertrain performance is linked with the operating speed of the vehicle, the energy consumption of the vehicles will be directly dependent on the vehicle speed. Therefore, the average speed of each driving cycle is considered here as an important parameter to understand the vehicle's performance and the results obtained later. The variation in the average speed of each of the drive cycles in the six different automotive markets are shown below in Figure 4–16.

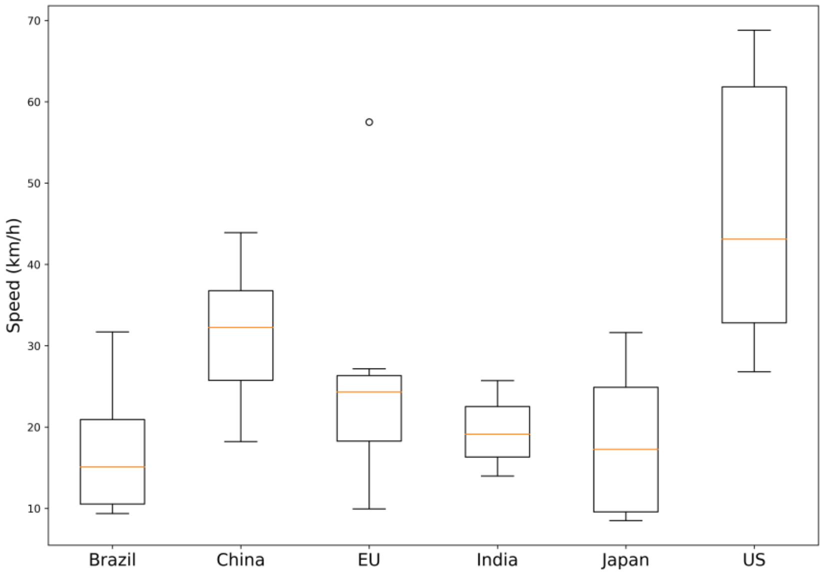


Figure 4–16: Variation in the average speed in six different regions. (Adapted from [21]*)*

The Figure 4–16 above represents the possible variations for the average speed in the different regions. The lowest speed is observed for Brazil and Japan, which truly represents the high traffic congested urban roads in the city areas. For the US the speed is found to be the highest and most varying, this too correctly represents the high-speed traffic in the US and the variation can be related with the fact that three different cities are evaluated there. China stands second in terms of average speed and that too can be associated with the good quality of roads and traffic management there. An exceptional point shown as an outlier for Europe represents an out of the box condition that has an average speed value beyond the upper and lower limit of the box. Thus, this variations in the average speed must be considered while analysing the following results.

b) Energy consumption

The energy consumption of each vehicle is an important parameter to represent the efficiency of it. As discussed, due to the changing speed of each driving cycle, the efficiency of the powertrain will be different in each case for the various vehicles evaluated. Hence, this sub-section highlights this aspect for the urban driving cycles in the major cities of the six largest automotive markets with varying velocity profiles. The energy consumption is the most looked after parameter of any vehicle due to two major reasons, for the emissions due to energy consumption based on legislation point of view. But also, for the energy or fuel cost to be paid during the life cycle of the vehicle based on a customer's point of view. Thus, this value is observed for the possible variation in six regions for each vehicle and is shown below in Figure 4–17.

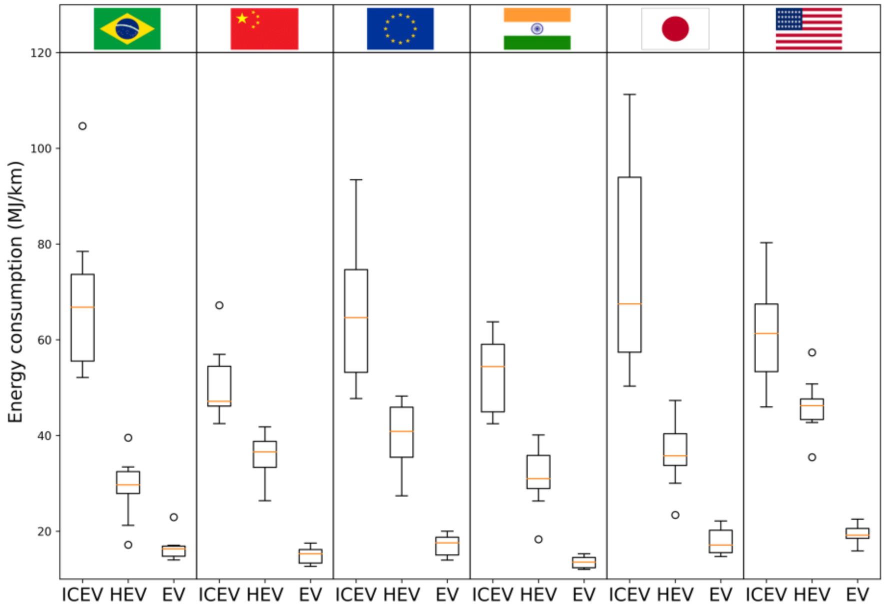


Figure 4–17: Energy consumption of the three different vehicles in the six different regions. (Adapted from [21]*)*

It can be seen in the Figure 4–17 that the energy consumption is the highest for ICEVs in all the six regions due to its poor efficiency, while the lowest for EVs due to its good efficiency. However, it can also be seen that the HEVs can be very energy efficient in the Brazil due to the low average drive cycle speed observed there mainly due to heavy traffic congestions. In the US though, HEVs are not very efficient since the average drive cycle speeds are high enough for the ICEVs to perform well. While in other regions, the low speed of the driving cycle makes the engine efficiency lower and consequently resulting in higher fuel consumption. This may be also understood with the fuel consumption maps shown in the previous chapter where at lower speeds the fuel consumption was quite high. The outliers here too define points are cases that have exceptional energy consumption than the normal trend or range followed in the specific evaluated region. To understand the effect of average speed with the energy consumption, the graph is plotted for the European drive cycles to show the matching trend below in the Figure 4–18.

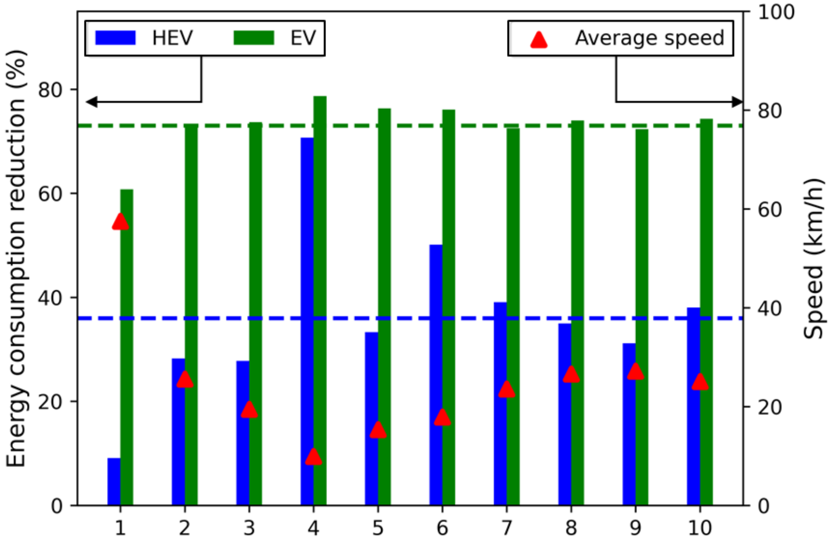


Figure 4–18: Energy consumption reduction in Europe by EVs and HEVs based on the drive cycle's average speed. (Adapted from [160]*)*

In Figure 4–18 the energy consumption reduction is shown by HEVs and EVs with respect to the ICEV's energy consumption. For lowest speed drive cycle the energy consumption reduction is highest while its lowest for the highest speed drive cycle. Further, for the drive cycle with highest average speed the energy consumption reduction by the HEV is very low, this can be attributed to the fact that the ICEV is performing quite well and therefore there is not much scope for the HEV to perform better. Even, for that drive cycle, the EV cam also just has 60% energy consumption reduction while for all the other drive cycles it is well capable to reduce by about 75%. Also, for the drive cycle with the lowest speed, it can be inferred that it is largely affected by traffic as the HEV alone can lead to more than 70% reduction in the energy consumption. Thus, the driving condition is very crucial factor in determining a vehicles' performance.

c) Driving range

The range of kilometres that any transportation vehicle can cover on full charge or tank is the most crucial need in terms of mobility, the real purpose of the vehicle. In this sense, it is very important to see what maximum distance the vehicles can cover by using the energy consumption values obtained for each drive cycle of the six different regions. It can also be referred by the term autonomy, as it means the maximum distance a vehicle can cover by being autonomous, i.e., without external refilling or recharging. This autonomy or range will differ for each drive cycle due to its varying energy consumption values. This variation is shown below in Figure 4–19 for the three vehicle types operating in the six largest automotive markets.

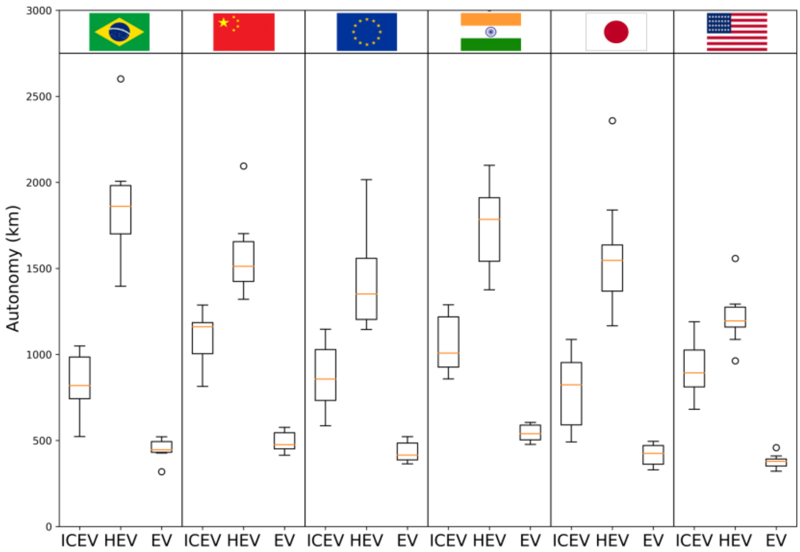


Figure 4–19: Autonomy of the different vehicle types in the six different regions. (Adapted from [21]*)*

There are several outliers observed in the Figure 4–19 above, which shows that the autonomy can change by a huge margin, especially as seen here for the hybrid vehicle in Brazil for instance. The calculation shows that the range can be up to more than 2500 kilometres, while for a case in US it can be as low as 1000 kilometres. Hence, it needs to be realised that these values are relative to the energy consumption obtained for that respective drive cycle only. In all the cases though, HEVs offer the maximum range while the EVs offer the lowest range. In fact, range of the EVs is about 500 kilometres only which is about half of the range of ICEVs and one third of the HEVs. This can be directly understood with the energy stored on-board the vehicle. While the BEV has the lowest energy consumption, it still has the lowest range due to the low energy density of the li-ion batteries. However, in case of HEVs there is an added energy storage possible in the small li-ion batteries other than the same 55 litre fuel tank as in the ICEV. Also, the HEV uses the best of both worlds, i.e., large energy density of the diesel fuel and highly efficient electric powertrain to have the best driving range. To have a detailed comparison, the change in the driving range of both EVs and HEVs is compared to that of the ICEV and shown below in Figure 4–20.

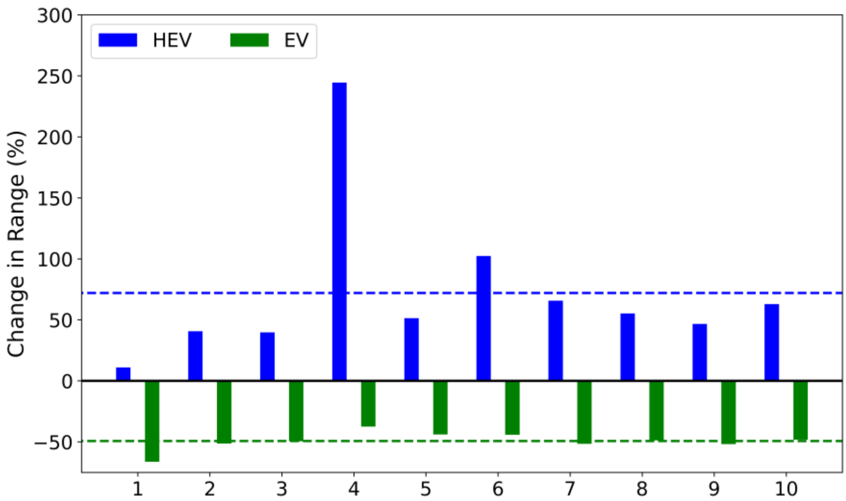


Figure 4–20: Change in the driving range by EVs and HEVs compared to ICEVs. (Adapted from [160]*)*

The Figure 4–20 above shows the change in percentage of the range or autonomy for the ten different drive cycle s in Europe by the HEV and EV, compared to the conventional ICEV. The dotted lines represent the average, and the EV shows about 50% less driving range while the HEV shows an additional range of about 75%. It is due to such results that the HEVs are called as range extenders. The increase in range of the HEV is again dependent on the energy consumption and therefore it can be seen that in the drive cycle number 4 for Europe, the increase can be of 250% which is only because the ICEV performs very poorly in that drive cycle due to very low average speed as discussed before. Similarly, in drive cycle one which has the highest average speed, the increase in range is very low due to the low energy consumption value of the ICEV itself. Thus, it can be understood that the vehicle range is completely dependent on the energy consumption value which in turn is depending in the driving conditions and speed of the drive cycles for which it is evaluated.

4.3.2 Life cycle assessment

This is the subsequent result section to the life cycle assessment methodology explained earlier in the chapter. The results obtained by following the steps or process mentioned in that leads to the following results explained here. To represent the main findings and convey the main message this sub-section is divided into three parts namely: Embedded emissions, Use phase emissions and life cycle emissions. Each of these parts are explained below in detail.

a) Embedded emissions

This part focuses mainly on the emissions related to the manufacturing of the different vehicle types, maintenance, and end-of-life cycles. These are represented all together as constant in each of the six markets considering the assumption that the same set of vehicles is used in all the six different regions to focus primarily only on the variation that may occur on the life cycle emissions due to the use phase emissions. The main findings or the set of values obtained based on the explanation provided in the methodology section are shown below in Figure 4–21 for the three different vehicle types.

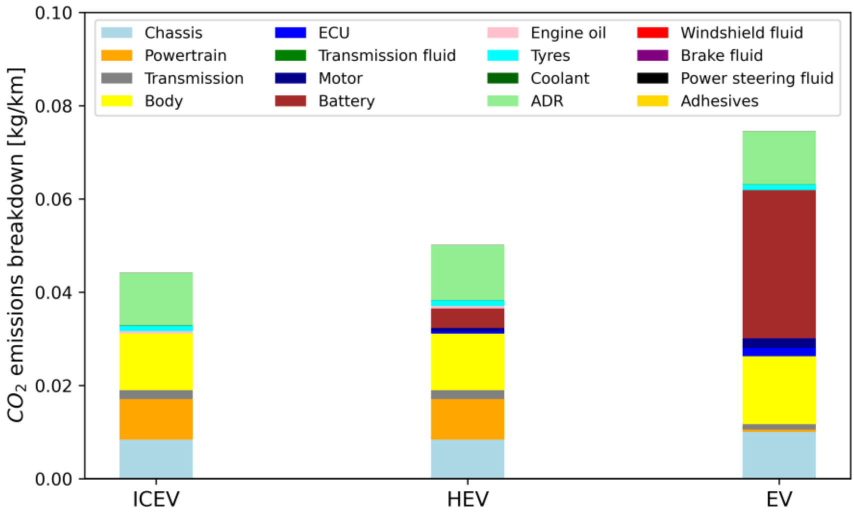


Figure 4–21: Embedded GHG emissions for the three different vehicle types. (Adapted from [21]*)*

In the Figure 4–21 above, the highest embedded emissions are observed for the EVs which is almost around double of the value obtained for the ICEV. The main cause for that can be identified by the additional Brown coloured patch in the hybrid and electric vehicles. This represents the emissions due to the battery pack in both these vehicle types, varying size of it in the two vehicles. Due to the large size of the battery packs in the EV SUV considered for this study (90 kWh) to ensure higher driving range, the emission for the electric vehicle becomes significantly high than the ICEVs and the HEVs. To have a better estimate of the share of battery emissions compared to all others in the total embedded emissions Figure 4–22 is shown below.

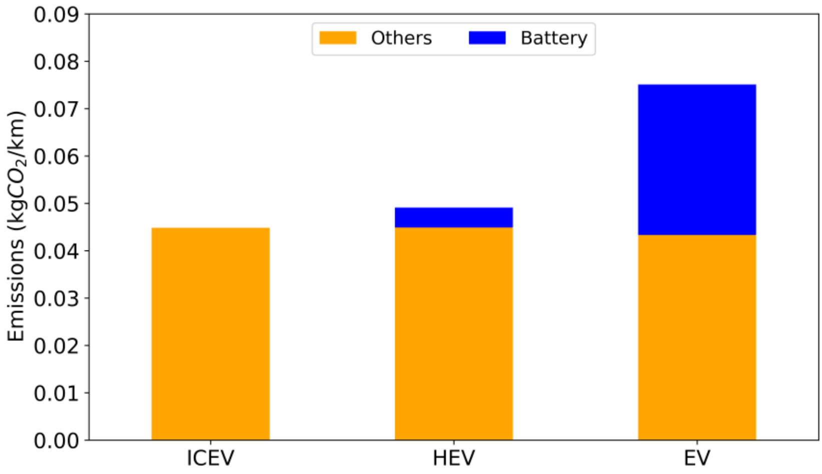


Figure 4–22: Embedded emission of the different vehicle types. (Adapted from [160]*)*

The Figure 4–22 above shows that apart from the batteries, the embedded emissions for the different vehicle types are similar. Thus, it is important to look for ways how these emissions coming from the battery pack manufacturing can be reduced. As mentioned before in the methodology section the electricity mixes of the location where the battery is manufactured is also very much responsible for these emissions. Thus, in this study a varying analysis for the electricity mix of Europe, Sweden and Germany is done to see its effect on the battery pack manufacturing emissions. The different values of the electricity mix calculation for the three different scenarios explained earlier in the methodology section is presented below in Figure 4–23 for Europe, Sweden and Germany.

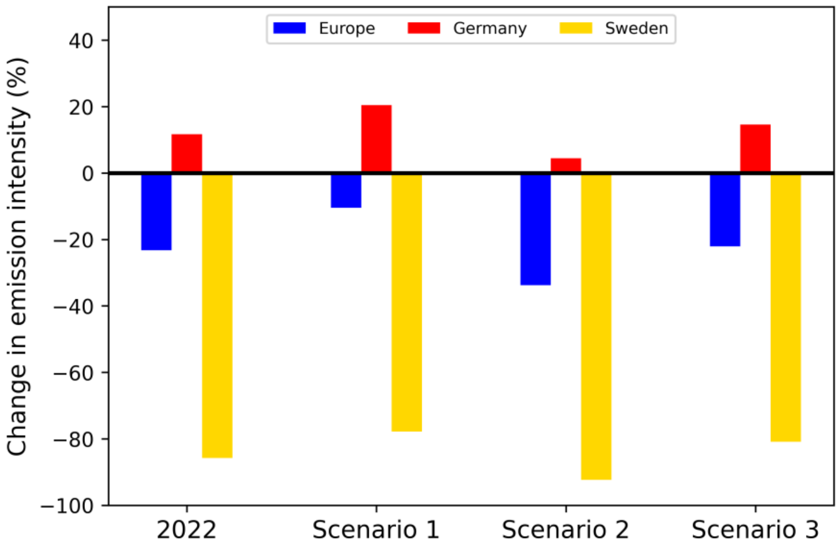


Figure 4–23: Variation in the electricity mix evaluated for Europe, Sweden and Germany. (Adapted from [160]*)*

The Figure 4–23 above shows the change in the emission intensities for Europe, Sweden and Germany in different scenarios compared to the average European electricity mix intensity in the year 2020. It can be observed that for Germany the emission intensity is always higher than the average European electricity mix's emission intensity of the year 2020. Further, it can be noted that in scenario 1, due to the usage of coal to replace Russian natural gas, the bars move up, which shows increase in the emission intensity. In scenario 2, due to the usage of nuclear as a cleaner source of electricity generation, the bars move downwards which implies decrease in the carbon emission intensities. Finally, for the scenario 3, again there is an upward trend but not as much as for the scenario 1. In fact, the 2020 trend is very much like that of scenario 3. Thus, we can say that by replacing the Russian natural gas with coal the emission intensity will become closer to what it was in 2020. While by replacing it with nuclear only will help in further decarbonisation and with a 50-50 share replacement by coal and nuclear it will remain same as what it is in 2020.

The effect of these changing values in the electricity mix intensities is then used to calculate the variation on the battery pack manufacturing emissions. The change in the emission trends for the battery pack manufacturing can be seen in Figure 4–24 below for the different scenarios.

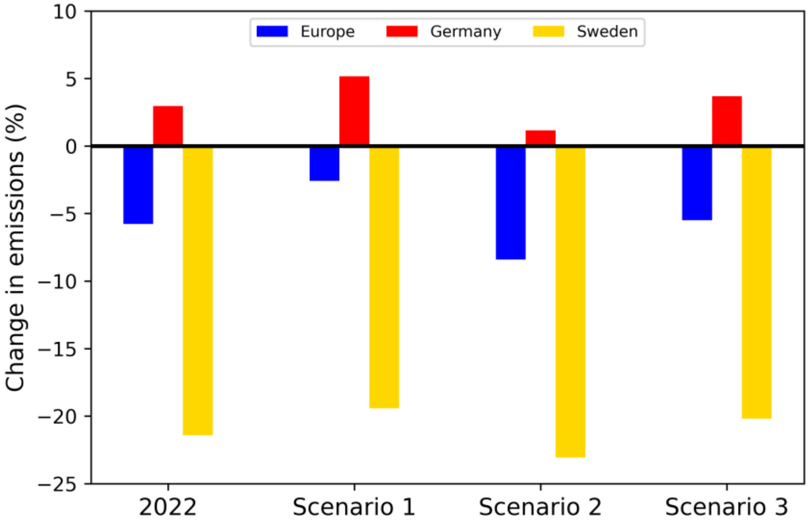


Figure 4–24: Change in the battery pack manufacturing emissions to the reference 2020 value. (Adapted from [160]*)*

From the values observed in the Figure 4–24 above it can be seen that the change with a factor of 0.25 can be experienced due to the change in the electricity mix emissions. Thus, it is important to consider the changing electricity mix of the location to assess the life cycle emission more accurately. These values are also later used for the life cycle emission results for the targeted study within Europe to evaluate the change in the electricity mix. For the analysis of the six largest automotive markets the assumption is made that same vehicle is evaluated in all the six markets to focus only on the effect of the drive cycles and highlight the impact of the use phase.

b) Use phase emissions

This part highlights the emission variations due to the changing drive conditions by using several different drive cycles within each region or country evaluated. This is done to highlight the possible variation among different regions and within a region itself. The results are presented separately for the Well-to-Tank (WTT) and the Tank-to-Wheel (TTW) phase of the vehicles in the different regions. The total use phase emissions are the sum of both these emissions which makes the Well-to-Wheel (WTW) emissions. Firstly, the WTT emissions for the three vehicle types can be seen below in Figure 4–25 for the six largest automotive markets.

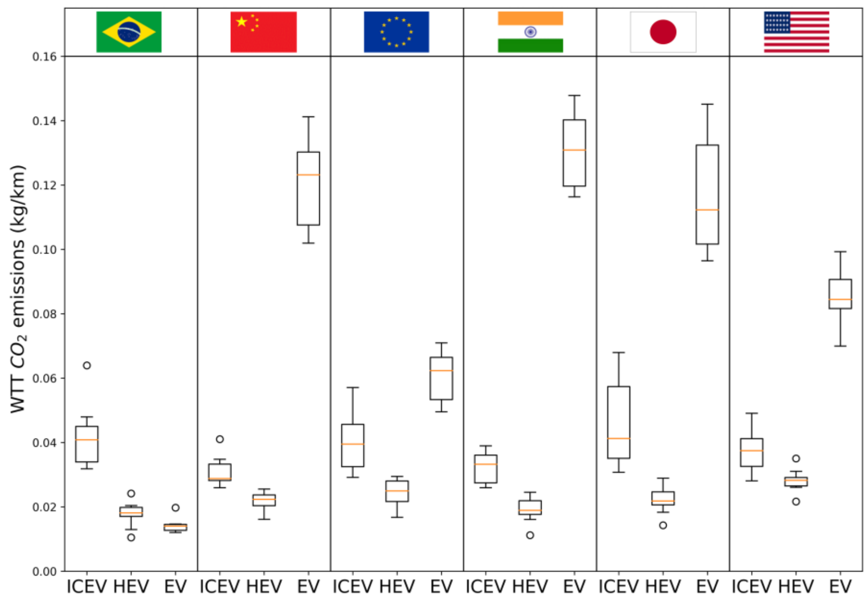
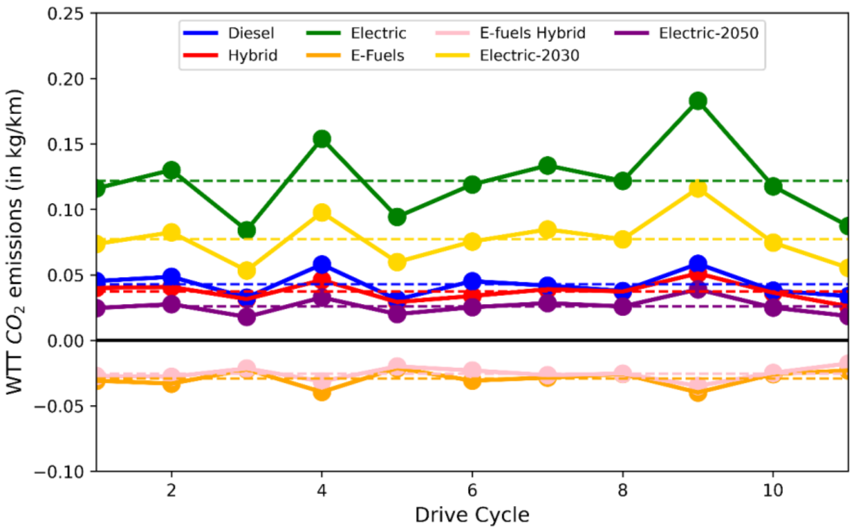
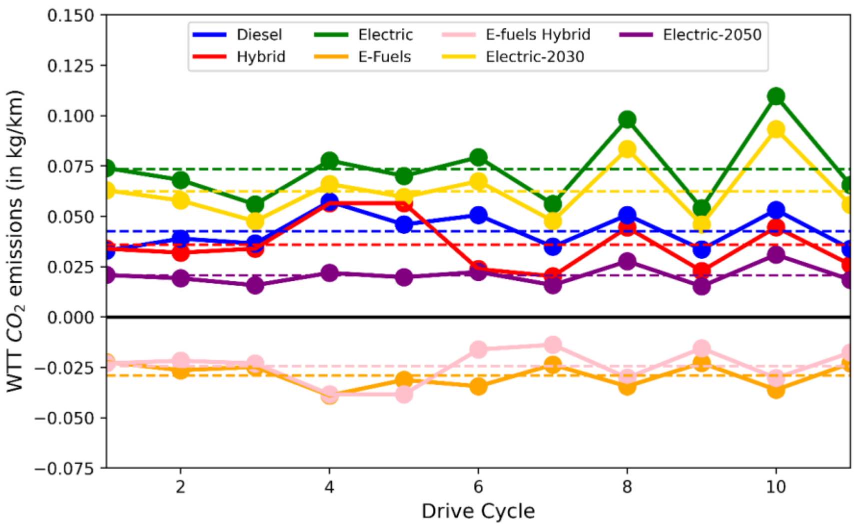


Figure 4–25: WTT emissions in the six different regions. (Adapted from [21]*)*

The WTT emissions as shown above in Figure 4–25 shows that the EVs generally have a very high WTT emissions as compared to the ICE based vehicles. The WTT emission of the EVs mainly depends on two main things, the drive cycle, and the local electricity mix. Thus, these values are calculated by the energy consumption values obtained from the 0D simulation for real world drive cycles and by the electricity mix's emission intensity of each region. However, the bigger impact on the value is due to the electricity mix as countries like China, Japan and India, that have the highest emission intensities, have the highest WTT emissions for the EVs. Similarly, Brazil whose electricity mix is very clean makes EV's WTT emissions there extremely low, even lower than ICEVs and HEVs. The effect of energy consumption is evident while comparing the ICEVs and HEVs though as the HEVs have lower WTT emissions in all the six regions due to lower energy consumption because of better efficiency. To understand the variation within the regions the values are shown below in Figure 4–26 for US and EU to understand the variation possible within a country alone.



(a)



(b)

Figure 4–26: WTT emission variation with (a) US and (b) EU.

The results shown above in Figure 4–26 for the two regions individually shows the effect of the drive cycle energy consumption on the WTT emissions. The use of e-fuels is also presented here for the ICEVs and HEVs for its emission reduction potential. Further, focusing on the TTW emissions, it is only accounted for the ICEVs and the HEVs as the EVs is free of tailpipe emissions due to no combustion involved. These values are mainly dependent only on the drive cycles or the energy consumption values, and it also has the maximum contribution towards the life cycle of any vehicles. This too depends on the vehicle efficiency and thus have similar trend to the one obtained for the energy consumption from the 0D simulation results. The different TTW emission values obtained in the six largest automotive markets are shown below in Figure 4–27.

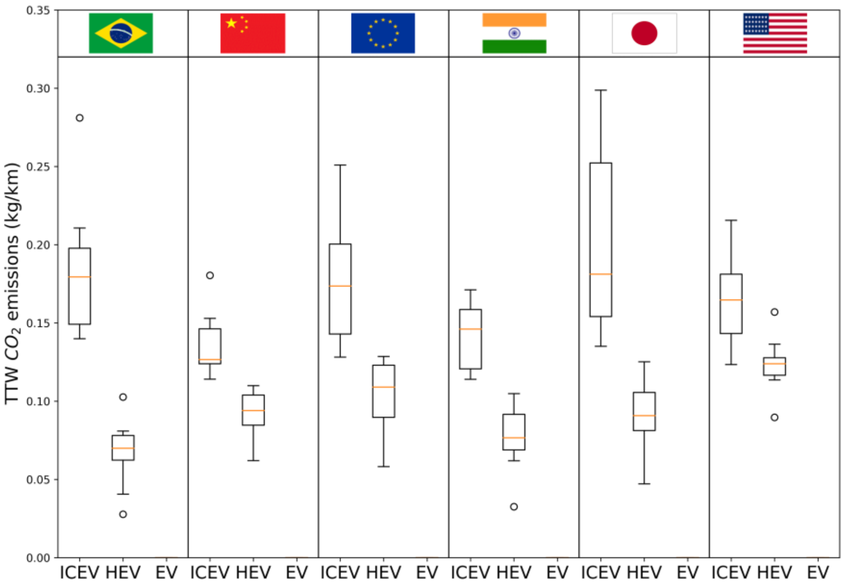
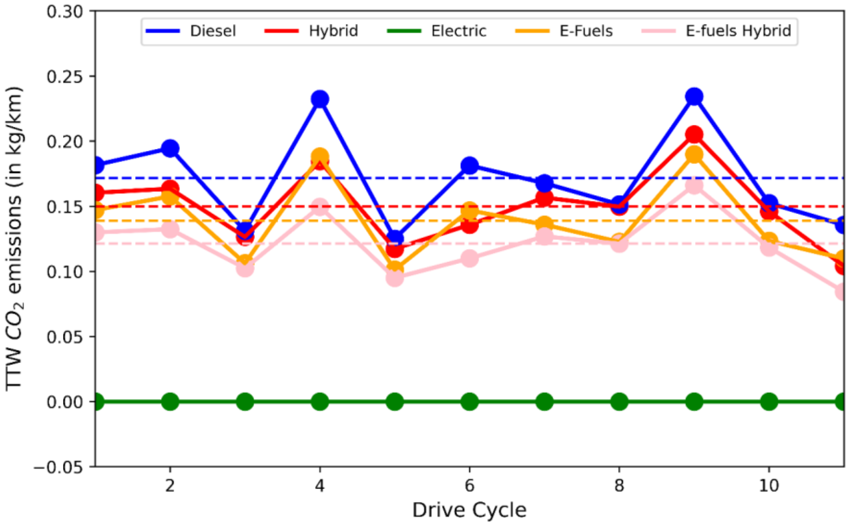
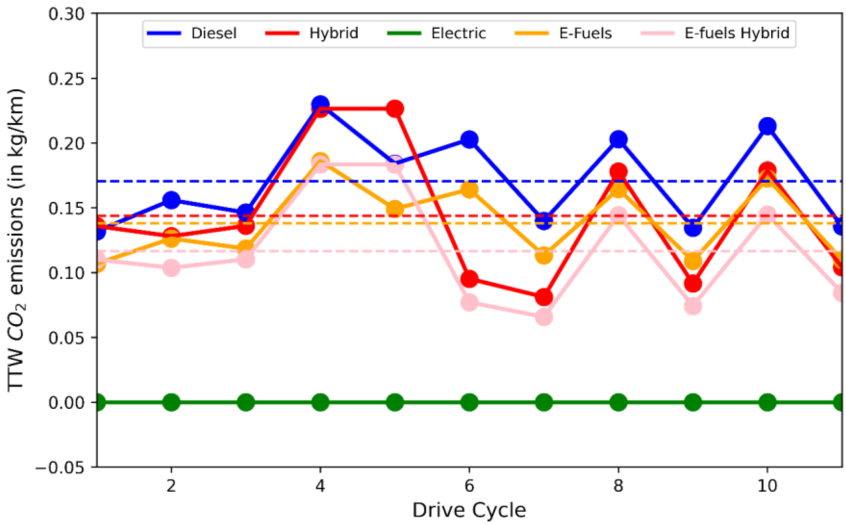


Figure 4–27: TTW emissions in the six different regions. (Adapted from [21]*)*

The results shown above in Figure 4–27 shows the significant emission reductions, in terms of tailpipe emissions, possible with HEVs. It can be easily observed that for Brazil and Japan the difference between the emission values is relatively large due to the low drive cycle speeds for both the regions. This can be related to higher traffic congestions and thus poor performance of the ICEVs than HEVs. Similarly, for USA which has the highest drive cycle speeds, the TTW emission difference is quite less between the HEVs and the ICEVs. Further, it can be observed that the variation within a region can be significant by seeing the large length of the boxes and the upper and lower extreme range. To see this variation the TTW emissions for the different drive cycles used in the evaluation for US and EU are shown below in Figure 4–28.



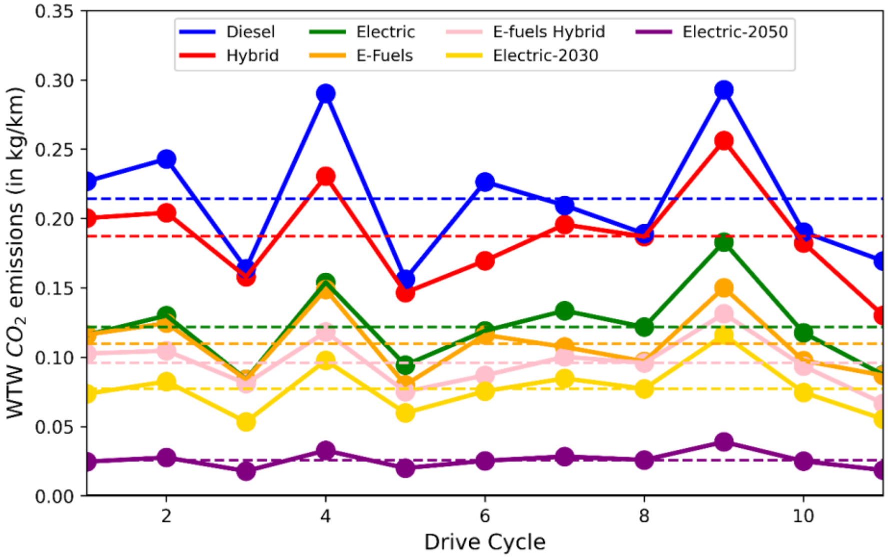
(a)



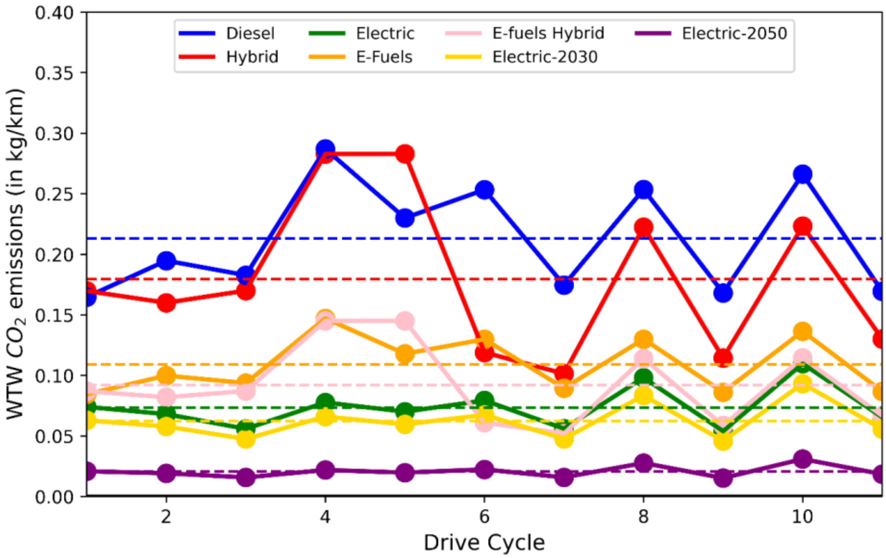
(b)

Figure 4–28: TTW emission variation with (a) US and (b) EU.

In the Figure 4–28 above, it's shown how the emissions vary for both ICEVs and HEVs when powered with diesel as well as e-fuel. It can be noted that the green line represents the zero TTW emissions from the EVs. However, as mentioned earlier the WTT emissions of EVs can itself be significantly high as the TTW wheel emissions of the ICEVs for instance, in India. The WTT emissions of EVs are around 0.13 kg/km in India, while the TTW emissions from the ICEVs are around 0.15 kg/km. This makes the EVs loose the advantage for emission reduction due to the electricity mix's high emission intensity. However, for a region like EU where the emission intensity is not very high the WTW emissions reductions from EVs can be quite significant. However, that too depends on the energy consumption values with changing drive cycle conditions. Hence, it is important to estimate the right vehicle technology in terms of the driving conditions it will be subjected to. Thus, to estimate it better, the WTW emissions of the different vehicle types are shown for the US and the EU in Figure 4–29 below.



(a)



(b)

Figure 4–29: WTW emission variation with (a) US and (b) EU.

It can be seen in Figure 4–29 that despite the low electricity mix emission in US and EU, still based on the drive cycle there can be vast difference in the emission values on a WTW basis. For both US and EU, it is observed that there can be some drive cycles where the performance of an EV can be like the one observed for a HEV. Also, it can be concluded that ICEVs and HEVs, when used with e-fuels can be emitting the same as an EV till the year 2030. After that, if the grid decarbonisation continues the right track, EVs will continue to become the cleanest vehicle option in terms of WTW emission reductions. To estimate the effect of grid decarbonisation in another way, the WTW analysis was also done within Europe for EVs with the average European, German and the Swedish electricity mix. This was done to see the effect on electricity grid emissions, after Russia stopped natural gas supply, by replacing it with coal and nuclear power. The change in electricity mix intensities is shown already in

Figure 4–23, the resulting effect on the well to wheel emissions are shown below in Figure 4–30 below.

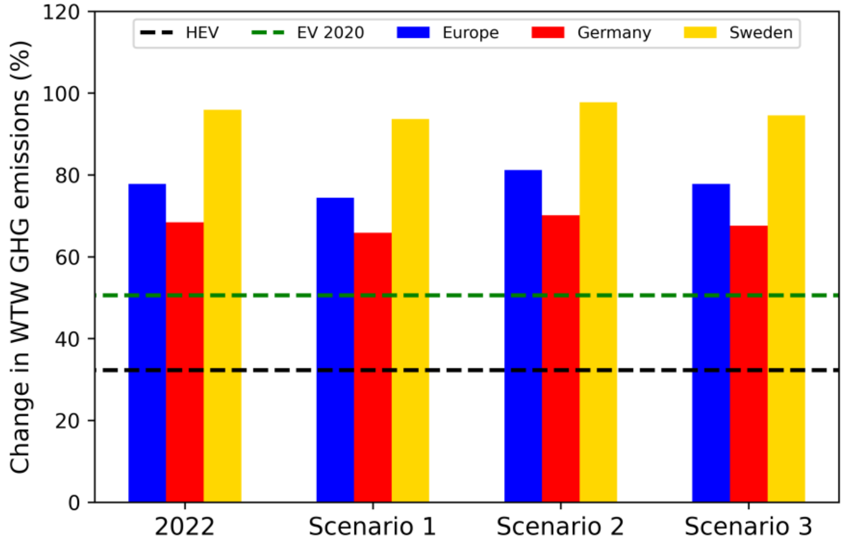


Figure 4–30: Effect on the WTW emissions with changing electricity grid emissions. (Adapted from [160]*)*

The Figure 4–30 above shows the emission reduction possible by the EVs charged by different electricity mix as compared to the emissions from a conventional diesel vehicle. The dotted black line represents the emission reductions possible with HEVs, while the green dotted line represents the reduction possible using average European 2020 electricity mix. On a WTW basis, EVs surpass HEVs due to decarbonised 2022 electricity mix and because the values here shown is for the average of the drive cycles. However, as shown earlier in Figure 4–29 the WTW emissions vary a lot due to the drive cycles and thus must be acknowledged that these values can vary a lot. Therefore, to make sure that the emissions are maintained low, the electricity mix decarbonisation is very important.

c) Life cycle emissions

Finally, this part highlights the main findings for the overall life cycle emission results. As explained earlier the life cycle emissions calculation is done by accounting the emissions coming from the manufacturing, use, maintenance, and end-of-life phases of the vehicle's life cycle. While all the results related to each phase is presented already, here it is shown how it appears as a final value after all the values are put together. For this, first, the life cycle emissions variation for the ICEV, HEV and EV is shown below in Figure 4–31 for the six largest global automotive markets.

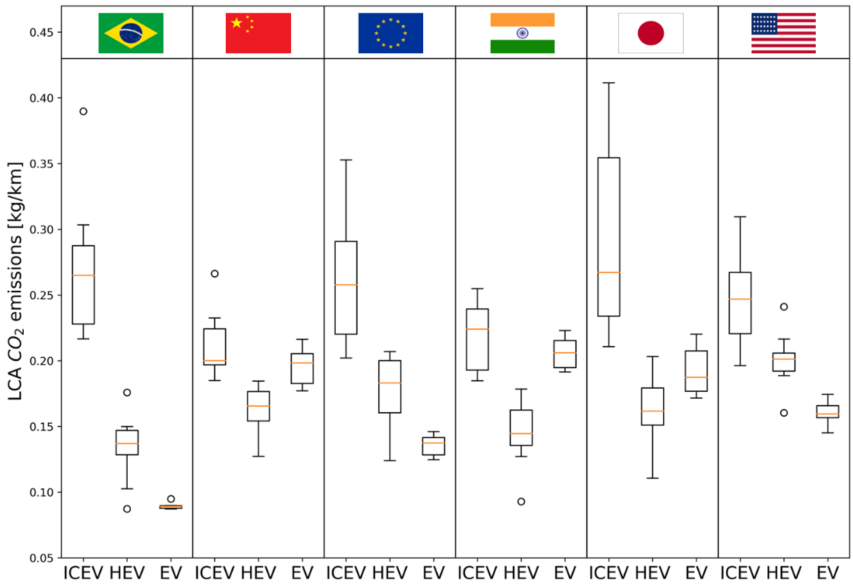
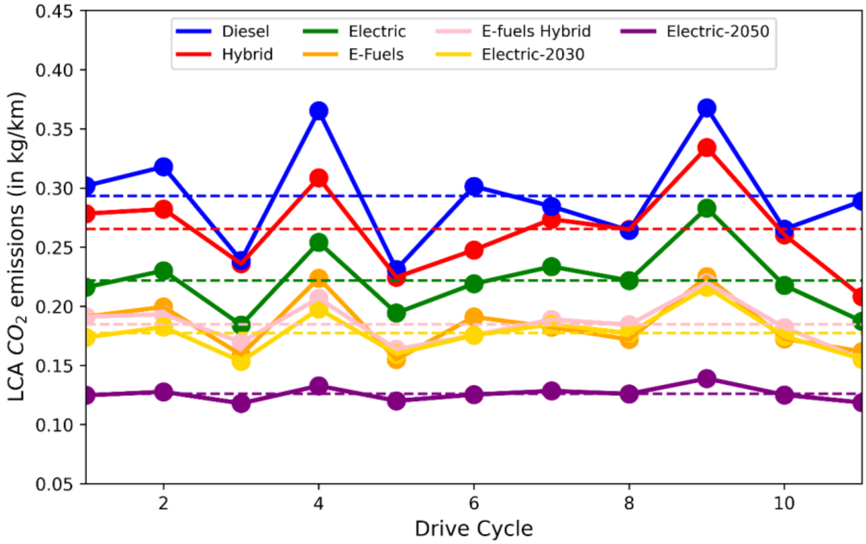


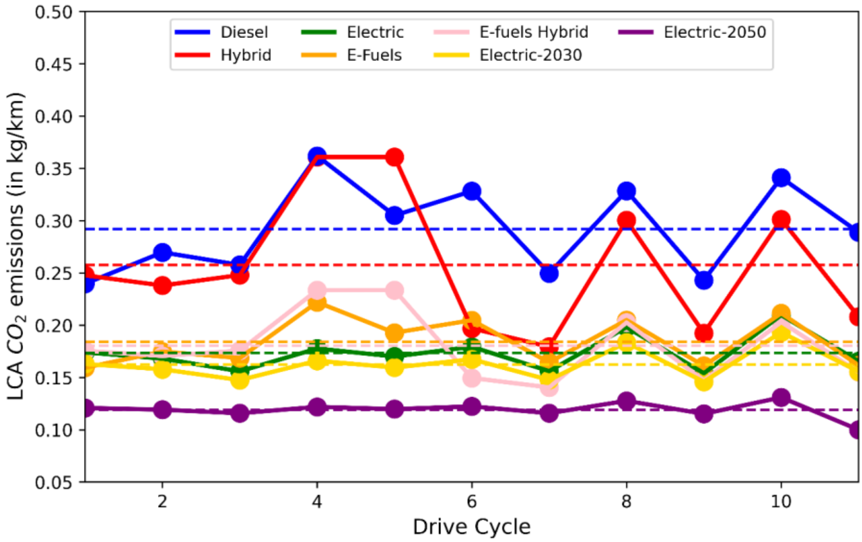
Figure 4–31: LCA emissions in the six different regions. (Adapted from [21]*)*

The Figure 4–31 above shows the final values obtained for the life cycle emissions of CO_2 in the six largest automotive markets for the ICEV, HEV and EV. It can be observed that EVs have the lowest emissions in Brazil, Europe, and US, while HEVs are the lowest emissions in China, India, and Japan. This can be directly linked with the emission intensity of the electricity mix of these regions, Moreover, the driving conditions have a huge impact on the emissions of the ICE powered vehicles while for the

EVs electricity emission intensity is more crucial. The reason behind HEVs perform very well in Japan is the high traffic congestion within the city of Tokyo leading to low average drive cycle speed. This makes ICEVs have very high emissions in city-based traffic for Japan but also for Europe. It should be again noted that the error bars show how much the difference can be in the values with changing drive cycles. Further to understand the variability within a region, the results are shown below in Figure 4–32 of the different drive cycles considered for the US and EU.



(a)



(b)

Figure 4–32: LCA emission variation with (a) US and (b) EU.

It can be seen in Figure 4–32 that the emissions values significantly vary for few exceptional drive cycles which is why the emission reduction potential of each vehicle type depends on the drive cycle. Further, it is important to observe that although the difference in the WTW emissions between the EVs and ICE powered vehicles were higher, in terms of LCA emissions it gets lower. This is due to the higher embedded emissions for EVs as shown earlier in the previous part. Hence, despite higher emissions for the cradle-to gate phase, EVs can offset its higher embedded emission value during its life cycle till it finishes the cradle-to-grave period. However, this again depends on the region. As mentioned earlier, for countries with higher emission intensity of the electricity mix such as India, China and Japan, the emission can't be offset at all till the end of a 10-year life cycle. To better clarify this aspect the evolution of the life cycle emissions is shown below in Figure 4–33 in the six different regions.

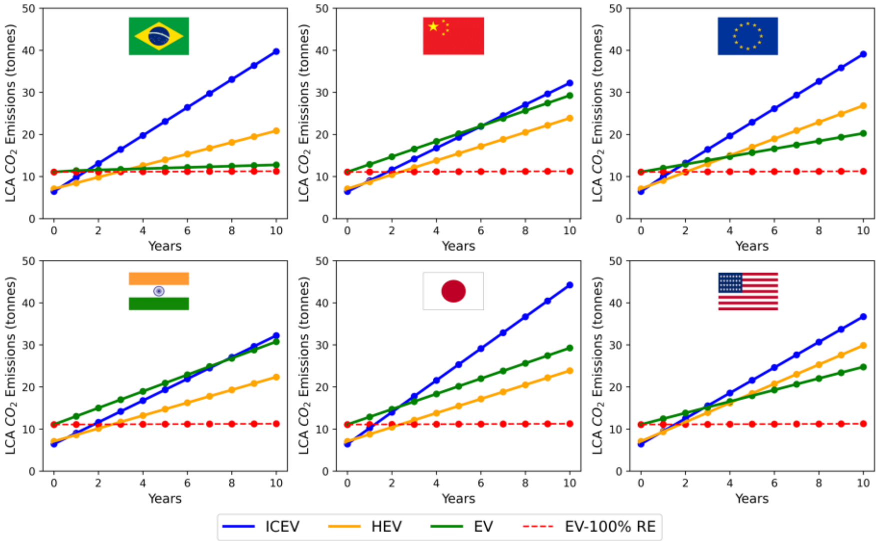


Figure 4–33: Life cycle emissions evolution for a period of 10 years in the six different regions. (Adapted from [21]*)*

The Figure 4–33 shows the evolution trend for the three different vehicle types as observed over the 10-year life cycle period. The red line here represents the maximum emission reduction potential of an EV when powered with 100% renewable energy source. It is marked here to see how much the different regions are far from achieving the maximum emission reduction potential of the EVs. It can also be seen after which year of operation EV can offset the added embedded emissions in each of the different region. Finally, to see the effect of varying decarbonisation level of electricity emission intensity within Europe on the life cycle emissions of EVs, Figure 4–34 is presented below.

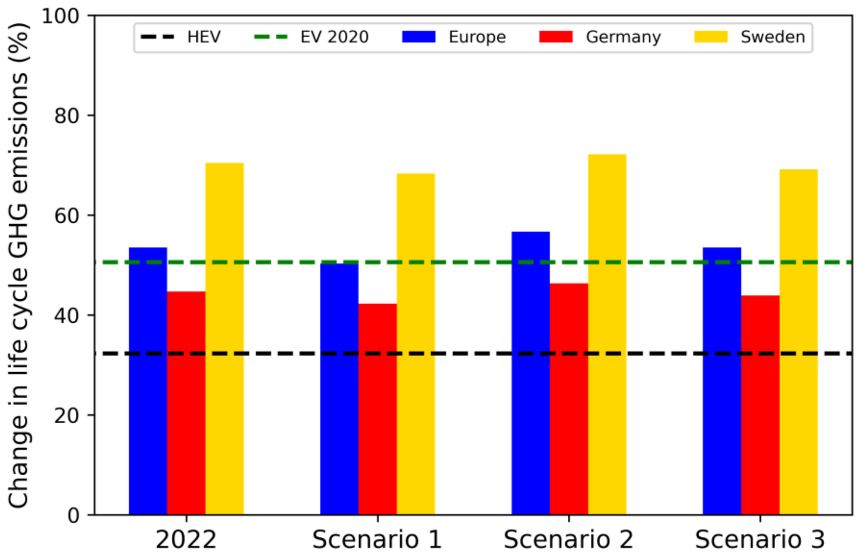


Figure 4–34: Change in the life cycle emissions due to varying level of emission intensity of the electricity mix in Europe, Germany and Sweden. (Adapted from [160]*)*

As shown in Figure 4–34, in terms of life cycle emissions, the change in the year 2022 before and after the cut down of natural gas by Russia, the emissions are quite like the one that were in the year 2020. For the scenario 1 the emission values will be back to the 2020 levels, for scenario 2 it will be the best option to keep up the decarbonisation plans and aspirations of the EU. While scenario 3 will lead to the same level as it were before Russia cut the natural gas supply. Thus, to keep the decarbonisation going and to make EVs a decarbonising option, the electricity grid of every region must be powered by low carbon emission sources and replace the fossil-based sources. Otherwise, HEVs are potent technology that provides decent level of decarbonisation all around the world irrespective of the local electricity mix's carbon emission intensity.

4.3.3 Total cost of ownership

This part is a consequent result section of the Total cost of ownership methodology earlier in this chapter. The results obtained upon following the steps mentioned in the methodology section are discussed and presented here. To highlight the main findings this sub-section is divided into mainly three parts: Vehicle Cost, Cost of operation and total cost of ownership. Each of these parts are explained below in details highlighting the main findings.

a) Vehicle cost

This part presents the calculated cost for each of the three vehicle types in the six largest automotive markets, i.e., Brazil, China, Europe, India, Japan and USA. The cost of ICEV and EV is taken to be of a similar commercial vehicle sold in that country and then its distribution based on different components is calculated. These costs are then used to calculate the cost of the HEV based on the assumption and methodology discussed before in the previous section. These costs are shown below in the Figure 4–34 to highlight the cost distribution among different components considered for the overall vehicle cost.

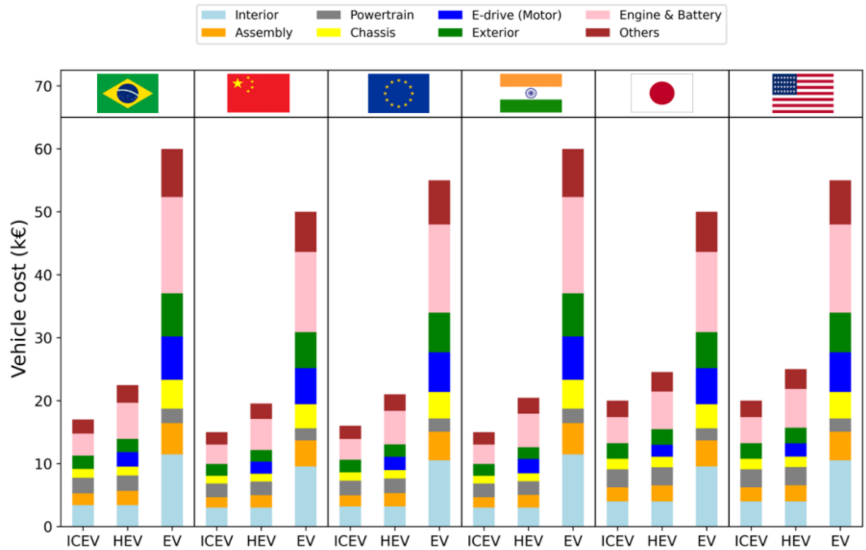


Figure 4–35: Vehicle purchase cost distribution in the six regions by components. (Adapted from [21]*)*

In the Figure 4–34 the cost of EVs in all the six regions is more than 2.5 times. The main reason associated with this is the cost of the large battery pack as shown in the pink colour. Also, the cost is variable and lowest for EVs in China and Japan. While it is maximum for the EVs in Brazil and India. This can be directly related to the presence of the EV manufacturing industry in these regions, since in China and Japan the EV manufacturing has already taken shape, in Brazil and India it is currently at a very initial stage. Thus, the industrial set up is also very much needed for the vehicle cost to come down or else most of the components must imported. The cost of the different vehicle types in the six markets is used later for the final total cost of ownership calculation.

b) Cost of operation

The cost of operation mainly represents the cost of the energy consumption needed during the use phase of the vehicle for its entire life cycle. This is calculated for all the six different regions by keeping in mind the variable cost of diesel and electricity in each of them, and by keeping into account the energy consumption for each vehicle type in the different regions. The variation in the energy consumption due to the different drive cycles considered is also an important factor for the variation in the energy cost within a region itself. Thus, Figure 4–36 below represents the variation in the cost of energy or fuel for six different global regions.

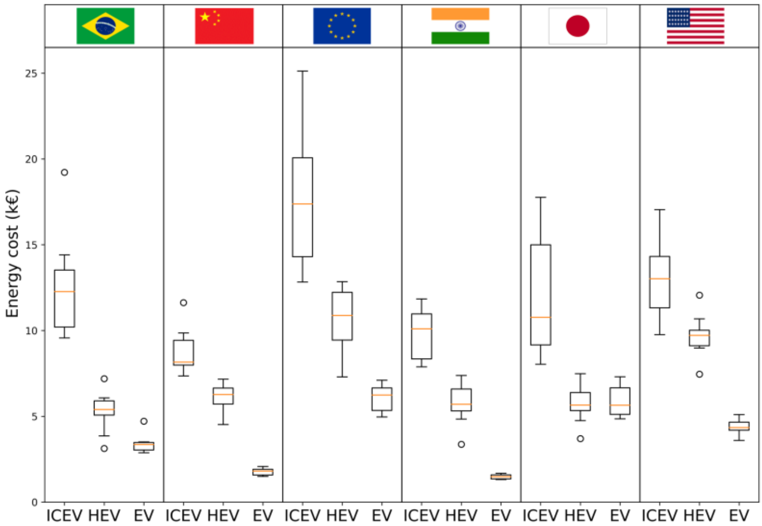


Figure 4–36: Energy cost variation in six different regions. (Adapted from [21]*)*

It can be seen in the Figure 4–36 above that the energy cost variation within each country too can be varying by a high margin. Also, it needs to be understood that the cost per unit for diesel and electricity varies a lot locally as well. Thus, it is important to see the effect of the electricity within a region as well. For this the evaluation is done considering the prices in EU, Germany and Sweden for different years before as well as after the effect of the on-going energy crisis there. These results can be seen in the Figure 4–37 below for the three different vehicle types with an average energy consumption value for the 10 European drive cycles evaluated earlier through 0D simulations.

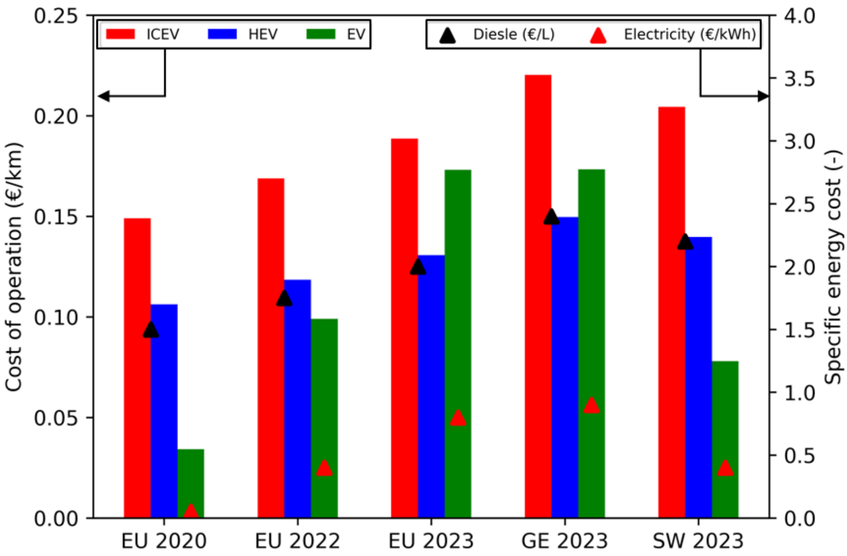


Figure 4–37: Cost of operation for different scenarios in Europe. (Adapted from [160]*)*

In the Figure 4–37 above the effect of the varied specific energy cost, i.e., in €/L for diesel and €/kWh for electricity, can be seen on the cost of operation for each vehicle type. It can be also observed that in the 2023 scenario for the average European case and German case, the cost of operation of the EV can be as high as that of the ICEV. In fact, the cost of operation of a HEV will be the most economical option. This makes one think how important the specific cost of energy is to make a choice about which vehicle type to use for a low cost of operation. Specially if the vehicle purchase cost is already very high like for the EVs. However, it must also be noted that the 2023 values used here for the specific energy cost are forecasted ones based on assumptions and thus are not the real current values that might be by the time this thesis is read. For this, a study is done to see the variability in the cost of operation for the three vehicle types while considering variation in the specific energy cost. This is shown in Figure 4–38 below to see the cost of operation of a vehicle type for different specific energy costs.

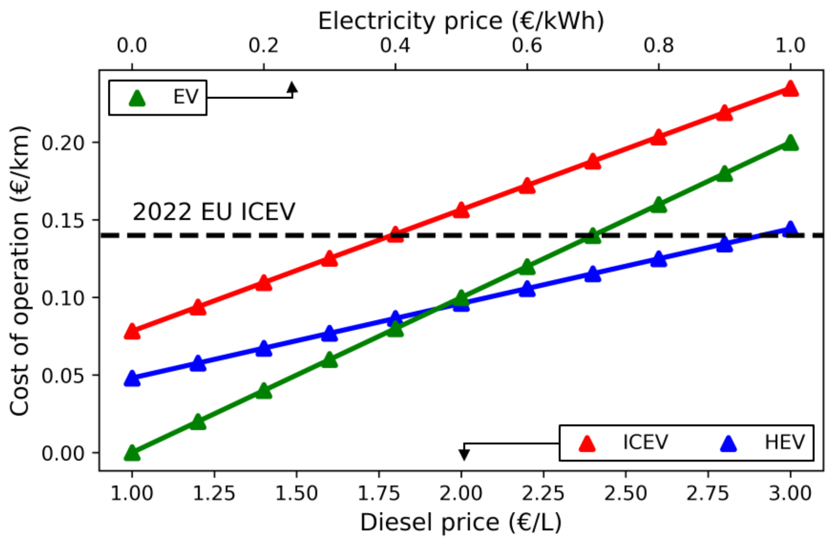


Figure 4–38: Variation in the cost of operation for variable specific energy cost. (Adapted from [160]*)*

In the Figure 4–38 above, the sensitivity of EVs is higher than ICEVs and HEVs to the specific energy cost, as even with a higher scale of 0.25 €/L compared to 0.2 €/kWh for EVs, the slope of EVs (in green) is the maximum. Further, it can also be noted that if the cost of electricity continues its trend towards the value of 1 €/kWh, it will lose the advantage of lower cost of operation than both HEVs and may even loose it with ICEVs. Thus, in current times when the cost of electricity in Europe is very high, EVs are not that beneficial in terms of its low cost of operation as it was in the year 2020.

c) Total cost of ownership

This part shows the final total cost of ownership values obtained by keeping into account all the associated costs linked to it, as mentioned previously in the methodology section. All the costs are used specific to each vehicle type and the location where it is bought and used. The results obtained for the six largest global markets are shown below in Figure 4–39, with the distribution of costs based on the types considered in this study.

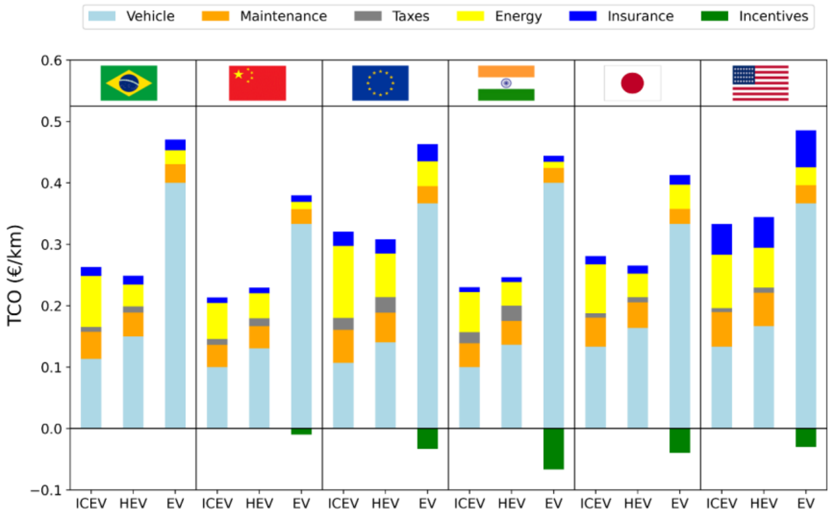


Figure 4–39: Total cost of ownership distribution by different costs considered for the six different regions. (Adapted from [21]*)*

In the Figure 4–39 above the total cost of ownership can be seen as a sum of all the associated costs for its calculation. The incentives offered for the EVs in each region is mentioned in green as a negative value as it will be reduced from the total cost of ownership calculated. In Brazil there is no incentives offered for the EVs and only it is tax free currently which makes it suer expensive currently in the Brazilian market. Whereas, in regions like China, US, EU, Japan and India, although it is still the most expensive option, due to the incentives offered it is marginally reduced. In India due to the lower specific energy cost and high incentives (for 90kWh battery pack), despite high vehicle purchase cost, the TCO is comparable to that in China and Japan. Moreover, in the results above the average European electricity price of 2020 is used which has changed a lot by the time the thesis is written. Thus, it is also important here to mention the effect on the TCO with variation in the specific energy cost for Europe and within

Europe as obtained for the European energy crisis evaluation. This can be seen below in the Figure 4–40.

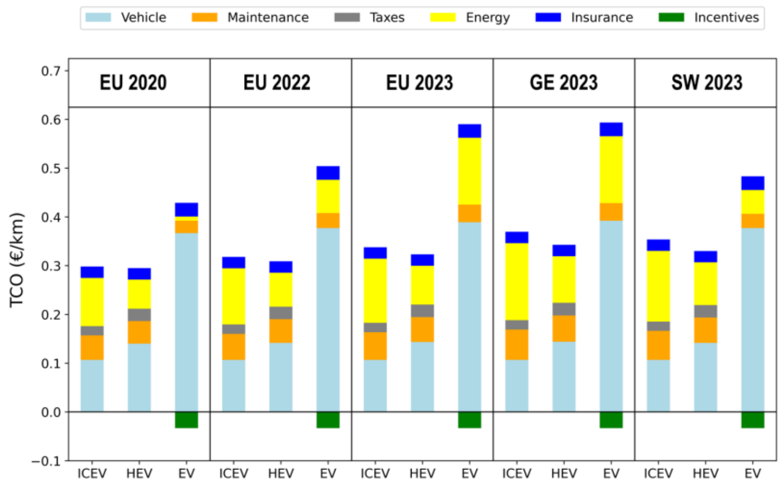


Figure 4–40: Total cost of ownership for the different European scenarios. (Adapted from [160]*)*

It can be observed in the Figure 4–40 above that the TCO of EVs will keep on increasing for the future years unless the cost of electricity is brought back to the 2020 levels. Further, it is important to note that the HEVs will always be a cost saving option irrespective of the specific energy cost due to its better energy consumption values than an ICEV. Although the vehicle purchase cost of the HEVs is higher than the ICEVs too, due to the saving in the cost of operation it offsets it and becomes the cheapest option in terms of TCO. This can be seen in the Figure 4–41 below.

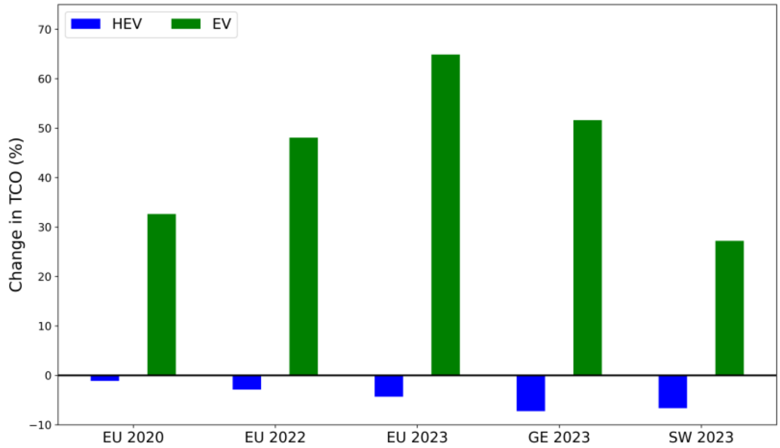


Figure 4–41: Difference in the TCO for HEVs and EVs as compared to ICEV. (Adapted from [160]*)*

The Figure 4–41 above shows the effect of electricity price increase for future scenarios on the increase in its TCO as compared to an ICEV. Moreover, it is also observed that the HEV is always a cheaper option even when compared to the ICEV. This is due to the lower cost of operation of HEVs as shown in the previous part, where it was to be the cheapest option in each region and within Europe for the different scenarios. It is important to understand that although both HEVs and EVs are expensive in terms of vehicle purchase cost, the HEVs offset it quite quickly due to better energy consumption and as the difference is not much. On the other hand, although EVs are very energy efficient even than HEVs, due to the vast difference in the vehicle purchase cost it is not able to offset the TCO at the end of a 10-year life cycle in any of the six regions evaluated for this study. This is shown in the Figure 4–42 below with more details.

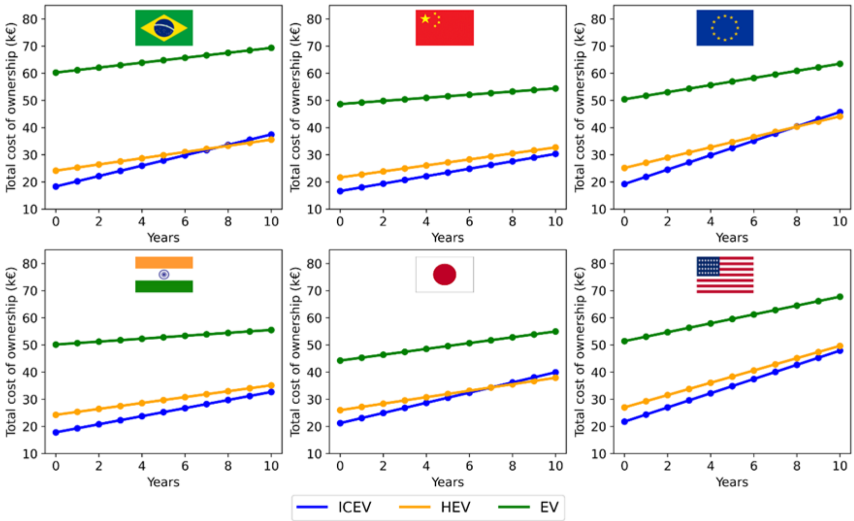


Figure 4–42: TCO evolution for 10-year life cycle in the six regions. (Adapted from [21]*)*

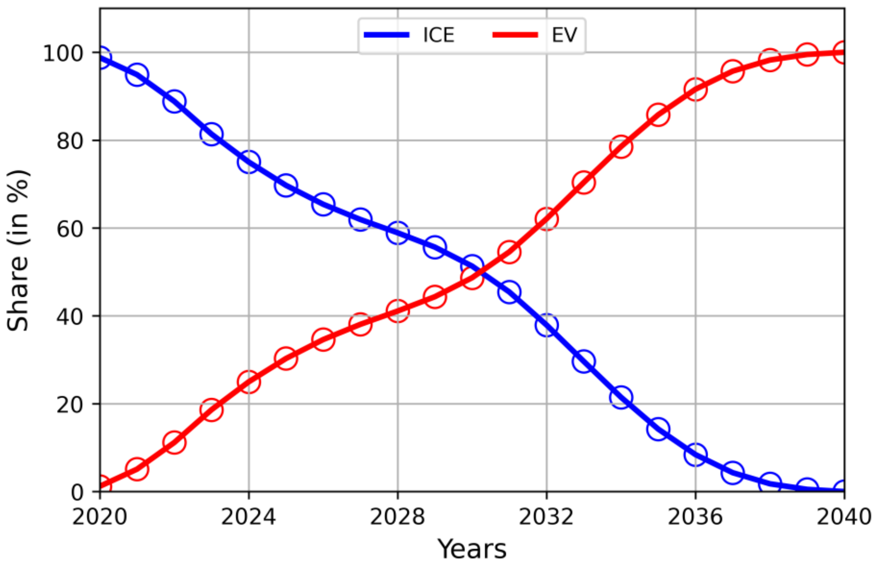
In the Figure 4–42 above the evolution of the TCO is shown for each of the evaluated regions. While the HEVs becomes cheaper or at least comparable than ICEVs at the end of the 10-year life cycle, the EVs remains to be the most expensive. In fact, in Brazil, where no incentives are offered, the gap is very big and can't be filled with an incentive offered as high as in India. In countries like India, China and Japan the slope for the EV (in green) is not very high due to the low cost of operation attributed to the low cost of electricity there. But for US and EU the slope is very big which shows the effect of high electricity cost in those regions. Hence, the TCO are dependent on several key factors including Vehicle cost, energy consumption, specific energy cost and incentives or government subsidies (like no taxes) offered in the market.

4.3.4 Fleet Assessment

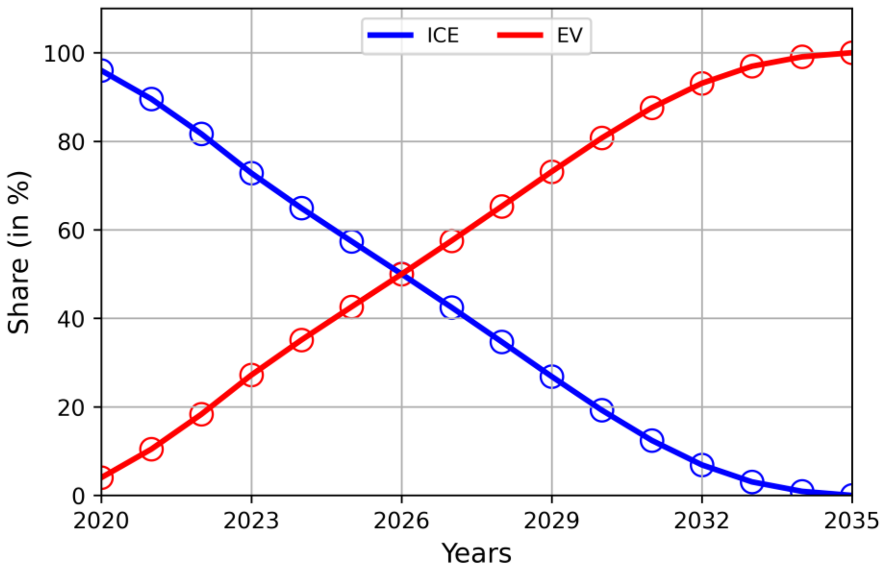
This final sub-section of the results section shows the effect of using EVs and e-fuelled ICEs and HEVs for the decarbonisation of the vehicle fleet. The focus is on the European and the US automotive fleet as that is where the target of 100% EV sales is being considered. For this assessment the fleet distribution for the future years is first calculated by keeping into account the targets of EV sales to be imposed in these two automotive markets. Later, for the calculated fleet distribution, the decarbonisation potential of EVs is compared with e-fuels use on a well-to-tank and life cycle basis, for the same vehicle fleet distribution. The results are shown below in two different parts: Fleet distribution and Fleet emissions.

a) Fleet distribution

As mentioned in the methodology section earlier, the vehicle fleet distribution for ICEV and EV is done using Weibull functions for both EU and US separately. The target for EU is to reach 100% EV sales by 2035, while for US it is to reach 100% EV sales by 2040 and an intermediate target of 50% EV sales by the end of 2030. Keeping these targets in mind the distribution of vehicle sales for the two regions is calculated considering the annual vehicle sales. Thus, the current vehicle sale percentage for EVs is considered for each of the region and accordingly the forecast is made for the future years for each of them using the Weibull functions as mentioned in the methodology section. The Figure 4–43 below shows the distribution of vehicle sales obtained for ICEVs and EVs in both US and EU for the future years till the vehicle sales of 100% EVs is not reached.


ICE
EV
100
80
60
40
20
0
Share (in %)
2020
2024
2028
2032
2036
2040
Years

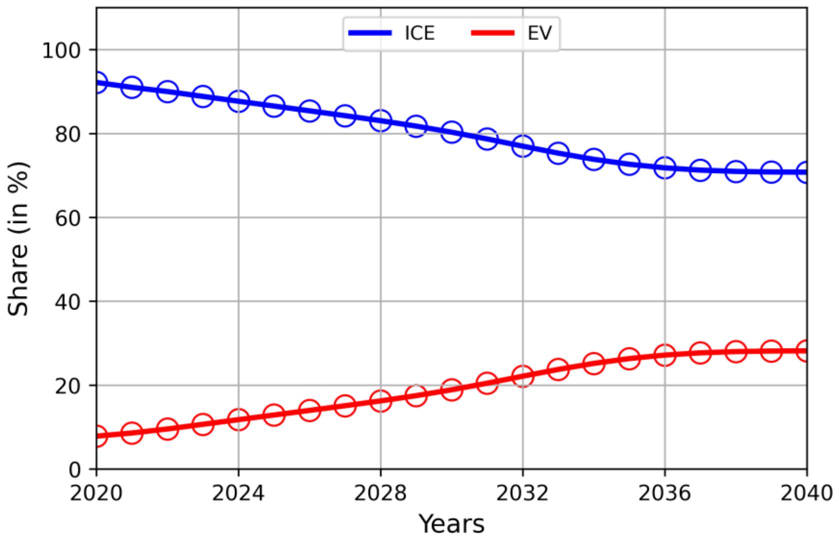
(a)



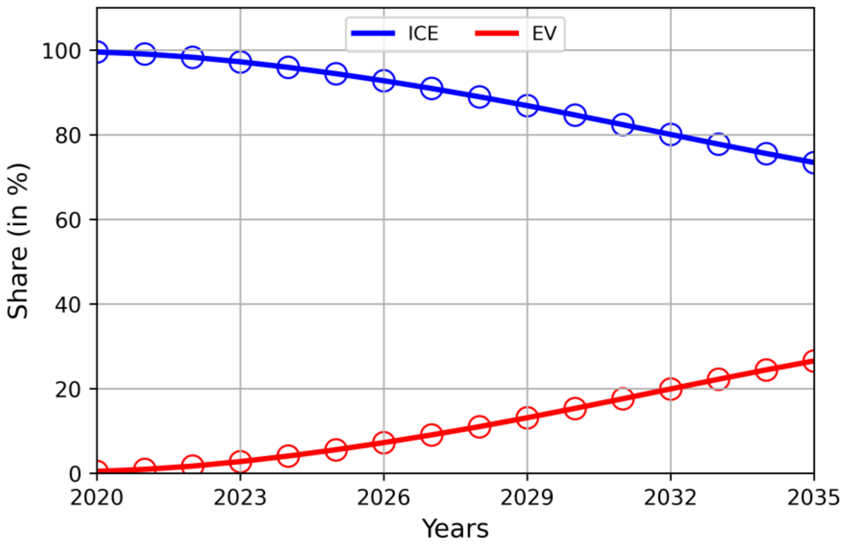
(b)

Figure 4–43: Change in the vehicle sales in the (a) US and (b) EU. (Adapted from [159]*)*

In the Figure 4–43 above the annual sales distribution of the new vehicles are shown, and it can be observed that in EU the share of EV sales needs to go higher very quickly. In fact, by 2023, at the time of writing this thesis, the share should be of about 30% but it is still below 20%. This shows how challenging it could be to reach the target levels needed to have 100% EV sales by 2035. Moreover, it is important to understand that even if a 100% EV sales target is achieved, it doesn't mean at all that the entire vehicle fleet in that region is made up of electric vehicles. There will be still a majority of vehicles in the fleet will still be of ICEVs despite having 100% EV sales. To understand this Figure 4–44 below shows the share of EVs and ICEVs in the total vehicle fleet of the US and EU.


ICE
EV
100
80
60
40
20
0
Share (in %)
2020
2024
2028
2032
2036
2040
Years

(a)



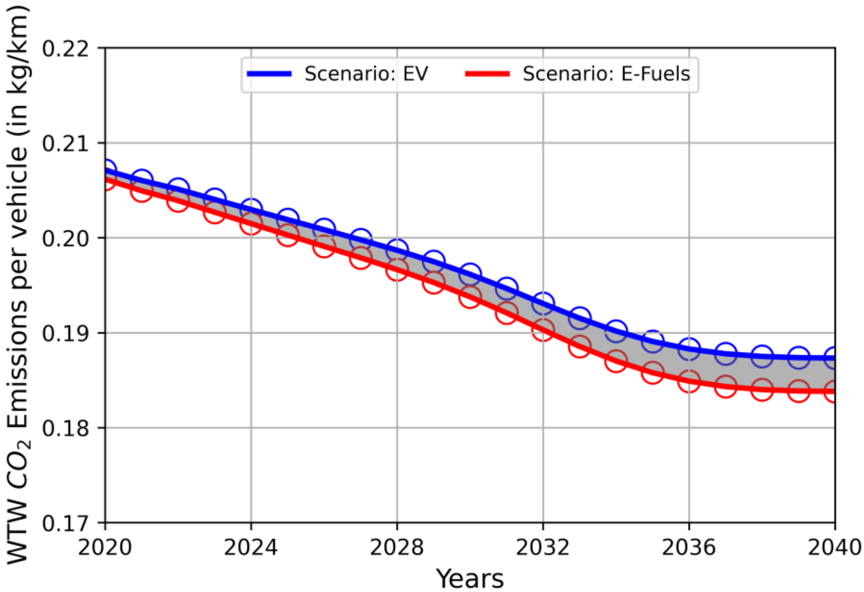
(b)

Figure 4–44: Change in the total vehicle fleet in (a) US and (b) EU. (Adapted from [159]*)*

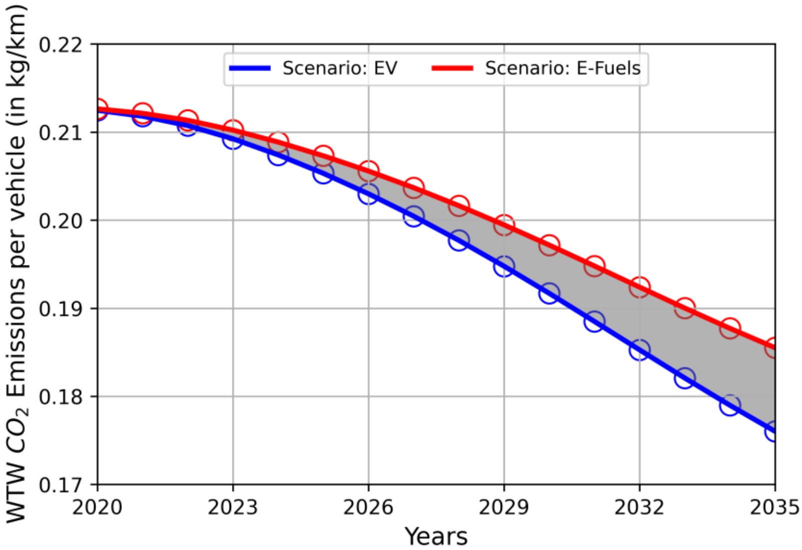
It can be seen in the Figure 4–44 above that in the total vehicle fleet the share of EVs still be relatively small than the ICEVs. This should help one to realise that despite having 100% EV sales in these future years there will still be a large amount of ICEVs running on the road and will be having tailpipe emissions which may not be in-line with the initial intention to reduce the tailpipe emissions of the total vehicle fleet. Thus, an alternative solution needs to be investigated to reduce the emissions coming out from the ICEVs that will be running on the roads in the future years even after the sales of 100% EVs is met.

b) Fleet emissions

To understand the effect of the fleet emissions with the variation in the fleet distribution as shown in the previous part a comparative study is done for EVs and using e-fuels. On the other hand, although e-fuels does have tailpipe emissions, it has negative well-to-tank emissions as it is made from carbon capture systems which takes the CO_2 from the atmosphere and combines it with renewably produced hydrogen. Moreover, it needs to be understood that the environment is affected by the total emissions and not just tailpipe emissions. Thus, in the Figure 4–45 below the total effect on the well-to-wheel emissions of the average fleet is shown below per vehicle in the US and EU.



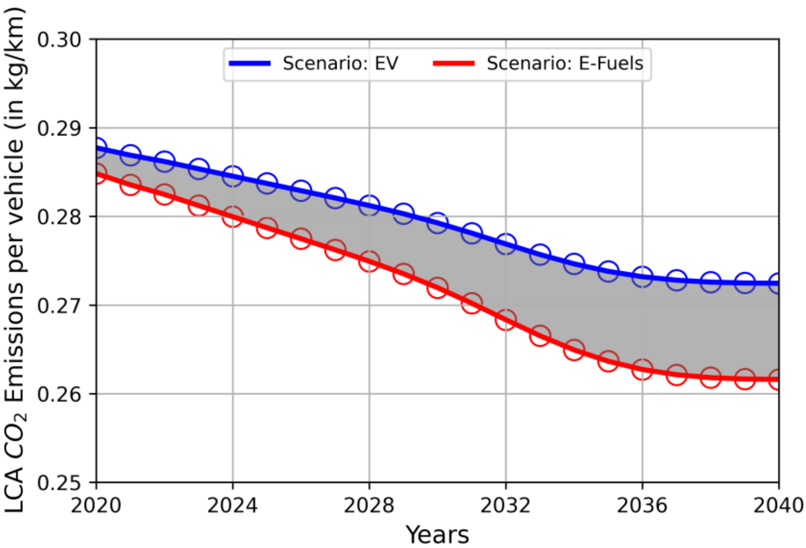
(a)



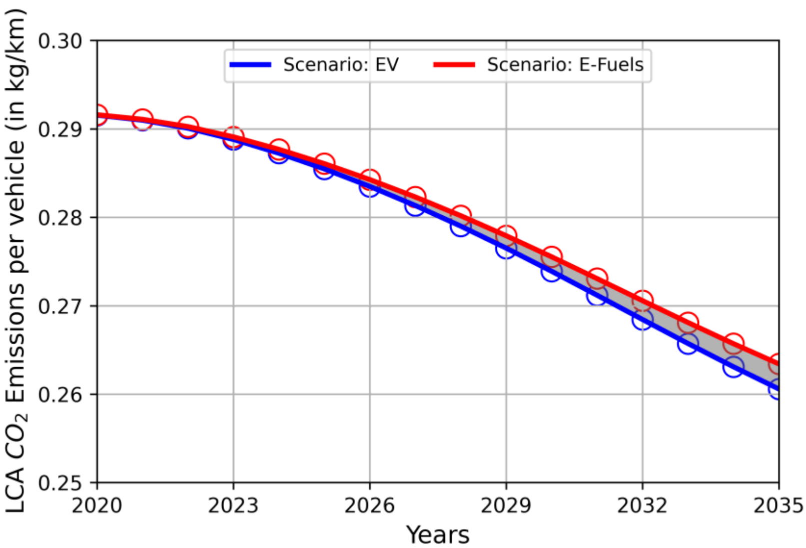
(b)

Figure 4–45: Change in the average WTW fleet emissions per vehicle in (a) US and (b) EU. (Adapted from [159]*)*

In the Figure 4–45 above, in the US, using e-fuels is a more efficient way to reduce the emissions while in the EU, EVs are more efficient way for emission reduction. This is mainly due to the cleaner average electricity mix in the Europe compared to the average electricity mix in the US. Thus, it can be said that with cleaner electricity in the future, the e-fuels can become less efficient option in decarbonising the fleet as the WTW results of emission results shows that since 2030 itself. However, this will only be the case on a WTW basis, but for the overall life cycle basis the results will be different. When considering the higher embedded emissions of the EVs compared to the ICEVs and HEVs, mainly due to the battery emissions, the impact on the life cycle emission reduction for the total fleet can vary significantly. This variation can be seen below in Figure 4–46 for the US as well as EU.


Scenario: EV
Scenario: E-Fuels
LCA CO_2 Emissions per vehicle (in kg/km)
0.30
0.29
0.28
0.27
0.26
0.25
2020
2024
2028
2032
2036
2040
Years

(a)


Scenario: EV
Scenario: E-Fuels
LCA CO_2 Emissions per vehicle (in kg/km)
0.30
0.29
0.28
0.27
0.26
0.25
2020
2023
2026
2029
2032
2035
Years

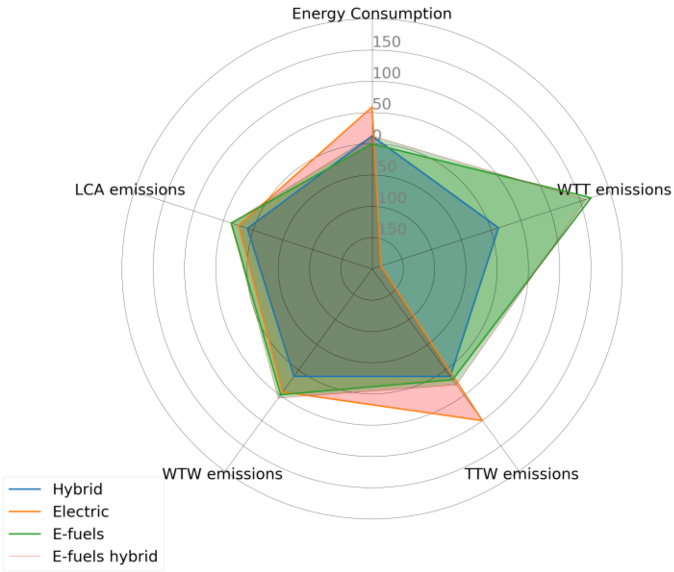
(b)

Figure 4–46: Change in the average fleet life cycle emissions per vehicle for (a) US and (b) EU. (Adapted from [159])

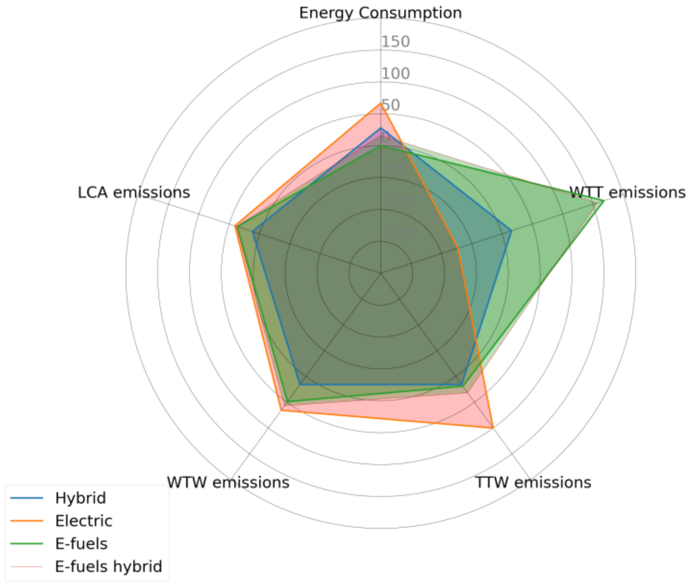
In the Figure 4–46 above, the trend has changed for the life cycle emissions in both the regions when compared to the one for WTW emissions. The gap between the average fleet emissions per vehicle has increased between the EVs and e-fuelled ICEVs in the US while the gap in EU has reduced. The reason is that due to the added higher embedded emissions of the EVs, the e-fuels becomes more potential option for life cycle emission reduction in the US. While in EU, EVs becomes equivalent to the e-fuels for their life cycle emission reduction potential. In the calculation above for e-fuels the manufacturing and other embedded emissions are also considered. However, as they can be a drop-in solution, the embedded emissions may be also ignored considering that it is used in the same old vehicle. But to address the EV sales increase issue the results are compared for a case when a new EV is bought with a case when a new ICEV powered with e-fuel is bought as the demand in new vehicle sales is supposed to be constant.

4.4 Summary and Conclusions

In this chapter a detailed performance of the different vehicle types is done on real drive cycles for a real-world assessment using 0D simulations. The 0D simulation results, mainly the energy consumption, is then used to do the well-to-wheel analysis by calculating the WTT and TTW emissions for each vehicle type. Further, the life cycle emission analysis is done keeping into account the embedded emissions of each vehicle type during the manufacturing, maintenance, and end-of-life phases. This life cycle emission calculations are done for six largest automotive markets. However, the use of e-fuels is only considered in US and EU as the target of 100% EV sales are imposed only in these two regions and thus it was realised that investigating an alternative option is important for both these regions. The summary of results obtained from the 0D simulations, and the life cycle emission calculations is shown below in Figure 4–47 for the US and EU.



(a)



(b)

Figure 4–47: Summary of the life cycle emission results as a % difference from ICEV results in the (a) US and (b) EU. (Adapted from [159]*)*

Complementing the emission part, the life cycle costing or the total cost of ownership calculation is also done in each of the six largest automotive markets. The EVs are found to be the most expensive vehicle type in all the six markets, although it is the most decarbonising option in countries like, Brazil, EU and US, where the electricity grid is relatively clean. The specific energy cost in each of the market is a big factor in the total cost of ownership and thus the local factors play a very important role in the practicality of any vehicle type being adopted. Main parameters effecting can be energy consumption, electricity mix, electricity cost, etc. To understand which vehicle type is better in a techno-economic way, Figure 4–48 below is shown for the six different markets.

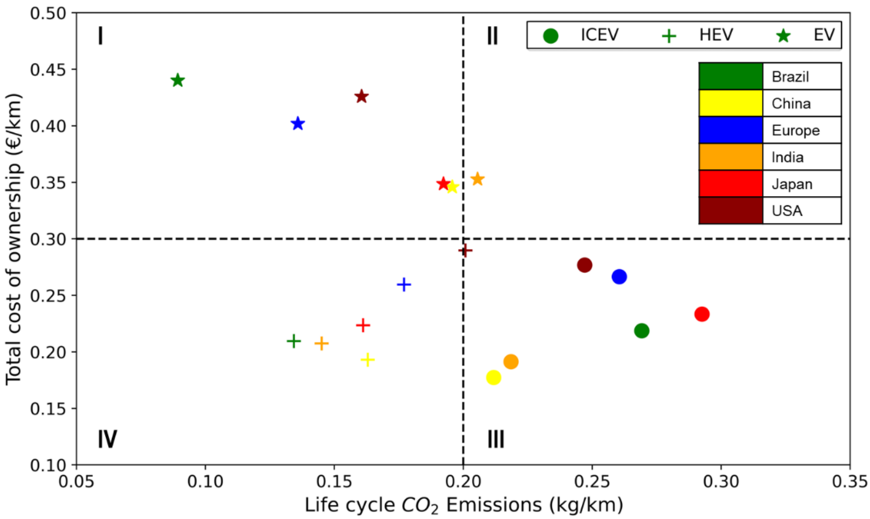


Figure 4–48: Life cycle emissions vs TCO for ICEV, HEV and EV in six different regions. (Adapted from [21]*)*

The Figure 4–48 above shows four different quadrants labelled from I to IV, where quadrant IV is where the cheapest and most decarbonising options are present while in quadrant II the most emitting and costliest option is present. The HEVs for all the six regions comes in quadrant IV, which is a clear representative that hybrid vehicles are the most economical way to decarbonise the light duty sector while being the cheapest as well. The EVs though can be even higher decarbonising solutions, in some regions, its high TCO values can be a big cause of its restricted market penetration. A fleet analysis is also done at the end for US and EU alone to see what the effect on the average fleet emissions per vehicle will be, even if the future sales target for EVs are met. The results are compared with new EV sales with new ICEV sales powered with e-fuel to see which option has more decarbonisation potential. It was found that while EVs can be a better option in EU in terms of WTW basis, on a life cycle basis it will lose the advantage and will be like that of using e-fuel ICEV. For the US, due to relatively carbon intensive electricity mix, e-fuels are a better option in terms of WTW basis and life cycle basis.

Chapter 5

Heavy duty vehicles

Content

5.1 Introduction

The heavy-duty vehicle segment are the backbone of the Transportation sector as it is a part of every industry supporting transport related activities. This includes Class 7 and 8 type of vehicles that helps in transportation of large number of passengers and heavy goods. However, it is the second largest contributor of transportation sector's emissions by about more than 30%.[179] Thus, it is very much important to find solutions to decarbonise this too, after the light duty vehicle segment. As described in the first chapter the focus of this research is on the urban road transportation, the vehicle type mainly considered for this are buses. The city buses operated by different public or private companies for mass public transit can be running in different conditions.[180] These conditions can be:

I. Traffic congestion
II. Bus size
III. Passenger capacity
IV. Road quality

Each of the above parameters will affect the speed at which the vehicle has been running and in turn the powertrain efficiency leading ultimately to the energy consumption. Hence, the real drive assessment is very important for this sector and especially for buses to have the real energy consumption values. By using the real-world energy consumption, the life cycle assessment of these vehicles can be done to see the life cycle GHG emission intensity of each vehicle in different driving conditions to understand the variation possible.[181] Accordingly, the right solution can be adopted by keeping in mind the use case parameters while operating in urban road conditions around the world.

This Chapter is based on the same approach, starting by explaining the numerical model developed for the different buses, the different fuel and powertrain options considered, with its evaluation on real drive cycles.

Next, the life cycle assessment is discussed by focussing each of the life cycle phases of the buses, i.e., Manufacturing, Use, Maintenance, and End-of-Life.[182] Further, the cost analysis is done considering the CAPEX and OPEX for each of the evaluated powertrain technology. Finally, fleet assessment is done to assess which of the technology can be the most efficient in terms of both emission reduction as well as cost effectiveness.[153] The analysis was done for the four largest Spanish cities (Madrid, Barcelona, Valencia and Sevilla) due to the familiarity of the authors with the city's bus transit system and availability of fleet data. The corresponding results are then presented with discussions to back the main findings of the research.

5.2 Methodology

This section highlights the methodology followed in this chapter to obtain the results and conclusions for the techno-economic analysis performed for Buses. This includes the 0D vehicle modelling for the different bus types, the life cycle assessment methodology, the approach used for the cost analysis and finally the fleet assessment performed for the bus transit fleet of Valencia. The subsequent sections will explain each of them in more detail for a clear understanding.

5.2.1. 0D Modelling

As mentioned previously, just as in case of light duty vehicles, the 0D modelling of the buses are done using the GT Suite software too. This starts with the selection of different bus models which are most used in the fleet of buses ran by the public bus transit companies of Madrid, Barcelona, Valencia and Sevilla and on the different fuels and powertrain technologies considered for the bus's operation in these cities. And then the bus routes were selected for which the real drive cycle data were used for the overall energy consumption of each bus type.

a) Vehicle types

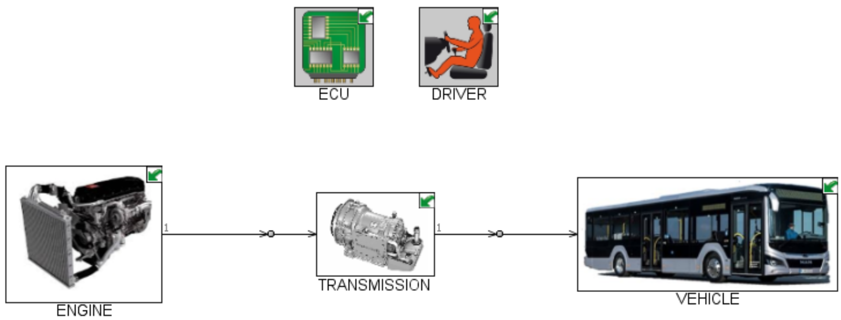
Overall, five different bus models were chosen as the most used ones in the 4 cities which includes three standard 12m city buses but also two articulated 18m buses. The equivalent 0-D model were made for each of them using the GT suite package by means of the details and vehicle specification of each of the components associated with each different bus type. The main specifications considered for the five evaluated buses to develop the 0D vehicle model are presented in Table 5–1.

Table 5–1: Specifications for the different Bus types. (Adapted from [153])

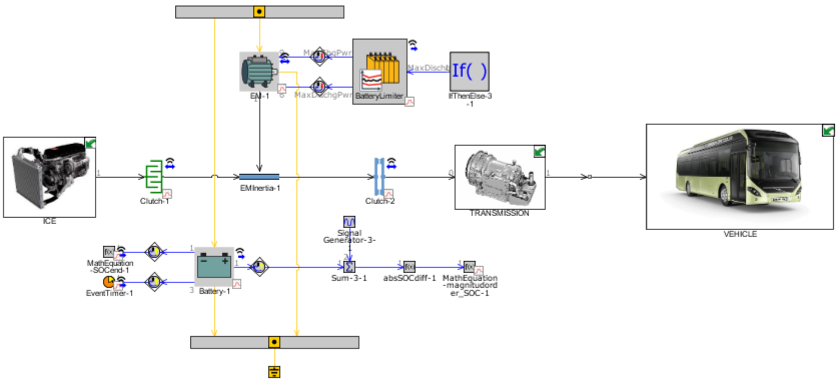
Parameter	Diesel (DB)	Hybrid (HB)	Electric (EB)	Articulated Diesel (AD)	Articulated Hybrid (AH)
Bus					
Model Name	MAN Lion's City G	Volvo 7900 Hybrid	BYD 12m eBus	MAN Lion's City G	Volvo 7900 Hybrid
Engine Type	D1556 LOH, Euro6	Volvo D5K 240, Euro6	Electric	D2066 LUH Euro6	Volvo D5K 240, Euro6
Passenger Capacity	83 & 110	95 & 120	80 & 100	136	150
Gross Weight (kg)	19000	19500	19500	28000	29000
Rated Power - Engine/Motor (kW)	265/0	180/150	0/150x2	265	180/150

Maximum Torque – Engine/Motor (Nm)	1600/0	918/1200	0/550x2	1250/0	918/1200
Battery Capacity (kWh)	-	8.9	348	-	8.9
Length (mm)	12185	12000	12200	17980	18134
Width (mm)	2550	2550	2550	2500	2550
Height (mm)	3060	3280	3370	2880	3280

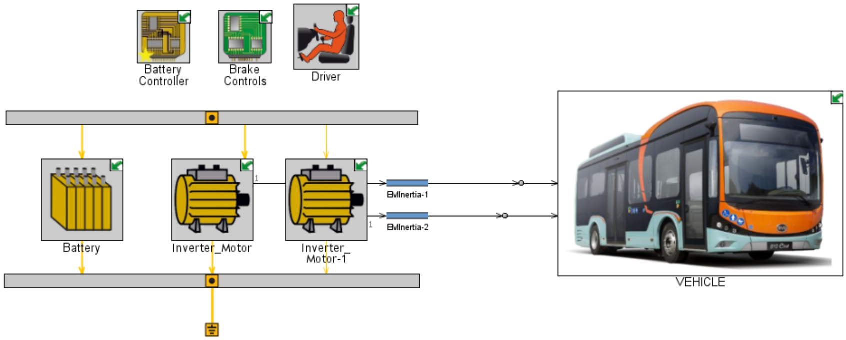
Based on Table 5–1, the 0D models were made and validated with its evaluation on homologation cycles to match the fuel consumption values as reported officially by the vehicle manufacturer.[183–186] The 0D models were made for each of the vehicle types as shown below in Figure 5–1, including the Standard diesel, Standard P2 hybrid, Standard Electric, Articulated Diesel and Articulated P2 Hybrid bus models.



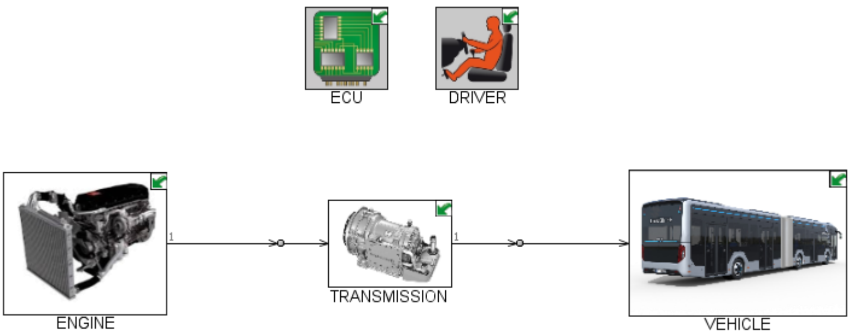
(i)


EM-1
BatteryLimiter
IfThenElse-3-1
ICE
Clutch-1
EMInertia-1
Clutch-2
TRANSMISSION
VEHICLE
Signal Generator-3-
MathEquation-SOCend-1
EventTimer-1
Battery-1
Sum-3-1
absSOCdiff-1
MathEquation-magnitudorder_SOC-1

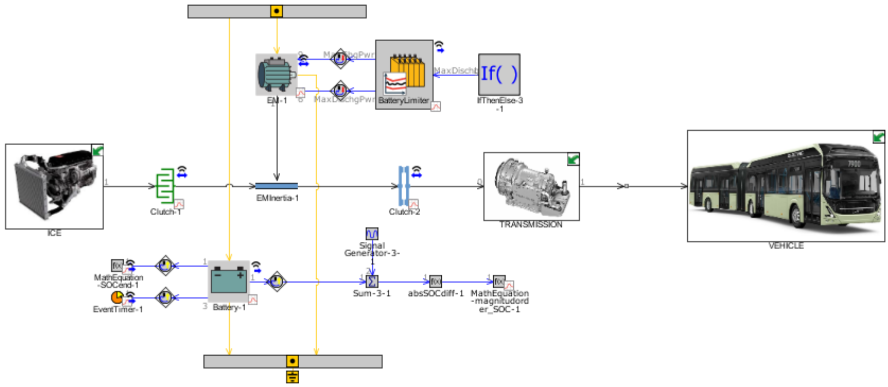
(ii)


Battery Controller
Brake Controls
Driver
Battery
Inverter_Motor
Inverter_Motor-1
EMInertia-1
EMInertia-2
VEHICLE

(iii)


ECU
DRIVER
ENGINE
TRANSMISSION
VEHICLE

(iv)



(v)

Figure 5–1: 0D vehicle models developed using the GT Suite package for (i) Standard 12m Diesel, (ii) Standard 12m P2 Hybrid, (iii) Standard 12m Electric, (iv) Articulated 18m Diesel and (v) Articulated 18m Hybrid Buses. (Adapted from [153]*)*

b) Powertrain types

For the overall evaluation of buses different powertrain configurations are considered, including the conventional diesel configuration, P2 hybrid configuration, full electric configuration but also the synthetic drop-in e-fuel, oxymethylene-dimethyl-ethers (OMEx) for the ICE based configurations. Thus, this study overall considers two additional powertrain configurations as e-fuelled Conventional bus and e-fuelled P2 hybrid bus. Also, the electricity mix considered for the use in electric buses is the average European 2019 mix but also the future scenario for 2030 and 2050. Therefore, for this study, five different types of fuels are considered, diesel and OMEx for the ICE and P2 hybrid buses, and average European electricity mix of 2019, 2030 and 2050 for the full electric bus. The main properties of the five fuels are summarised in Table 5–2.

Table 5–2: Properties of different fuels considered for the evaluation. (Adapted from [153])

Parameters	Diesel	OMEx	Electricity	Electricity 2030	Electricity 2050
Lower Heating Value (MJ/Kg)	42.5	19.8	-	-	-
Density (kg/m3) @ 15 °C	850	1050	-	-	-
Viscosity (mm2/s) @ 40 °C					
Cetane number	55.7	72.9	-	-	-
TTW CO_2 emission potential (kg CO_2/ kg of diesel)	3.2	2.47	0	0	0
WTT CO_2 emission potential (g CO_2/ kg of diesel)	0.79	-0.53	3.99	3.39	1.11

Hence, it can be said that nine different bus transport technologies are considered for this evaluation. The Table 5–3 summarises the total eleven technologies evaluated in this study by highlighting the bus type, powertrain configuration and the fuel used.

Table 5–3: List of different types of bus powertrain technologies considered for the evaluation.

Size	Powertrain	Fuel
Standard (12m)	Conventional	Diesel
		OMEx
	Hybrid	Diesel
		OMEx
	Electric	EU 2019
		EU 2030
		EU 2050
Articulated (18m)	Conventional	Diesel
		OMEx
	Hybrid	Diesel
		OMEx

The eleven different bus technologies are evaluated for a wide spectrum of results to have a comparison of which is the best option depending on the use case.

c) Drive cycles

As mentioned earlier, the evaluation of the buses is done for the four largest cities of Spain. This is considered as these cities have the maximum population and usage of the bus transit systems. Thus, the emissions from these cities are the highest and it is very much needed to look for decarbonisation options to address the issue of urban road transportation. In this sense, the ten most used bus lines of each of the four cities are taken for the evaluation. These bus routes ID are mentioned below with its scheduled number of stops and covered distance in Table 5–4 for the four Spanish cities by also mentioning the Bus transit company of each city.

Table 5–4: Details of the bus routes selected in Madrid, Barcelona, Valencia and Sevilla for this study. (Adapted from [182]*)*

S. No.	Madrid (EMT)[187]			Barcelona (TUSGSAL)[188]			Valencia (EMT)[189]			Sevilla (TUSSAM)[190]		
	ID	Stop	Distance (km)	ID	Stop	Distance (km)	ID	Stop	Distance (km)	ID	Stop	Distance (km)
1	34	41	12.74	B4	39	11.5	9	25	8.92	2	27	10.57
2	27	27	7.86	B12	8	8.4	10	26	7.5	27	27	10.21
3	70	29	10.16	B14	32	8.5	19	28	8.33	32	22	7.13
4	C11	32	11.7	B18	13	5.83	70	32	9.16	C2	21	10.53
5	C2	30	8.97	B20	46	13.74	89	22	5.76	C1	19	8.32
6	21	35	10.05	B21	17	6.2	90	19	5.36	13	22	7.05
7	31	27	8.25	B25	40	13.5	92	39	11.42	LE	9	9.94
8	28	30	9.36	B34	32	10.33	93	28	10.3	LN	11	8.46
9	35	39	13.42	M6	18	6.93	95	39	12.77	EA	11	14.76
10	38	34	11.03	N5	25	7.46	99	43	15.4	5	28	11.32

The Table 5–4 shows the range of different bus routes considered in this evaluation among the four Spanish cities. The variation occurs in the number of stops from 8 to 46, while the variation in the distance is observed from 5.36 to 14.76 kilometres. The velocity-time evolution for each of these bus routes were calculated by using GT RealDrive©, ProfileGPS feature where the data from GPS were obtained. This is done by considering a given line and designing their corresponding individual drive cycles (n-1), where n is the total number of stops (n). For example, a line with 3 stops (A, B, C) will have 2 GT RealDrive© cycles, A to B and B to C. Also, to have a real like scenario, a gap of 15 seconds is added between each stop as a stop condition for passenger loading/unloading, using a MATLAB® code. This is done for every bus stop according to the number of stops involved in each specific bus route. The drive cycle data obtained from this methodology was validated by the data provided by TUSGSAL during a similar project done for Barcelona and it matched quite well. Hence, the same process is used for this research to carry techno-economic assessments. The process is explained pictorially below in Figure 5–2 by taking the example of Line 10 of Valencia and M6 of Barcelona.

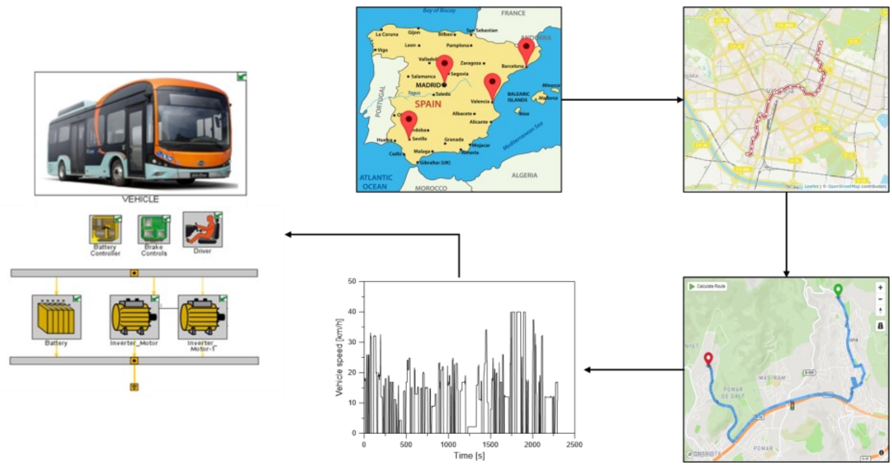


Figure 5–2: GPS based information obtained for the different bus routes in a step-by-step process for the bus transit network in the four largest cities of Spain. (Adapted from [182]*)*

As shown in the Figure 5–2, it is very interesting to see the response of the different buses on these routes for the energy consumption values and consecutively the GHG emissions. Therefore, this study is carried out by running the 0D vehicle models on these drive cycles in a two-step process. Firstly, the three standard bus models with conventional, hybrid and electric powertrain is evaluated in all the 30 routes to evaluate the performance of these technologies for its life cycle GHG emission potential. For this first step, only diesel fuel is used for the conventional and hybrid bus while for the electric bus, average European electricity mix of 2019, 2030 and 2050 are used.[182] This is done to understand the average possible emission reduction by hybrid buses and electric buses in the current as well as future scenarios. In the next step a dedicated fleet assessment is done for Valencia by considering the total number of buses operated by EMT Valencia © and the types of buses operated in each of the bus routes.[153] All the eleven bus options as mentioned in Table 5–4 are evaluated for this study to estimate the best possible case for each bus line. The optimisation of the bus fleet is done to explore different pathways to meet future emission reduction targets. The results of both these studies are presented later.

5.2.2. Life cycle assessment

This section highlights the main parameters and assumptions considered for the life cycle assessment of GHG emissions from the different bus powertrain technologies. The section is divided into each phase of the life cycle to explain the calculation methodology phase-by-phase for easy understanding and stating the flow of the evaluation. The life cycle kilometres for each bus type are taken to be 800,000 kms and emissions from each phase is calculated by keeping that in mind.[191] The following sub-section addresses each phase.

a) Manufacturing

The manufacturing or the production phase of the buses is also referred to as the Cradle-to-Gate phase that includes all the emissions coming from the raw material extraction phase to the final product delivery to the customer. For the evaluation of buses this is done in a simple step by step approach as explained below.

1. Obtaining the weight distribution of the vehicle type by different components as considered in the life cycle model in the GREET software.[151]
2. Calculating the weight of each component using the weight distribution and the gross weight (excluding battery) of the bus models.
3. Multiplying the weight of each component with its corresponding GHG emission footprint.
4. The total emissions for the manufacturing phase are then calculated by adding all the emissions of each component.

The weight distribution for different powertrains as considered for different vehicles in GREET is shown below in Table 5–5 and the manufacturing phase emissions are calculated using the same. The terms DB, AD, HB, AD and EB represents standard diesel, articulated diesel, standard hybrid, articulated hybrid and full electric bus respectively.

Table 5–5: Weight distribution and emission footprint of the different bus components as used in this study. (Adapted from [192]*)*

Part	Weight distribution (%)			GHG footprint (kg/kg)		
	DB & AD	HB & AH	EB	DB & AD	HB & AH	EB
Chassis	34.9	34.7	39.1	2.59	2.59	2.59
Powertrain	10.5	10.3	0	2.81	2.81	0
Transmission	3.3	3.3	1.6	2.28	2.28	2.28
Body	11.6	11.6	12.9	3.76	3.76	3.76
Power Electronics	0	0.1	0.3	0	3.04	3.06
Motor/Generator	0	0.6	2.4	0	3.31	3.3

The Table 5–5 also shows the different components considered for each bus type and the corresponding GHG emission footprint of each in the unit kg CO_2 equivalent per kg of the component. While the total gross weight of the buses is mentioned already in the Table 5–1. Further, the battery emissions are calculated by considering details of the different battery technologies considered for the hybrid buses and the electric buses and is tabulated separately in Table 5–6.

Table 5–6: Different properties of the battery types used in the different bus models.

Parameters	Standard		Articulated
Powertrain	Hybrid	Electric	Hybrid
Chemistry	NMC	LFP	NMC
Energy density	150	100	150
Weight	120	3200	120
GHG footprint (kg/kg)	58.84	42.13	58.84

The GHG emission footprint of the battery includes the emissions coming from different processes of cradle-to-gate phase of the battery, battery management system and battery pack assembling process. The footprint is simply multiplied by the weight of the battery just as done for all other components of the vehicle. Thus, using these values the total Manufacturing phase emissions were calculated using equation 5.1 shown below.

$$CO_{2\,M} = \sum(F_{comp}) * (W_{comp}) \quad (5.1)$$

b) Use

The use phase emissions are calculated with the Well-to-Wheel approach as explained in the Chapter 3. The energy consumption is obtained from the 0D simulation results obtained for each bus type in the different bus routes. With this energy consumption, the Well-to-Tank phase emissions are calculated for the fuel consumption and electricity consumption depending on the type of bus powertrain. This was done using the well to tank emission potential of the different fuels considered, i.e., Diesel, OMEx and electricity fuels as mentioned in the Table 5–3. For the

WTT emissions from the electricity consumption, 90% charger efficiency is also considered to account for the charging losses.[193] Further, for the 2030 and 2050 WTT emissions for electricity consumption, electricity grid decarbonisation of 15% for 2030 and 71.5% for 2050 is considered.[194] The equation 5.2 to 5.5 are used for calculating each of these emissions and are mentioned below:

$$CO_{2\,\text{WTT Fuel}} = \text{F}_{FP} * EC_{F} \quad (5.2)$$

$$CO_{2\,\text{WTT Elec}} = \frac{EC_{E} * F_{EP}}{C_{Eff}} \quad (5.3)$$

$$CO_{2\,\text{WTT Elec 2030}} = \frac{EC_{E} * (0.85 * F_{EP})}{C_{Eff}} \quad (5.4)$$

$$CO_{2\,\text{WTT Elec 2050}} = \frac{EC_{E} * (0.285 * F_{EP})}{C_{Eff}} \quad (5.5)$$

Next, the Tank-to-Wheel emissions are calculated, i.e., emissions coming from the tailpipe of the vehicles. For the electric buses it is automatically zero as there are no tailpipes in them. However, for the ICE based conventional and hybrid buses it is the largest source of emissions due to the significantly lower efficiency of the powertrain system and due to combustion of carbon-based fuels as compared to the full electric powertrain. The TTW emissions are calculated using the fuel consumption obtained from the 0D vehicle simulations and the GHG emission footprint of the combustion of the used fuel. The equation 5.6 used for its calculation is expressed below:

$$CO_{2\,\text{TTW}} = \text{F}_{DC} * EC_{F} \quad (5.6)$$

Finally, for the overall WTW emissions the WTT and the TTW emissions are summed up for the total emissions coming from the use phase. The equation 5.7 used is expressed below for a clear understanding.

$$CO_{2\,\text{WTW}} = CO_{2\,\text{WTT}} + CO_{2\,\text{TTW}} \quad (5.7)$$

c) Maintenance

During the lifetime of the vehicle there are several breakdowns and failures within the vehicle which needs to be taken care of. Specially in buses with higher life cycle kilometres this phase can have significant contribution for the overall life cycle kilometres. Thus, there could be several components that needs to be replaced to maintain the working condition of the buses for smooth running during its life cycle. Hence, it is considered that after each 10,000 kms the maintenance of the bus is done by replacements of certain major components which equals. The Table 5–7 below represents the different components considered in the maintenance phase with its individual weight or volume, the number of times it is replaced for the bus life cycle and its GHG emission potential.

Table 5–7: Maintenance data considered for the bus's life cycle analysis.

Component	Quantity (kg)	Replacements	GHG emissions (kg/kg)
Engine Oil	6.44	80	3.12
Coolant	10	80	3.59
Tyres	60	80	1.66

The cumulative emissions from the maintenance phase are calculated using the following equations 5.8 and 5.9 shown below:

$$\mathrm{N}_{main} = \frac{LCD}{\mathrm{LCD}_{comp}} \quad (5.8)$$

$$\mathrm{CO_2}_{main} = \sum\left(\mathrm{F}_{comp} * \mathrm{W}_{comp} * \mathrm{N}_{main}\right) \quad (5.9)$$

d) End of life

Upon completion of the life cycle kilometres of the bus it is subjected to the end-of-life phase where it is disassembled and recycled. As discussed earlier in Chapter 3 the core of this research is based on the GREET model and thus to calculate the end-of-life phase the emission footprint termed as assembly, disposal and recycling (ADR) is considered for each bus. This is directly based on the total weight of the vehicle that is subjected to the disposal phase. The Battery recycling is not considered separately as it is supposed that the waste batteries from these buses are subjected to second life following a sustainable approach.[195] The equation 5.10 used to calculate these emissions is presented below:

$$CO_{2\ ADR} = (F_{ADR} * W_{vehicle}) \tag{5.10}$$

In the equation 5.10 above, F_{ADR} refers to the emission footprint for the ADR phase per kg of the vehicle, while $W_{vehicle}$ is the total weight of the vehicle. Hence, adding up the emissions coming from all these four phases leads to the life cycle emissions from each of the bus. Which is presented by the equation 5.11, shown below:

$$CO_{2\ \mathrm{LCA}} = CO_{2\ \mathrm{M}} + CO_{2\ \mathrm{WTW}} + CO_{2\ \mathrm{main}} + CO_{2\ \mathrm{ADR}} \tag{5.11}$$

5.2.3. Cost analysis

To add the economic aspect to this study a cost analysis is also done for the buses. This is done by considering the Capital expenditures (CAPEX) and the Operating expense (OPEX) for each of the case. A detailed description about both these parts of the cost analysis is presented below in respective sub sections.

a) CAPEX

This type of cost is associated with the capital expenditures required for the operation of buses in the city on the different bus routes. For this study mainly the cost of the bus procurement by the bus transit companies in Spain is considered.[156,196–198] An additional cost for electric buses can be for the bus charging infrastructure development.[193] However, the focus of this cost analysis is to assess the economic impact on the bus transit companies only and it is supposed that the development of the charging infrastructure is responsibility of another external organisation.

Thus, only the cost associated with the bus fleet development is considered. This study also highlights and keep into account the fact that in case of drop-in e-fuels like OMEx the existing ICE fleet can be used and will not involve additional CAPEX.

b) OPEX

This type of cost is associated with the operating expenses associated with the different buses. Which means the cost expended during the use phase of the buses due to the energy consumption and during the maintenance phase for repairs. The evaluation is done separately for the energy cost for each bus considering the fuel or energy cost needed for the respective bus type during its life cycle while running each of the bus route analysed.[51,199] This is done using the equation 5.12 shown below, where C_T is the cost per trip in Euros/100km, C_E is the unit energy cost and EC is the Energy consumption in L/100km for diesel and in kWh/100km for electricity.

$$C_T \left(\frac{Euros}{100km}\right) = C_E * EC \left(\frac{L/kWh}{100km}\right) \tag{5.12}$$

This cost of operation is then included with the procurement cost of the bus for a life cycle cost assessment. The maintenance cost is sometimes included in the procurement contract agreed between the bus transit company and the bus manufacturer. Still the cost of maintenance is added separately for the replacement of general vehicle components during each vehicle servicing for GHG emissions calculation. The equation 5.13 below is used to calculate the C_{LCC} life cycle cost, where $C_{Vehicle}$ is the cost of vehicle procurement, C_E is the cost of energy, C_{Main} is the cost of maintenance and LCD is the life cycle distance of the vehicle.

$$C_{LCA} \left(\frac{Euros}{km}\right) = \frac{C_{Vehicle} + C_E + C_{Main}}{LCD} \tag{5.13}$$

Further, for this cost analysis the articulated buses are not considered as the focus is to evaluate a single bus size with multiple powertrain technologies. Thus, only the buses with standard 12m size are considered for the cost analysis performed here. The Table 5–8 below mentions the different CAPEX and OPEX costs considered for the different buses.

Table 5–8: Different costs in Euros (€) for the cost analysis of standard 12m buses.[51,199]

Powertrain	CAPEX	OPEX				
	Procurement	Diesel (per L)	OMEx (per L)	Electricity NC (per kWh)	Electricity FC (per kWh)	Maintenance
Conventional	250000	0.72	1	-	-	9520
Hybrid	305000	0.72	1	-	-	9520
Electric	700000	-	-	0.3	1	2965

In the Table 5–8 above the cost OMEx is considered for future scenario when it is mass produced not the current price where it is produced in pilot facilities.[200] Moreover, for electricity price for two different types of charging is considered, the normal charging (NC) and the fast charging (FC).[199] This is very much important for electric buses specially which have more than four to five times the battery capacity than in a passenger EV.[201] Thus, charging time is very important for buses and so is the type of charging used. Also, this difference in price is although for its OPEX, it is considered that it also considers the additional capital investment required for fast charging. The final energy consumption cost is shown later in the results section upon getting the energy consumption from the 0D simulations.

5.2.4. Fleet Assessment

The bus fleet assessment is done for the public bus transit company of the city of Valencia, La Empresa Municipal de Transportes (EMT) Valencia.[202] This is done to see how the bus fleet can be optimised to meet the future emissions reduction targets that can be soon imposed on the heavy-duty sector in Europe. Another motivation behind choosing

Valencia was its decision to make half of its fleet from hybrid buses by 2021 and author's familiarity with the city and bus routes operated in the city.[156] Thus, it is investigated what will be the GHG emissions reduction of the bus fleet upon using 50% hybrid buses in the fleet, the best bus powertrain to be run in each line for maximum emission reduction, as well as evaluating the use of e-fuels like OMEx in conventional and hybrid buses instead of new electric buses to meet future emissions reduction targets and the cost efficiency of both e-fuel pathway and full electric pathway.

a) Fleet optimisation

This optimisation is done for the 10 most used/crowded bus lines in Valencia considering the current types of buses that are used in each of those lines. The passenger numbers for 10 bus lines in 2019 can be seen in Figure 5–3.

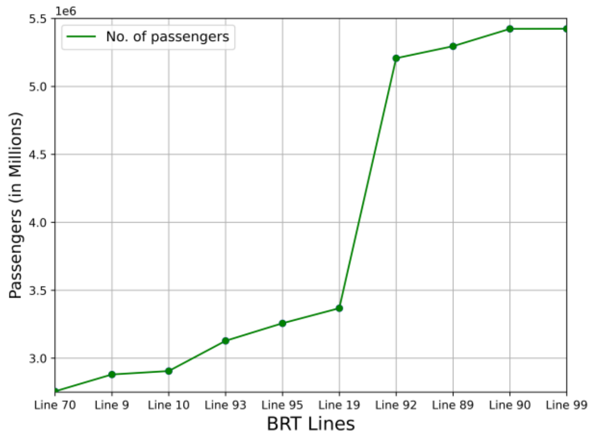


Figure 5–3: Number of passengers in the top ten most used bus lines in Valencia. (Adapted from [203]*)*

Further, it is also kept in mind which specific types of buses operate in each of the bus lines for a much more detailed and specific estimation of the bus fleet. The table below shows the different bus types operating in each of the bus routes in 2019 for the city of Valencia.[204]

Table 5–9: Different types of buses operated in the top ten most used bus lines in the city of Valencia. (Adapted from [205])

S. No.	Lines	Diesel	Hybrid	Diesel Articulated	Hybrid Articulated
1	9	×	×		
2	10	×	×		
3	19	×		×	×
4	70	×			
5	89	×		×	
6	90	×		×	
7	92			×	×
8	93	×	×		
9	95	×			
10	99	×		×	×

Also, the data for the total number of buses by different bus types is considered for Valencian fleet in the year 2019 and considering the fleet to be 50% hybridised by 2021, the updated bus fleet distribution is calculated. The Table 5–10 below shows the different bus types considered to be operating in each line and the number of each for different years.

Table 5–10: Distribution of the bus fleet by the different bus types for several scenarios. (Adapted from [153])

Bus type	Fleet 2019	Fleet 2021 (50% hybridised)	Normalised fleet 2019
Diesel	369	205	75
Hybrid	54	218	11
Diesel Articulated	31	31	7
Hybrid Articulated	36	36	7
Total	491	491	100

As shown in the Table 5–10, the total number of buses in the Valencian fleet was found to be 491, similarly the total number of bus routes in the city were found to be around 50. Thus, a fleet of 100 buses is considered for the 10 bus routes that are evaluated here in this study.

These 100 buses are distributed in the same ration as the 491 buses were distributed for the 2021 fleet. However, it was tough to get the data of the exact number of buses operated in each route based on bus type. Thus, an optimisation was done using a python code to see by using what number of buses based on bus type for each route, we can have the lowest amount of GHG emissions. The total number of each type of bus and the emissions out from each bus type in each route, as obtained from 0D simulation, were given to the code as input together with an initial value of 10 buses operating in each line. The code operated a minimisation operation to give the best possible combination of the number of different buses by type operating in each bus route for lowest emission values. The distribution of buses obtained are presented later in the results section.

b) Powertrain optimisation

To find a better solution for the hybridised Valencian fleet an optimisation was done for the 0D vehicle models by design of experiments (DOE) method. The motivation for this was to right size of the electric motor and the battery capacity of the bus models for each route so that the powertrain shows best efficiency and helps in the reduction of maximum amount of GHG emissions. For this the E-motor torque was varied from 600 to 1800 Nm while the battery capacity was varied from 7.5 to 37 kWh. This helped to obtain the best size of both the components to get the minimum emissions from the powertrains. Consequently, with these new values of emissions obtained for each bus powertrain, the fleet optimisation using the python code was done again to get the optimised bus fleet distribution to see if the distribution changes. The results are shown later in the results section.

c) Fleet evaluation

As mentioned before the main idea behind the fleet assessment is to see which technologies can help the bus fleet to become compliant with the future emission reduction targets. Thus, this is done at each step of the study multiple times, as follows:

i) Initially for the 2019 bus fleet.
ii) Then by varying the hybridisation level of the fleet from 0 to 100% as a sensitivity analysis.
iii) After fleet optimisation using the python code, from 0 to 100% optimisation.
iv) After the powertrain optimisation of e-motor and battery, with and without fleet optimisation, from 0 to 100% hybridisation.
v) And finally, by fully renewing the fleet with electric buses and by using e-fuels with varied hybridisation from 0-100%.

The results shown for each of these evaluations are presented next in the results section by comparing how far or close each pathway is from meeting the 2025, 2030 and 2050 emission reduction target of Europe.

5.3 Results and Discussions

This section shows the main results obtained for the buses evaluation as performed using the methodology discussed in the previous section. It is divided into four sub-sections corresponding to each sub-section as discussed in the methodology part. These four sub-sections include: 0D simulations, Life cycle assessment, Cost analysis and Fleet assessment. The key results for each of these parts are discussed below in detail.

5.3.1. 0D Simulations

This sub-section shows the different results obtained from the simulations of the 0D vehicle models using the GT suite package. These results are only for the standard 12m diesel, hybrid and electric buses and shows the average speed of each bus routes, the energy consumption and the driving range offered by each bus type. The results are presented below:

a) Average Speed

The first and the most important result obtained from the 0D simulation of the bus models is the average speed for the buses in each route. This is the target for the 0D simulations as the vehicle models are run to match these speeds so that it represents the bus schedule as planned by the bus transit companies of each city as closest as possible. The speed is a very important parameter for the performance of the bus powertrain as it directly represents the efficiency of the powertrain. At low speeds the ICE engine powertrain performs quite badly, and the fuel consumption becomes very high. Moreover, even in heavy traffic conditions where there are long duration halts the energy consumption will be high even for electric powertrains. For example, due to higher stop conditions a 9 km long bus route is covered by the bus in one hour but in a in case of normal running with less stop conditions it may be done in just 30 minutes or even less. Thus, the higher time taken will lead to higher energy consumption for the bus lines. The Figure 5–4 shows the variation in the average speed for each of the ten bus routes in the four Spanish cities, where the average speed for each city is represented by dotted lines.

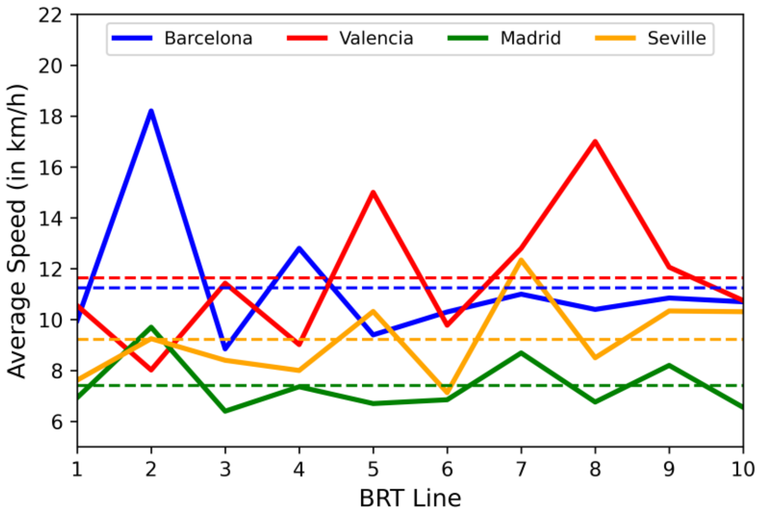


Figure 5–4: Average Speed variation for different bus routes in the 4 cities. (Adapted from [182]*)*

In the Figure 5–4 the solid line shows the variation of the average speed among the 10 bus routes. Where the Green colour is for Madrid, Blue for Barcelona, Red for Valencia, and Yellow for Sevilla. While the dotted lines represent the average of the 10 bus routes in each city. For Valencia and Barcelona, the average is higher than Sevilla and Madrid. This is because some high-speed lines can be observed for Barcelona and Valencia which are operating outside the city region in lesser traffic areas. While in Madrid and Sevilla the average speed is comparatively less due to the bus route operating more in cities in high traffic condition. Further, for Madrid the average speed was found to be the lowest as it is the most populous city of the country and the city-based bus routes operate under very high traffic congestion situations. The performance of each powertrain is highly dependent on these speed values at which it is evaluated.

b) Energy consumption

The energy consumption is obtained directly from the GT simulation results and is converted in the unit Mega joules per kilometre for the three bus types, i.e., diesel, hybrid and electric. In the Figure 5–5 the variation in the energy consumption values for the ten different bus routes evaluated for each of the four different Spanish cities can be observed. The Diesel bus is represented in Blue, Hybrid in Red and the Electric bus in green colour with the dotted lines representing the average for each bus type.

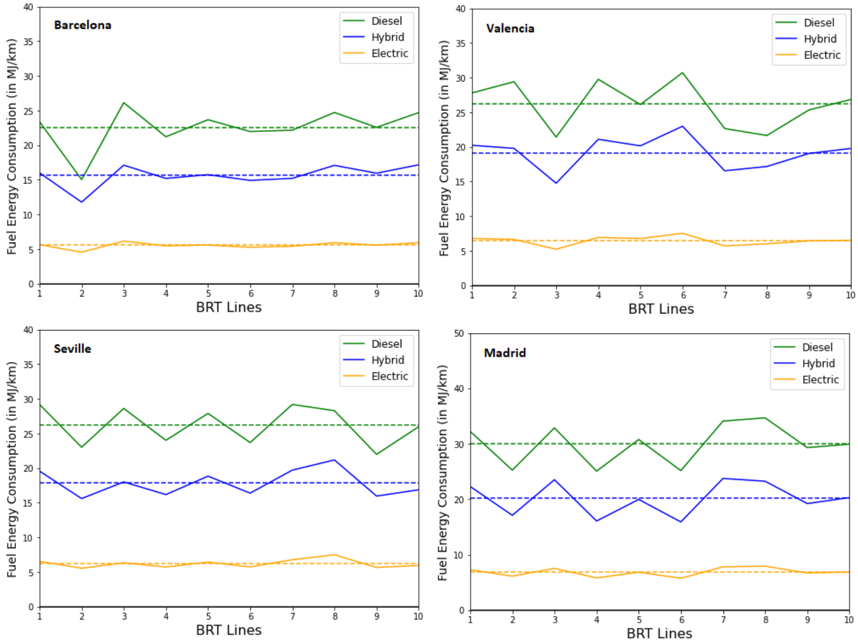


Figure 5–5: Energy consumption (MJ/km) variation in the four cities. (Adapted from [182]*)*

Figure 5–5 shows that the emissions in Madrid and Seville is on the higher side while for Valencia and Barcelona it is lower. This is exactly following the trend of decreasing or increasing average speed of the bus routes in each of the city. The decreasing trend of average speed was Barcelona, Valencia, Seville and Madrid. Consecutively, the decreasing trend in energy consumption is found to be Madrid, Seville, Valencia and Barcelona. Further, as the objective of this work was to see the decarbonisation that can be obtained with options other than the conventional diesel buses, the reduction in GHG emissions is calculated for the hybrid and the electric buses as percentages. The Figure 5–6 below shows the emissions reduction by hybrid and electric buses in the four cities with an error bar for each representing the variation among the ten-bus line for each case. The hybrid buses are represented in light grey colour and electric buses are represented in dark grey colour.

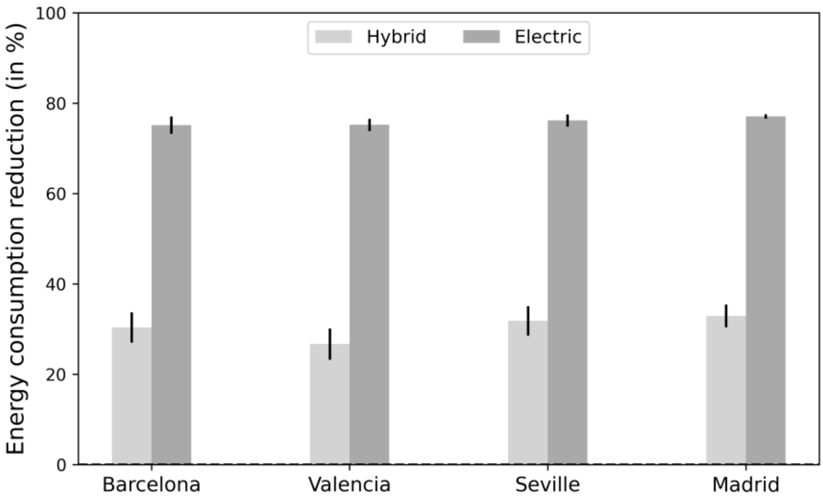


Figure 5–6: Energy consumption reduction in % for the four Spanish cities. (Adapted from [182]*)*

It can be seen in Figure 5–6 that the reduction from electric buses is around 75% while from the hybrid buses it is around 30%. Further, although the reduction from the electric buses is almost the same in each of the city, reduction obtained from hybrid buses are different. This is because the ICE performance is highly dependent on the drive cycle, i.e., the speed at which the bus is operating. This is also the reason why the error bars for the hybrid cases are larger than the electric ones due to higher variability in energy consumption related to the speed variation. This is even visible in the Figure 5–6 where the variation in electric buses energy consumption is not as high as compared to the ones for diesel and hybrid buses.

c) Autonomy

An important parameter to consider for transport technologies is the driving range or autonomy that it can offer. This is mainly dependent on two aspects: the energy stored on-board the vehicle and the powertrain efficiency. The energy consumption is the result of the powertrain efficiency, the higher the powertrain efficiency the lower will be the energy consumption. It is due to this reason that electric vehicles are pushed currently in the transportation industry to replace the conventional ICE based vehicles. However, it lags heavily behind on the second aspect which is energy stored on-board due to the lower energy density of battery packs. Despite the recent advancements in the battery technologies, the EVs are not close to the energy density offered by liquid fuels. It is due to this reason that the energy stored in forms of liquid fuels is way lighter than installing large heavy battery packs. Due to this the range, or the distance covered by the vehicle with maximum possible on-board energy, is affected severely. The Figure 5–7 shows the variation in autonomy for the different bus types in the four Spanish cities.

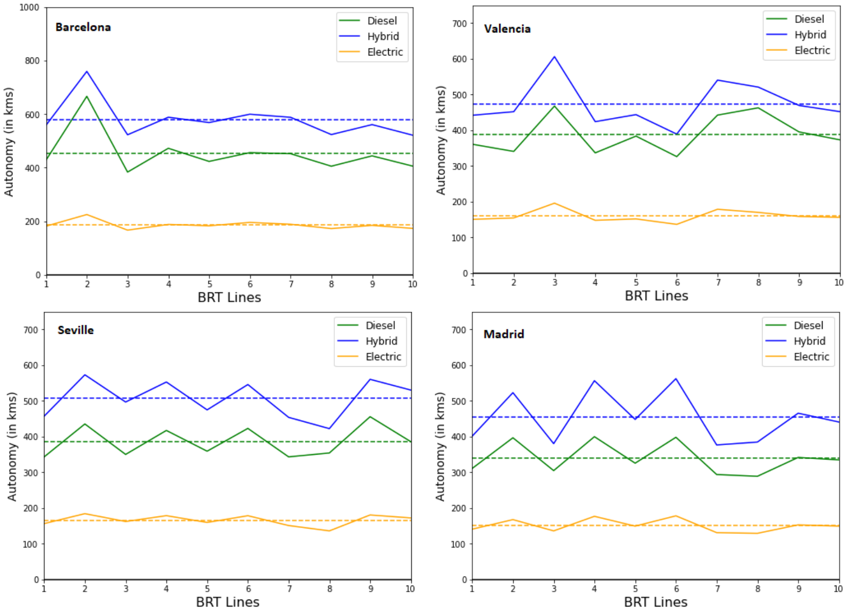


Figure 5–7: Variation in autonomy in the four Spanish cities. (Adapted from [182]*)*

The results above shows that the autonomy offered by the electric buses are way less than offered by the conventional diesel buses by about 200 kilometres. Whereas the hybrid buses act as a range extender and shows an additional driving range by about 100 kilometres. Thus, for heavy duty applications electric vehicles may not be a very feasible option as it generally operates on long distances. The results are presented as percentage change in the driving range are presented in Figure 5–8, where hybrid buses are shown in light grey colour and electric buses are presented in dark grey colours. The error bars show the variation due to different bus routes for each of the evaluated city.

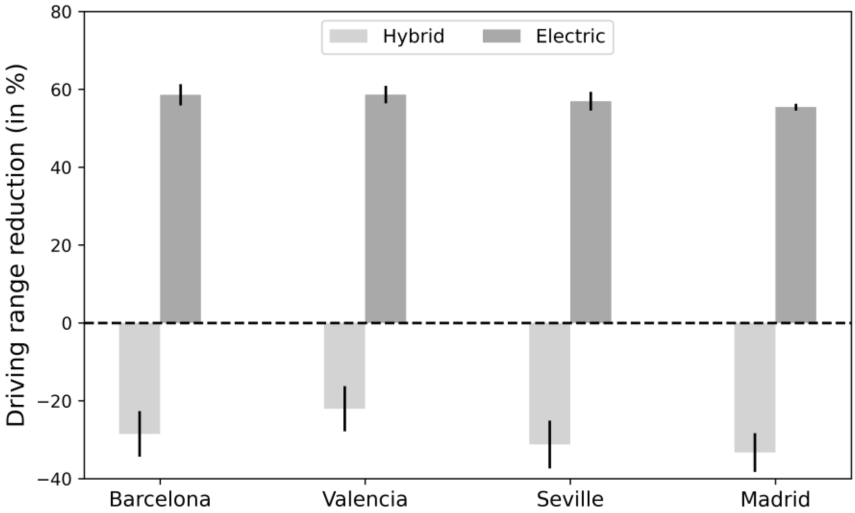


Figure 5–8: Driving range reduction in percentage for the different bus types. (Adapted from [182]*)*

The Figure 5–8 shows a reduction of about 60% in the driving range for the electric buses as compared to the conventional diesel bus. While the hybrid buses show an addition of 30% in the driving range due to its higher efficiency and lower energy consumption. The values vary just as the energy consumption reduction values vary for each of the evaluated cities. Thus, it can be said that despite better powertrain efficiency and lower energy consumption, the electric buses are not the best choice for heavy duty transportation due to the low driving range it offers because of the lower energy density of the batteries. The hybrid buses, however, offer better range due to its ability to store similar energy on-board and lower energy consumption than the conventional diesel buses.

5.3.2. Life cycle assessment

In this sub-section the GHG emissions related to the life cycle assessment are presented, mainly including the Well-to-Tank emissions, the life cycle emissions, and the split of life cycle emissions by components.

While the first two parts are shown with the variation due to the different drive cycle of each bus route, the third part only shows the average of all the four cities and thus, all the forty different drive cycles. It is also important to note that the values reported here are calculated for per passenger kilometre and thus is divided by the passenger capacity of each bus. Moreover, while the initial combined study for the four Spanish cities were done using the buses' passenger capacity as mentioned by the bus manufacturers, the fleet evaluation of Valencia was done by considering the passenger capacity of the buses as reported by the bus transit company of Valencia. The results are discussed in detail below:

a) WTT emissions

The Well-to-Tank emissions for different bus types are shown here which discusses the importance of fuel production pathways for not just the ICE based buses but for the electric powered buses. The results include the emissions due to the current average European electricity as well as for the electricity mix in 2030 and 2050. The results in Figure 5–9 shows the emissions in g/km.passenger in the four different Spanish cities considering the ten different bus routes in each for diesel (in blue), hybrid (in red), electric (in green), electric in 2030 (in purple) and electric in 2050 (in yellow). Further, the corresponding dotted lines represent the average emissions of the ten bus routes in each of the cities for the different bus types.

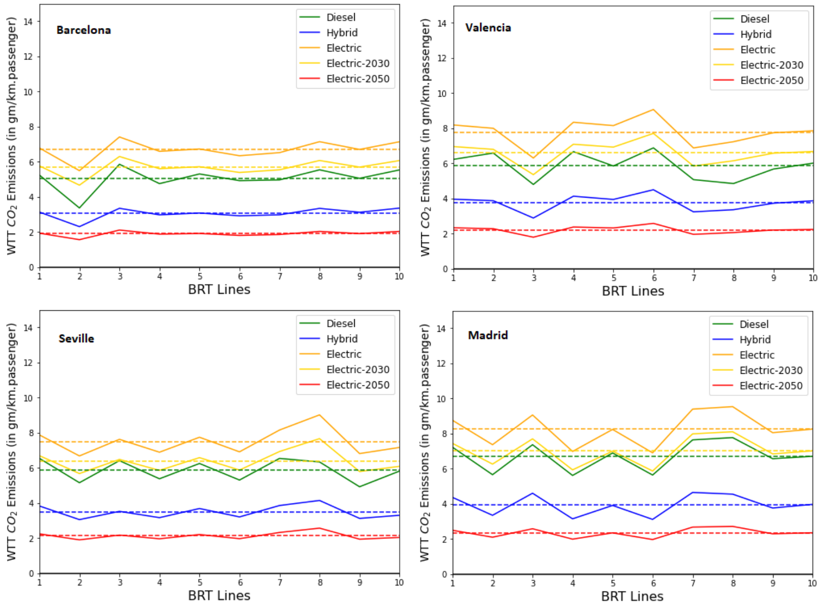


Figure 5–9: WTT emissions (g/km.passenger) in the four Spanish cities. (Adapted from [182]*)*

The results in the Figure 5–9 shows the GHG emissions coming from the fuel production pathway based on the energy consumption obtained from the 0D simulations for each bus type. Considering the WTT emissions, it is observed that the electric buses with the current average European electricity grid emit higher emissions than the diesel buses, while the hybrid buses emit much lower due to lower energy consumption. However, in future scenarios, even by considering the 2030 decarbonised electricity grid the emissions are still higher for the electric buses than the diesel ones. Only in the year 2050 with a super decarbonised electricity mix the emissions for the WTT phase for the electric bus will become the lowest. It is obvious that as the emissions value is in per passenger kilometre, therefore it is about 50 times lower than obtained for passenger cars measure without considering the passenger capacity. Thus, it can be easily said that public transportation is the best way for decarbonisation. Further, it is important to also evaluate the best powertrain technology within the public bus transportation of even further decarbonisation due to which this evaluation is performed. Thus, in Figure 5–10 the emission reduction is shown for hybrid and electric buses as compared to the conventional diesel buses.

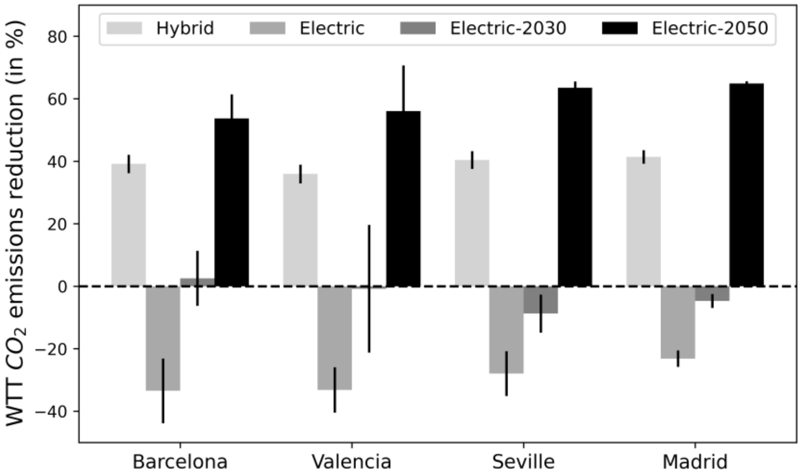


Figure 5–10: WTT emission reduction potential in the four Spanish cities. (Adapted from [182]*)*

The Figure 5–10 shows that as an average for the four Spanish cities the hybrid buses show a 40% reduction in the WTT emissions while the electric buses increase the emissions by 30% currently. With the 2030 electricity the emissions reduction is still not possible with the electric buses and will almost be at the same level as offered by the diesel buses. Only with the 2050 decarbonised electricity the emissions reduction will be achieved higher than that from the hybrid buses. The Tank to Wheel emissions is not showed discussed here it is none for the electric buses due to no tailpipe emissions. The hybrid vehicles do have it but is lower than for the diesel buses just as the WTT emissions depending mainly on its lower energy consumption leading to lesser fuel being burned by the powertrain.

b) Life cycle emissions

The life cycle emissions are calculated by including all the four different vehicle life cycle phases as mentioned in the methodology sub-section, i.e., manufacturing, use, maintenance and end-of-life. Initially this is done for only the standard 12m buses with the conventional diesel, hybrid and electric powertrains by using the manufacturer claimed passenger capacity. The evaluation made for the four different Spanish cities taking ten bus routes in each of them. The results in Figure 5–11 shows the life cycle GHG emissions in g/km.passenger in the four different Spanish cities considering the ten different bus routes in each for diesel (in blue), hybrid (in red), electric (in green), electric in 2030 (in purple) and electric in 2050 (in yellow). Further, the corresponding dotted lines represent the average life cycle GHG emissions of the ten bus routes in each of the cities for the different bus types.

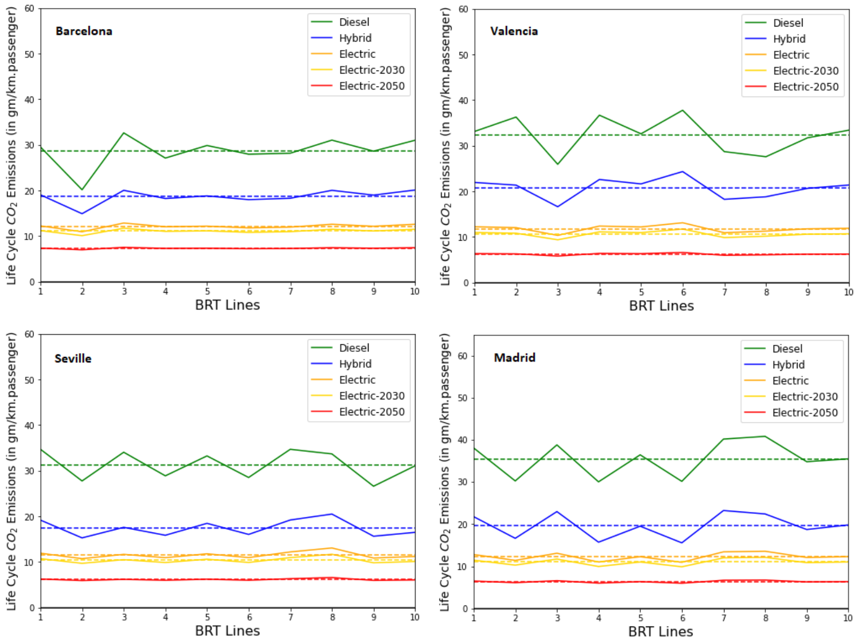


Figure 5–11: Life cycle emissions (g/km.passenger) in the four Spanish cities. (Adapted from [182]*)*

The Figure 5–11 shows similar difference in the order of values reported here for buses than for passenger cars due to the values evaluated in the nit per passenger kilometre travelled. Thus, in term of life cycle emissions too public transportation modes such as buses are a far better option for transport decarbonisation. It can be observed that the diesel buses emit the maximum amount of GHG emissions, then the hybrid and then the electric buses the least. The future scenarios of 2030 and 2050 reduces the emissions of electric buses even further due to the grid decarbonisation. However, it can be observed that the 2030 scenario and the current scenario doesn't affects much in the life cycle emission reduction as it is important to have a very large amount of emission reduction of the well-to-tank phase, while as shown in Figure 5–10 the well to tank emissions in 2030 for electric buses only becomes like the conventional diesel buses. Further, in Figure 5–12 we can see the reduction in life cycle emissions from the hybrid and electric buses in percentages for each of the four cities considered for this evaluation.

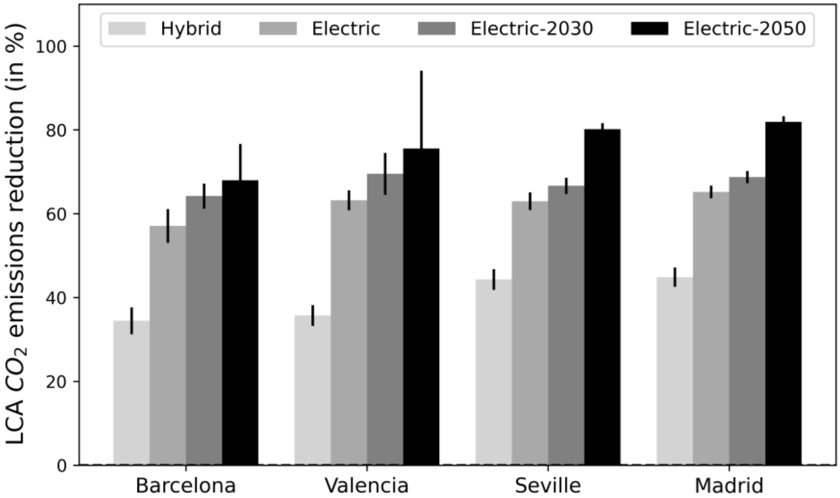
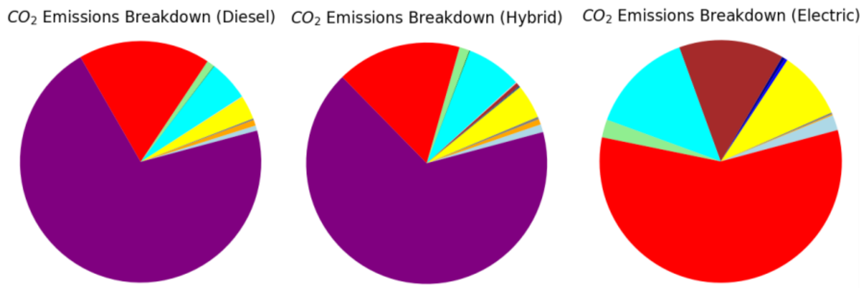


Figure 5–12: Life cycle GHG emission reductions by hybrid and electric buses in the four Spanish cities. (Adapted from [182]*)*

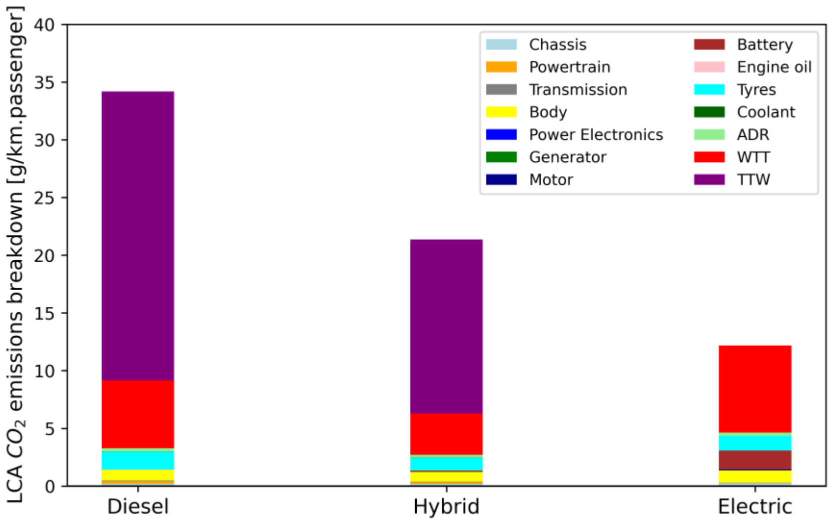
The Figure 5–12 shows an average reduction of around 40% by hybrid buses and around 60% by electric buses. The electric buses show below 70% reduction with the future electricity grid of 2030 and only in 2050 with a highly decarbonized electricity mix it is supposed to show a decarbonization potential of about 80%. The error bar for the 2050 electricity scenario for Valencia is extremely big, which is due to two reasons: first the high amount of change in the electricity grid decarbonization and due to the presence of some bus routes on which the diesel buses show very good powertrain efficiency. This is mainly due to the fact the optimal driving conditions offered by a few bus routes for better efficiency of ICEs, like high average speed and short distances. Hence, this is a clear indication of the importance of driving cycles on the energy consumption of a vehicle and so also on the life cycle emissions of it.

c) Life cycle emissions distribution

The life cycle emissions of the different bus type are dependent not only just the use phase or the WTT part, but also other aspects and the contribution of each component used in the manufacturing, maintenance and the recycling of the vehicle is as much important. And since it is life cycle emissions the contribution of each component matters and so does its accounting to look for the possibilities from where the emissions can be reduced. Also, it helps to highlight the different components considered in the life cycle assessment to communicate the depth in which the analysis is done for the life cycle of the product or vehicle, in the current work. In this sense, Figure 5–13 represents the distribution in percentage for each of the components and the split of emissions coming from each different component in g/km.passenger unit.



(a)



(b)

Figure 5–13: Average life cycle GHG emissions breakdown by (a) Percentage and (b) absolute values. (Adapted from [182]*)*

From the Figure 5–13, it can be observed that the clearly, the life cycle GHG emissions are highest of the diesel buses, lower for the hybrid buses and lowest for the electric buses. Further, it can be observed that for the diesel and hybrid buses the highest contribution of GHG emissions comes from the tank to wheel phase due to its tailpipe emissions resulting from the combustion of fossil diesel, during its life cycle. Whereas for the electric buses the maximum emissions contribution is by the well-to-tank phase, i.e., electricity production for charging of the batteries. Moreover, both the WTT and TTW phases together makes up the WTW or the use phase emissions, thus, the biggest problem for emissions from the transportation sector is its use phase. Therefore, emission reduction from the use phase alone will significantly reduce the emissions of the entire life cycle of the vehicle. Finally, it can be observed that the emissions coming from the batteries here is not very high. This is because of two reasons: higher life cycle of the Lithium Iron Phosphate battery chemistry and its lower emission footprint during production as compared to the industry conventional NMC battery chemistry. Thus, the battery replacement was not needed for the life cycle assessment of the electric buses.

5.3.3. Cost Analysis

This section analyses the economic efficiency of the different bus options to understand which option can be most cost effective for the emission reduction. Like the life cycle assessment section this analysis too is done for the standard 12m buses only. The results are presented in two different sub-sections: Cost per trip and Life cycle cost, below:

a) Cost per trip

As this research focuses on different bus routes operated in the four largest Spanish cities, it is important to calculate the cost of operating the bus routes. This cost is very important for the bus transit company that is operating the bus route for its business point of view to understand if operating a certain type of bus is profitable or not, based on the passenger frequency in each of the line. Thus, in the Figure 5–14 the cost per trip is evaluated and presented for the four different Spanish cities considering the ten different bus routes in each for diesel (in blue), hybrid (in red) and electric (in green). Further, the corresponding dotted lines represent the average cost per trip of the ten bus routes in each of the cities for the different bus types.

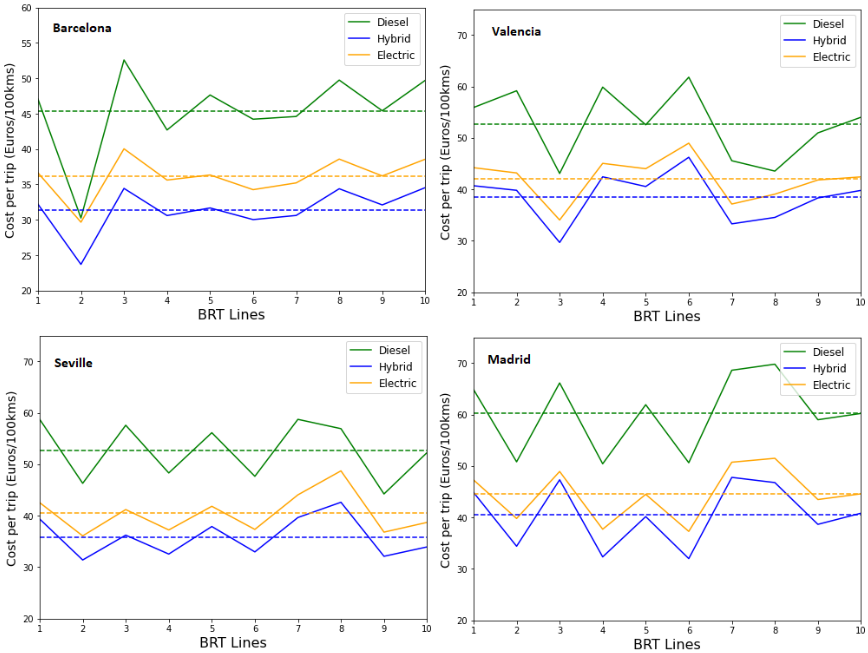


Figure 5–14: Cost per trip (Euros/100km) variation in the four Spanish cities. (Adapted from [182]*)*

The results in the Figure 5–14 shows that the cost per trip of the hybrid buses is the lowest even though the energy consumption of the electric buses is the lowest. This is because the cost of electricity in Europe are on the higher side, the cost per trip is not as low as of the hybrid buses. Further, the trend of the results can be found matching the trend of the results obtained for the energy consumption of the buses. Only due to the different cost per unit energy for electricity and diesel there is the variation in the absolute values obtained. However, it is to be note that the diesel bus is the most expensive bus type for operation in each of the lines. Therefore, Figure 5–15 is shown to see the percent reduction made possible by the other bus types for cost per trip in each of the four Spanish cities.

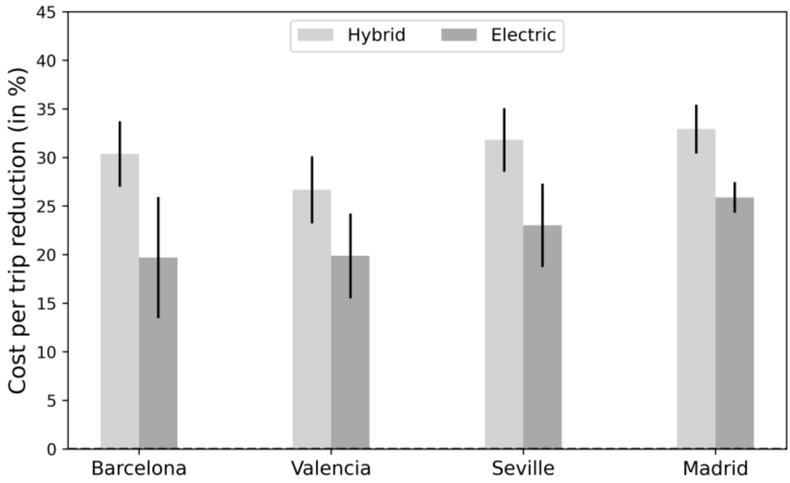


Figure 5–15: Cost per trip variation in the four Spanish cities. (Adapted from [182]*)*

The Figure 5–15 shows that the cost per trip gets reduced by 30% with hybrid buses (in light grey) and by 20% with electric buses (in dark grey). The error bars show the variation due to the different bus routes for both hybrid and electric buses in the four Spanish cities. It can be said that hybrid buses are a much better option for the bus transit company to operate which offers decent emission reduction while also offering maximum reduction in cost per trip for the different bus routes. However, it is also important to see the overall life cycle cost for each bus type for a broader overview of the associated costs which is discussed in the next sub-section.

b) Life cycle cost

As the conventional bus fleet comprises of only diesel buses it is important to renew the fleet with new technologies to ensure decarbonisation of this transportation sector. To do so it is important to assess the life cycle cost for the bus transit companies and not only the cost per trip as the buses needs to be first purchased to be integrated into the bus fleet. Once integrated into the fleet only then it can be operated in the different bus routes and be maintained for its complete life cycle. Thus, in the Figure 5–16 the life cycle cost is calculated and presented for the four different Spanish cities considering the ten different bus routes in each for diesel (in blue), hybrid (in red) and electric (in green). Further, the corresponding dotted lines represent the average cost per trip of the ten bus routes in each of the cities for the different bus types.

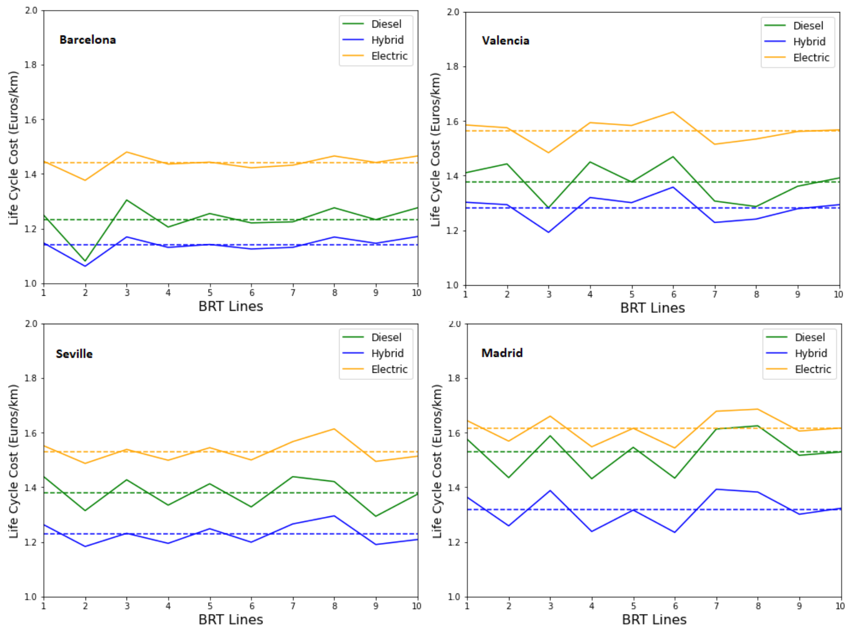


Figure 5–16: Life cycle cost (euros/km) variation in the four Spanish cities. (Adapted from [182]*)*

It is observed in the Figure 5–16 that in terms of the life cycle cost the electric buses are the most expensive ones while the diesel is the cheapest. This is due to the high cost of vehicle procurement for the electric buses as compared to the cheap diesel buses, mainly due to technology immaturity and high cost associated with battery manufacturing, containing rare earth metals. The cost of procurement for hybrid buses are higher too than diesel buses but due to its low energy consumption the added procurement cost gets covered by the savings in the energy consumption cost. Thus, it can be realised that in urban conditions where the hybrid buses can have a lot of energy/fuel savings for buses it can be a great option for emission reduction without adding much cost unlike the electric bus on a life cycle basis. The Figure 5–17 shows the change in the life cycle cost by hybrid (in light grey) and electric (in dark grey) buses compared to the conventional diesel one.

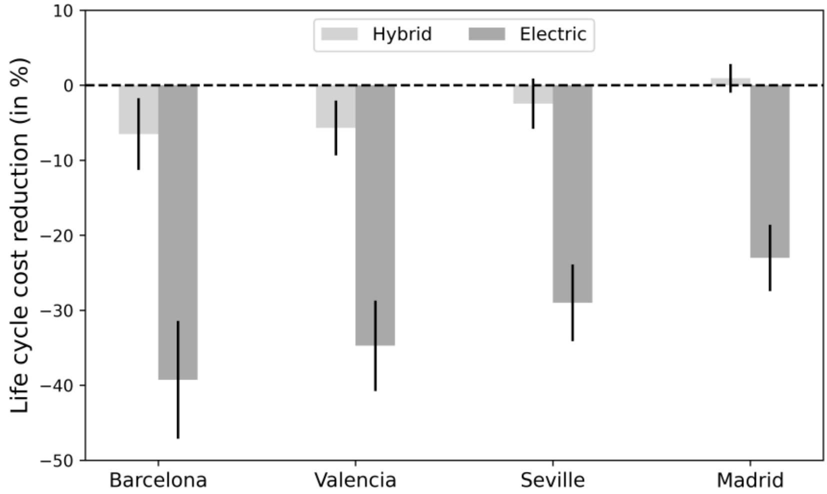


Figure 5–17: Life cycle cost variation in the four Spanish cities. (Adapted from [182]*)*

It can be seen in the Figure 5–17 that while the electric buses have more than 30% (average) addition in the life cycle cost, the hybrid buses have no significant change on the life cycle cost as compared to that of the conventional diesel bus. Further, in Madrid, where the bus routes have the lowest average speeds due to traffic congestion, the performance of the electrified powertrains is quite good. His is due to the inefficiency of the diesel buses in the city of Madrid and thus the energy consumption cost of the hybrid and electric buses becomes lesser as compared to the diesel one. Due to this, the LCC of electric bus is lowest in Madrid and for hybrid it shows a decrease in the life cycle cost instead of increase. However, the main conclusion can be made that even though the electric buses have the highest GHG emission reduction potential, it is not the best option in terms of cost due to high procurement cost associated with it.

Further, if the focus is only to have high emission reduction, then synthetic e-fuels can also be considered as a potential option. A lot of discussion has been done regarding the high cost of the e-fuels, however it is worth understanding that e-fuels are drop in solution for the current ICE fleet and so only the fuel cost must be considered and not the procurement cost for the fleet's decarbonisation. Thus, and evaluation for the life cycle cost is done with this approach for the E-fuelled diesel and hybrid buses. The results are then compared with the life cycle cost of the electric buses using the electricity price for the conventional chargers but also using cost of electricity for fast charging. This is important as the charging time for the buses which are equipped with large batteries can be very time taking and thus a fast-charging option is needed. The Figure 5–18 shows the life cycle cost comparison of the four different bus types, where E-fuel (D) represents a diesel bus fuelled with e-fuel, E-fuel (H) represents a hybrid bus fuelled with e-fuel, Electric (F) represents an electric bus with fast charging and Electric (C) represents electric bus with conventional charging.

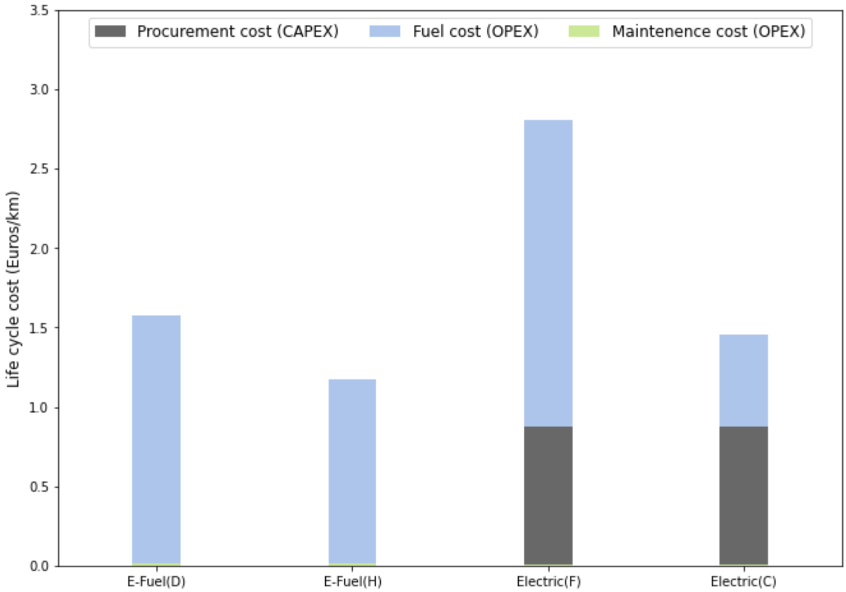


Figure 5–18: Life cycle cost comparison of Electric and E-fueled buses. (Adapted from [153]*)*

The Figure 5–18 represents that considering the e-fuel is used in the old fleet of diesel or hybrid buses, the life cycle cost of it will be almost equivalent to that for an electric bus with conventional charging. However, if the electric bus is charged with fast chargers the cost of the electric bus will become the highest. On the other hand, if the e-fuels are used in the hybrid buses the life cycle cost of it will be the lowest. Hence, it can be said that e-fuels are not a very expensive option as renewing the fleet completely with new electric buses can cost way much higher for the bus transit companies than simply switching to drop in renewable solutions like e-fuels. Considering this fact in the fleet assessment the e-fuel option is also included to see its potential to decarbonise the fleet in the following sub-section.

5.3.4. Fleet Assessment

This final part of the results section discusses the fleet assessment done for the city of Valencia for the ten most used bus routes in the city. Dedicated information related to the bus types and the number of buses of each type are considered. Just as in the methodology the results for the fleet assessment too are presented in three different parts: fleet optimisation, powertrain optimisation and fleet evaluation. The detailed results for each of these parts are presented below dedicated for each.

a) Fleet optimisation

To do the fleet assessment, it is important to know the number of buses running in each of the routes and the type of it. From the literature it was not possible to get that information, so an estimation was done to see the best distribution of buses to have the lowest emissions. It is assumed that for the ten bus routes a total of hundred buses are used, where ten buses are used for each bus route. Further, an initial approximation is done by simply taking the average of emissions from each bus type in the different bus routes and estimating the fleet emissions for the bus fleet distribution of 100 buses mentioned in Table 5–10. But to get to know what type of buses shall be operated in each of the lines for varying level of hybrid buses from 0 to 100%, the python optimisation is done to get the lowest emissions from the ten bus lines. The Figure 5–19 shows the emissions reduction values with and without this optimisation for the fleet, where the non-optimised fleet is represented in blue, and the optimised fleet is represented in purple.

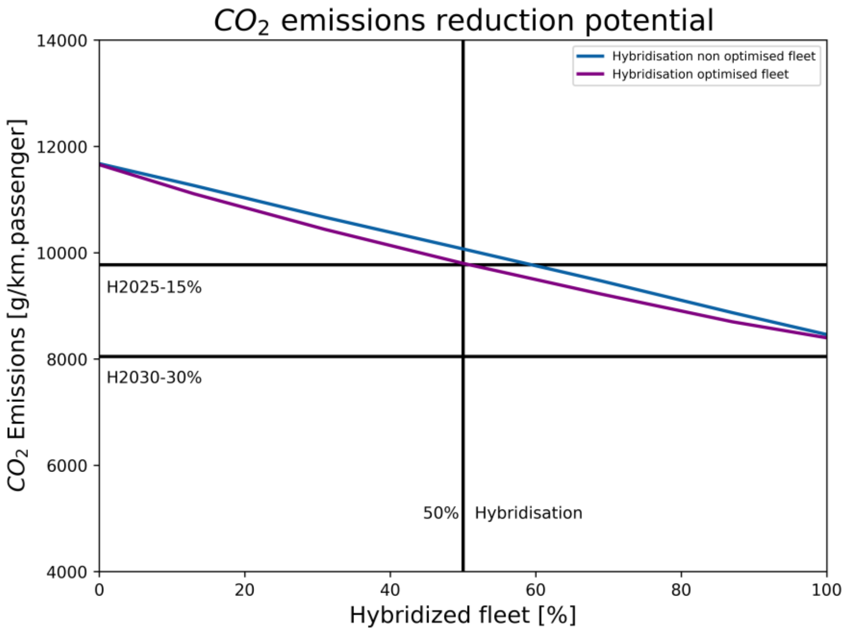


Figure 5–19: Fleet emissions with and without optimization. (Adapted from [153]*)*

It can be seen in the Figure 5–19 how the fleet emissions can be reduced with varied hybridisation levels from 0 to 100 % for two cases: with non-optimised fleet and with optimised fleet for lowest emission reduction. It can be observed that emissions with zero and 100 % hybridisation is very similar. This is since there are only two bus types for each of the extreme conditions, diesel standard and diesel articulated for 0% hybridised condition while hybrid standard and hybrid articulated for 100% hybridised condition. Also, the life cycle emissions values for each of the two types are quite similar when measured for per passenger kilometre. However, for the intermediate hybridisation levels it can be seen there is a reduction in emissions with the optimised fleet. The interesting part is that with optimised fleet distribution a 50% of total hybridisation of fleet can meet the 2025 emission reduction target. This is good for the city of Valencia as they had set the ambition of 50% hybridisation of its fleet by 2021 and that can help it to meet the anticipated limits to be set for the year 2025. However, to meet the 2030 emission reduction target even 100% of fleet hybridisation will not be enough and so other ways needs to be investigated for the bus fleet to reach future emission reduction targets. In the following ways different ways to are discussed to make it possible.

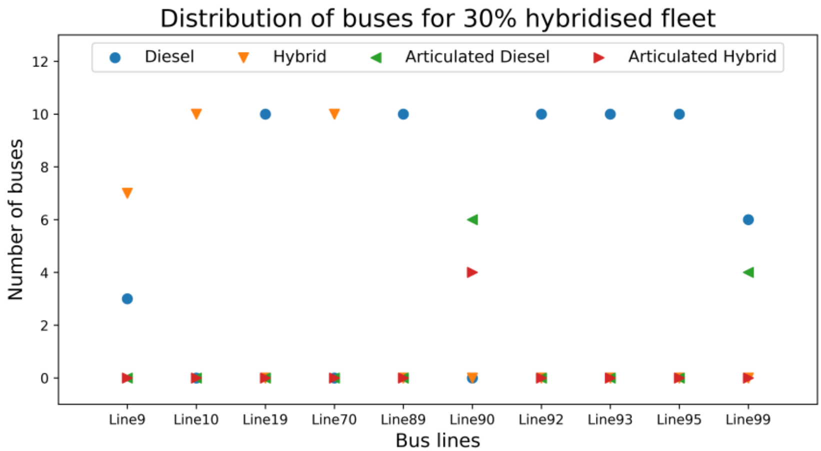
b) Powertrain optimisation

The powertrain optimisation was done to obtain the best battery capacity and E-motor torque capacity for each bus route to get the lowest possible emissions for the hybrid buses. This sizing of battery and e-motor is done to see the maximum possible value of decarbonisation obtained with the best hybrid powertrain configuration. Which was done by performing a parametric study by varying the battery capacity from 7.5 kWh to 37 kWh while e-motor maximum torque value was varied from 600 Nm to 1800 Nm. The Table 5–11 shows the corresponding values of battery capacity and E-motor torque for both the hybrid and articulated hybrid buses in each of the ten lines in the city of Valencia.

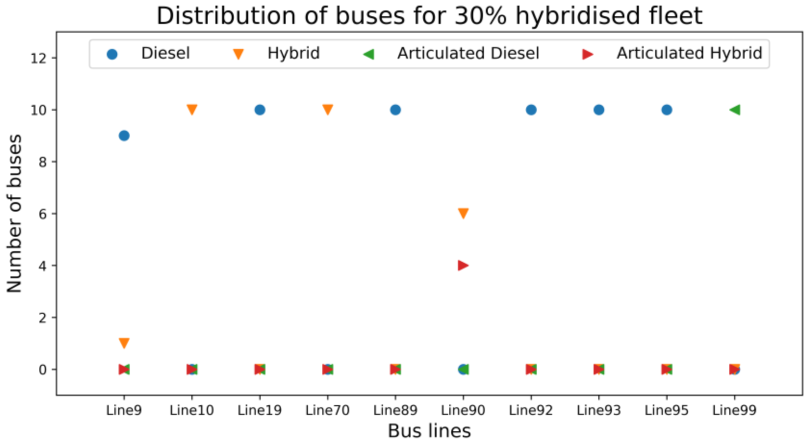
Table 5–11: Battery and E-motor sizing for the ten bus routes. (Adapted from [153]*)*

S. No.	Hybrid		Articulated Hybrid	
	Battery Capacity (kWh)	E-motor torque (Nm)	Battery Capacity (kWh)	E-motor torque (Nm)
Line 9	36.02	1237.63	36.98	1114.79
Line 10	36.02	1237.63	36.98	1114.79
Line 19	34.95	1373.02	36.98	1114.79
Line 70	36.02	1237.63	36.98	1114.79
Line 89	36.02	1237.63	34.67	900.05
Line 90	36.02	1237.63	36.15	1725.80
Line 92	35.16	742.06	29.69	672.05
Line 93	34.95	1373.02	33.15	1257.12
Line 95	34.18	1726.60	36.15	1725.80
Line 99	34.95	1373.02	34.40	839.37

From the Table 5–11 increasing the battery capacity of the buses to 36 kWh is recommended for all the lines as it is obtained for all the bus lines for the bus types. Further, for E-motor maximum torque capacity it was found that the pre used 1200 Nm was ok for most of the bus lines. Hence, it was concluded to use a 36-kWh battery and the same 1200 Nm motor for further evaluation to explore possible pathways to reach future emission reduction targets. The fleet optimisation was done again using the python code and a change was observed for the bus distribution. The Figure 5–20 shows the distribution of buses obtained by considering a 30% hybridised fleet for both before and after the powertrain optimisation.



(a)



(b)

Figure 5–20: Distribution of buses by type for the ten bus routes. (Adapted from [153]*)*

The Figure 5–20 shows that by changing the powertrain configuration of the hybrid buses based on the results from the parametric study, the distribution of the buses has changed. This change in the bus distribution in indicator of the fact that the emissions value can be further decreased with these new powertrain configurations of the hybrid buses. Also, electric buses are also simulated for its emissions value and are presented in the Figure 5–21 together with other evaluated bus powertrain types.

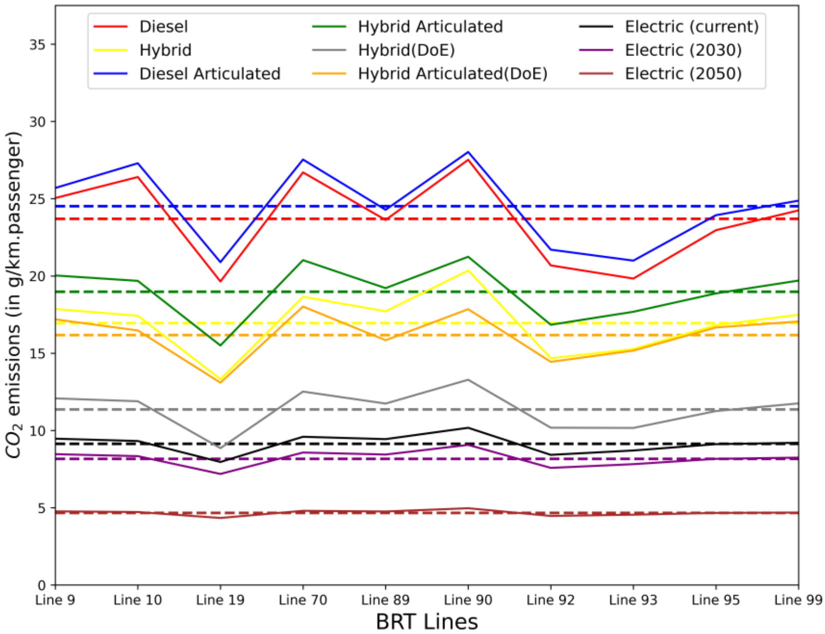


Figure 5–21: Life cycle emissions variation of different bus powertrains for the ten bus routes. (Adapted from [153]*)*

Figure 5–21 represents the variation in the emissions for different bus types in the ten different bus routes for Valencia. The emissions for the diesel standard (in red) are the maximum followed by diesel articulated (in blue), with very similar values. The next most emitting bus type is the hybrid articulated (in green), followed by hybrid standard (in yellow) which is also like the one obtained for hybrid articulated after the results obtained from the DoE (in gold). Then comes the hybrid standard bus with DoE (in grey) followed by the electric buses powered by current electricity mix (in black), then by 2030 electricity mix (in purple) and finally with 2050 electricity mix (in brown). The dotted lines are the average values shown of the emissions obtained for the ten bus routes of each bus type. Considering the above obtained life cycle GHG emission values the evaluation is done for the bus fleet to have maximum emission reduction to meet future emission targets. The results are presented in the following part of this sub-section.

c) Fleet evaluation

Based on the new powertrain configuration for the hybrid buses after the battery and e-motor sizing the evaluation is done to see the new emission reduction possible for the fleet by varying the hybridisation percentage from 0 to 100. Further, as the new distribution of buses were also obtained with the optimisation done using the python code, the evaluation is done for this new fleet distribution too. The results are shown in Figure 5–22 where these results (in orange) are shown together with the previous obtained result as shown in Figure 5–19. The results in dotted orange are for the new emission values obtained after the DoE using the previous fleet distribution and the one in solid orange line is with the new bus fleet distribution.

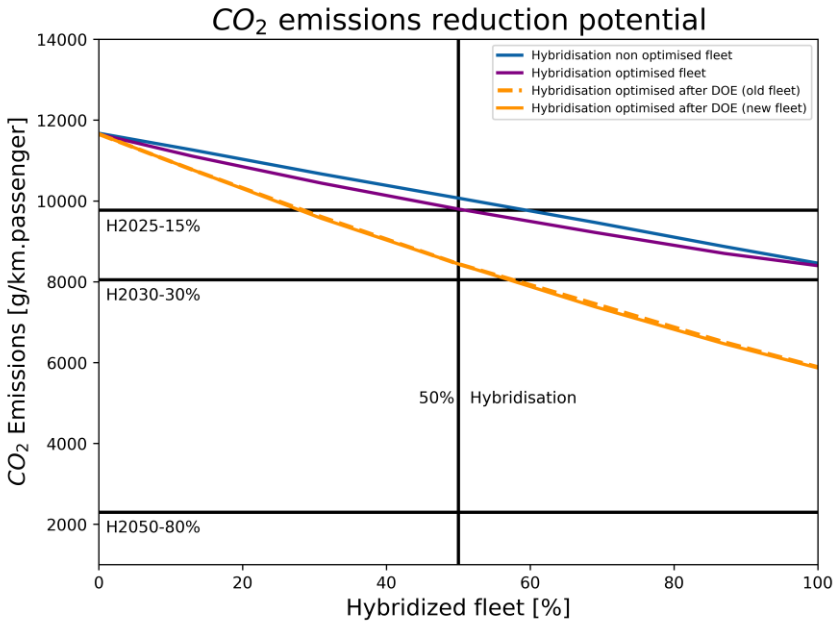


Figure 5–22: Life cycle GHG emission reduction for the bus fleet with optimized powertrain. (Adapted from [153]*)*

The Figure 5–22 shows that the results obtained with the new battery size for the hybrid buses was able to significantly reduce the fleet emissions with increasing level of fleet hybridisation. In fact, the 2030 emission reduction target can be easily met with less than 60% of fleet hybridisation. It was also observed that by re-optimising the bus distribution the fleet emission reduction changed marginally and to ensure the maximum reduction the values obtained with this new distribution was considered for further assessment. The results show that even with the best possible hybrid powertrain configuration, the 2050 emission reduction target can't be met and thus the options of electric buses and e-fuels are considered for the bus fleet scenario beyond the year 2030. The results obtained are shown in Figure 5–23, where the Full electric fleet is represented in dotted red lines while the use of e-fuels is shown in green.

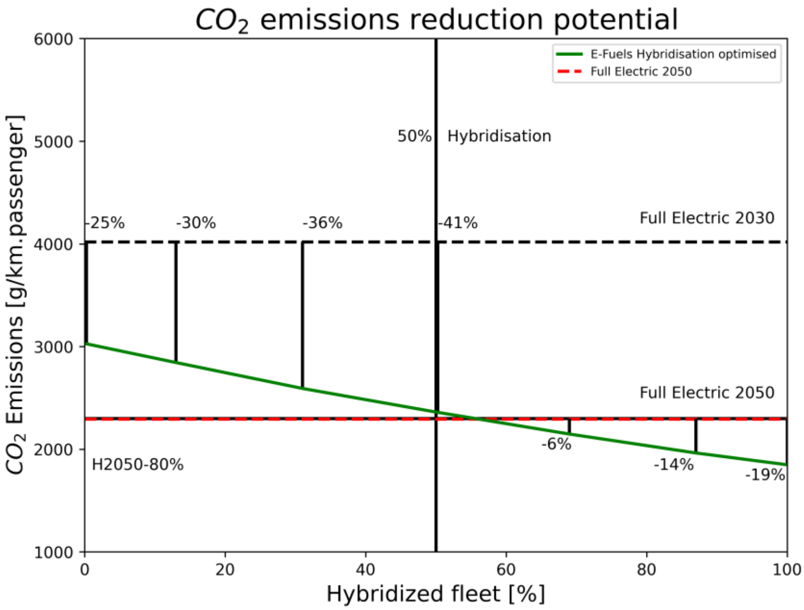


Figure 5–23: Life cycle GHG emission reduction for the bus fleet using electric buses and e-fuels. (Adapted from [153]*)*

In the Figure 5–23, we can observe that only with a fully electrified fleet the 2050 emission reduction targets can be met. However, by using e-fuels instead of diesel we can achieve it with the current mix of conventional and hybrid buses itself. As mentioned previously, with 60% hybridisation the 2030 target can be met while using diesel, in the same fleet using e-fuel can lead to achieving the 2050 emission reduction target. Thus, no new busses will be required to be purchased and only by changing the fuel, horizon 2050 will be reached for the bus fleet. A summary of the emission reductions possible with e-fuel usage for different fleet hybridisation levels is shown in Table 5–12 indicating the emission reduction possible with full electric fleet 2030 and 2050 as reference.

Table 5–12: Emission reduction with varied level of hybridization using e-fuels as compared to fully electric bus fleet scenarios of 2030 and 2050. (Adapted from [153]*)*

% Hybridisation	% Reduction	Reference
0	-25	Full Electric 2030
13	-30	Full Electric 2030
31	-36	Full Electric 2030
50	-41	Full Electric 2030
55	2050 target compliant	
69	-6	Full Electric 2050
87	-14	Full Electric 2050
100	-19	Full Electric 2050

The Table 5–12 shows that e-fuel can be a better option than fully electric fleet in the 2030 as well as in 2050 scenario and can help to achieve 2050 emission reduction targets with not 100% hybridisation but just 60%. This result is very important for the bus transport companies, and they can think what they really need to do for having emission reduction from its fleet for the future years. The Figure 5–24 shows the summary of the results obtained from the fleet evaluation by showing the emission reduction potential of each pathway considered for this evaluation.

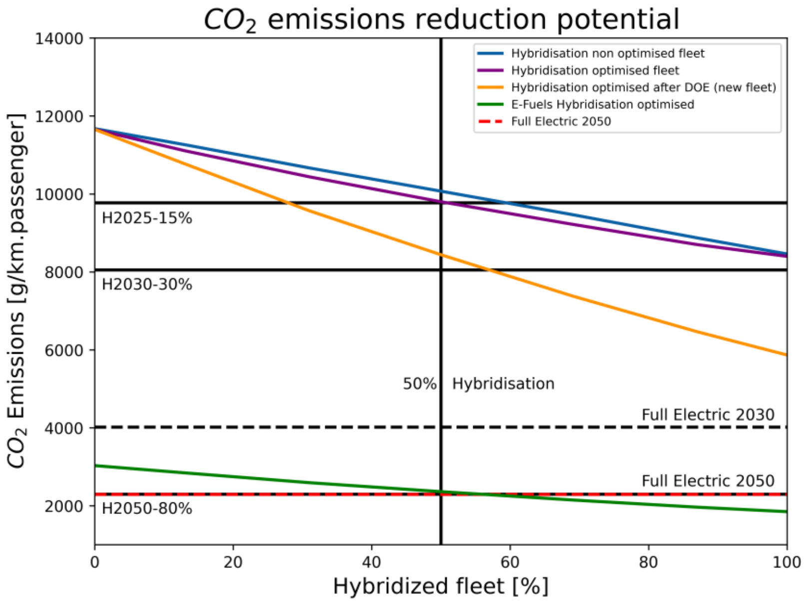


Figure 5–24: Overview of emission reduction pathways for the bus fleet to meet future emission reduction targets. (Adapted from [153]*)*

From Figure 5–24 it is observed that in case of Valencia, as they already have about 50% hybrid buses, by making it just 60% they can fulfil the 2030 target and then by using e-fuels instead of diesel for their fleet it can even meet the 2050 target. In case of electric bus pathway, it needs to be understood that entire fleet must be replaced and that will result in additional emissions and cost as discussed in the cost analysis. Hence, this study must provide a clear insight to the bus transportation companies to follow the right pathway to ensure maximum emission reduction by ensuring minimal impact on the environment and the cost.

5.4 Summary and Conclusions

This chapter discussed the problem of emissions for the Heavy-duty transportation sector on the urban use of buses. The different possible options in terms of fuels, powertrains as well as bus size are evaluated to see which of them is the best solution for the emission reduction of the bus fleet. As a first step, a general study of emission reduction from hybrid and electric buses are evaluated in the four largest Spanish cities, which was published in the peer-reviewed journal *Applied Energy*.[182] As a second step a fleet assessment focussed on the city of Valencia was done to see how the fleet can be decarbonised to meet the future emission reduction targets of the year 2025, 2030 and 2050. This work was published as a second article in the peer reviewed journal *Energy*.[153] Further, the results that were obtained from these studies were also presented in the meetings of the System Analysis task of the International Energy Agency's Clean and Efficient Combustion Technology Collaboration Program (Combustion TCP).[206] The main summary of the results for the life cycle emission reduction are presented in Figure 5–25 for the different bus powertrain types for the standard 12m buses as considered in this study.

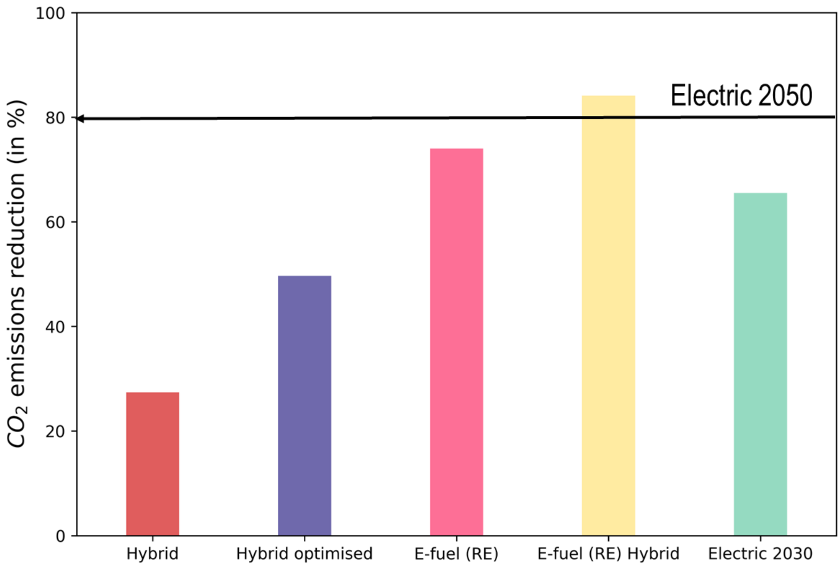


Figure 5–25: Life cycle GHG emission reduction potential of different bus types.

In the Figure 5–25, the electric buses (in black solid line) and the e-fuel powered hybrid buses (yellow bar) are the only two powertrain options that can help to achieve emission reduction of 80%, which is the 2050 target. The conventional diesel bus powered by e-fuel can also lead to more than 70% emission reduction while the e-fuelled hybrid buses offer even higher than 80% emission reduction. These values for e-fuel buses are calculated by including the manufacturing of the vehicle too but it can also be avoided if the comparison must be made about the fleet modification emissions. However, considering the overall life cycle of each bus, the emissions value shown here also considers the manufacturing emissions.

It can be concluded from this study that to meet the 2030 emission reduction targets a fleet of full electric buses is not really needed. Using the hybrid buses with the optimal battery and motor size the emission reductions can be reached for the year 2030. However, for further reduction in emission to meet 2050 target other options needs to be considered. For this, the option of e-fuel usage is found to be more sensible than changing the fleet to fully electric buses. Which is true in terms of both, emissions but also cost. Due to the high procurement cost of an electric bus the cost analysis shows that it will not be a profitable option for any bus operator soon even due to higher energy efficiency of the bus powertrain. Further, despite the high cost of e-fuels as it can be used in the current fleet of buses its cost of operation is the only added cost for the bus company. Thus, use of e-fuels will help to meet the GHG emission targets of 2050 while also not demand of higher investment costs as needed for the electric buses.

Chapter 6

Conclusions

Content

6.1 Introduction

In this last chapter, the final conclusions from this research work are discussed and highlighted for the better understanding of the user. The contribution of this work to the scientific society and within this research domain is also explained. This chapter can be indeed used to verify if the initial objectives set for the fulfilment of this thesis are achieved or not by the readers. Finally, several ideas are presented as future works, which are currently in progress by the authors, some have been addressed by other members of the research group and some ideas are planned to be later in the future by the authors.

6.2 Summary and conclusions

The research work done during the development of this thesis is mainly focussed on evaluating the different powertrain technologies for its potential to be used to decarbonise the transportation sector. The primary motivation for this study is the increasing push by the policy makers globally and especially in Europe, to switch towards full electric transportation. This is mainly done by emphasising on the zero-tailpipe emissions aspect of the electric vehicles, however there are several factors beyond tailpipe that contributes towards CO_2 emissions. This involves phases beyond the use phase or the operation phase, that are part of the vehicle's life cycle, which also has an impact on the environment. Moreover, other than emissions the cost associated with the electric vehicles is also very high that is a huge bottleneck towards its mass adoption. As these vehicles must be sold and purchased by a customer its cost is very much important. Thus, a techno-economic assessment has been done for different vehicle types to investigate the most feasible options for the decarbonisation of the road transportation sector.

As structured, this thesis starts off with highlighting the environmental impact that the transportation sector has, in the introduction chapter. It includes the historical policies and legislations set in different regions globally to keep a check on emissions as well as the future targets. Keeping in mind the electric vehicles as a decarbonizing option, the emissions associated with it on a life cycle basis are highlighted that must be considered while setting policies related to decarbonisation in any part of the world. Further, the economic impact of these electric vehicles is also discussed by focussing on the cost disparity between it and the conventional ICEVs. The main drivers for this high cost of the EVs are also to understand why it is so high. Thus, the first chapter intends to primarily highlight the issues with full electric vehicles as the ultimate solution for the decarbonisation of the road transportation sector.

Secondly, in the next chapter the focus is to highlight the diversity within the road transportation sector related to the different vehicle segment as well as other potential options for decarbonisation. The goal is to underline that to decarbonise the vast road transportation sector, a mix of solution is what is needed to make decarbonisation practically possible. The chapter also focuses on what things have been missing in the current literature and why a life cycle approach is needed to evaluate the emissions as well as the cost associated with each decarbonising solution. In this sense, the motivation behind the study and the objectives set for this research work has been mentioned, including the research framework followed. This was followed by the description of the experimental and numerical tools as well as the methods used in order to fulfil the research objectives. The major methods used to calculate and obtain the results for the different vehicle types is explained in detail for a clear understanding.

Finally, the outcomes from the different evaluations over the course of the thesis are presented in two dedicated chapters for the light duty and the heavy-duty vehicle segments. Both these chapters involve a description of the methodologies followed for the different evaluations performed and then the obtained results. The work included in these chapters are the ones that have already been published and is an outcome of the work done for the development of thesis alone. For light duty segment, the SUV type vehicles were evaluated, and it was obtained that the manufacturing emissions for the EV segment is the highest. This means that the emission savings from the use phase gets largely cancelled, which in turn is dependent on the variation in the electricity emission intensities of different regions. The electricity emission intensities not only impact the emissions from the use phase but also on the manufacturing phase, including the emissions from the battery manufacturing process as well as other components. Also, OMEx as an alternative fuel to diesel was also evaluated and was found to be as capable as EVs for decarbonising the fleet. Thus, it was concluded that as a short-term solution hybrid vehicle can be the best fit for vehicle decarbonisation while maintaining cost efficiency. While e-fuels can be considered as an intermediate solution till low carbon intensity of electricity is achieved in a region with which EVs become more decarbonising.

Heavy duty vehicles, buses are evaluated in different cities across Spain to see mainly the variability among the bus routes. The different bus models are assessed on bus routes with real world data obtained from GPS. The overall observation was that hybrid buses were capable to provide significant emission reductions while also maintaining cost parity. However, the full electric buses provided a little higher emission reduction but were incurring significantly higher costs. Detailed study for Valencia's bus fleet showed that to meet long term 2050 targets, e-fuels can be a very promising solution. Further, as the e-fuels can be used in the old existing buses, it will also not impact the cost too, for the electric bus, cost of its procurement needs to be included. Thus, it can be concluded that for the heavy-duty vehicles too, hybrid powertrain is the most feasible solution for the short-term targets. For the long-term targets, e-fuels can be a more efficient option for emission reduction till a low emission intensity for the electricity is achieved.

Hence, from this thesis it can be concluded that to address the issue of climate change and the environmental impact of road transportation, life cycle assessments focusing on the emissions and cost is important. Thus, to have a sustainable transition of the road transportation sector, hybrid vehicles need to be immediately implemented in the global fleet. While for fully electrified vehicles there needs to be more advancement related to its manufacturing and applicability for different vehicle segment. However, alternative fuels such as e-fuels can be used as an intermediate solution for emission reductions as a drop-in solution in the existing vehicle fleet. In the long term, electric vehicles powered from electricity with a very low carbon intensity can be similar in terms of emissions as an e-fuelled ICEV or HEV. It can be then left to the buyers to decide what to pick among these different sustainable transportation options. Hence, the focus for the policy makers around the world must be on the development of multiple decarbonised powertrain options as based on the use case the choices may vary.

6.3 Contributions and publications

In pursuit of the fulfilment of the research objectives for this thesis three original research articles have been published in high impact factor journals. Also, two presentations were given in SAE World Congress with its publication as a peer reviewed SAE technical paper. The publications are listed below in the same order in which they were submitted.

International Scientific Journal:

1) García, A., Monsalve-Serrano, J., Lago Sari, R., and Tripathi, S., "Life cycle CO_2 footprint reduction comparison of hybrid and electric buses for bus transit networks," Applied Energy 308:118354, 2022, doi:10.1016/j.apenergy.2021.118354.

2) García, A., Monsalve-Serrano, J., Lago Sari, R., and Tripathi, S., "Pathways to achieve future CO_2 emission reduction targets for bus transit networks," Energy 244:123177, 2022, doi:10.1016/j.energy.2022.123177.

3) García, A., Monsalve-Serrano, J., Martinez-Boggio, S., and Tripathi, S., "Techno-economic assessment of vehicle electrification in the six largest global automotive markets," Energy Conversion and Management 270:116273, 2022, doi:10.1016/j.enconman.2022.116273.

Peer reviewed articles and Conferences:

1) Garcia, A., Monsalve-Serrano, J., Villalta, D., and Tripathi, S., "Electric Vehicles vs e-Fuelled ICE Vehicles: Comparison of potentials for Life Cycle CO_2 Emission Reduction," SAE Technical Papers, SAE International, 2022, doi:10.4271/2022-01-0745.

2) Garcia, A., Martinez-Boggio, S., Monsalve-Serrano, J., and Tripathi, S., "Impact of the 2022 European Energy Crisis on its Transportation Decarbonization Ambition: Life Cycle Techno-Economic Analysis," SAE Technical Papers, SAE International, 2023, doi:10.4271/2023-01-0554.

6.4 Suggestions for future work

In addition to the evaluation performed for this thesis, several related topics or areas were noted as possible related to this research topic. After addressing these topics more clarity on the choice of the right powertrain technology can be done. Some of these topics have been addressed by other researchers within the research group while some are being carried out currently and not included in this thesis due to time constraints. While some of the topics have been identified to be addressed in future by the research group members. These areas are explained below in dedicated sections for better understanding.

6.4.1 Evaluating fuel cell vehicles

As explained in the introductory chapter, fuel cell vehicles are a good alternative to the battery electric vehicle as they do not need large battery packs due to the presence of an on-board energy generation system.[207] Further, with the future legislations being focussed on zero tailpipe emissions, only battery and fuel cell electric vehicles are the possible options to fit in. Thus, the evaluation of fuel cell electric vehicles can be interesting as well, to see how good or bad it is in terms of cost and emissions. Its life cycle analysis was also taken into consideration by the end of the PhD using similar 0D methodology as followed by other members of the research group.[208] However, it is not included in this thesis as it was not defined in the initial objectives set for the PhD thesis and considering the time constraints.

Nonetheless, to expand the range of considered vehicle technologies as much as possible, at the end of the PhD, a research stay at Clean Combustion Research Centre of King Abdullah University of Technology in the Kingdom of Saudi Arabia was done. During this time the evaluation of fuel cell buses was done for both its emissions as well as cost for Spain, India and Saudi Arabia on real drive cycles of its public transit routes. The results from this collaborative work have been consolidated into a research paper which is currently in the review stage and should be published in the future few months. As the paper is not yet published, its details and results are not mentioned in this thesis. However, the evaluation was done for only buses and not passenger cars as it was already done by other colleagues of the research group. More evaluation on fuel cells from the research group is expected in the future as well with the addition of experimental facilities at the institute this year.

6.4.2 Using marginal electricity emission intensity

An important aspect of electricity emissions as well as cost is that it changes from time to time depending on several external sources. This is mainly due to the varying demand of electricity due to which the source of electricity generation is varied which ultimately its emission intensity and specific cost. As this depends on the energy demand, it is highly variable from country-to country with varying mix of technology it uses to fulfil the variable demand. Normally, the increased demand is met by fossil-based fuels which increases the emission intensity as the renewable sources are limited and might be already being used to its maximum capacity. While for, lower energy demands the emission intensity will obviously decrease by the lowered use of carbon intensive electricity generation technologies. Hence, as the electricity demand varies during the entire year, due to variation in the weather, as well as during a day, this marginal electricity mix must be considered for life cycle analyses.

However, as the average emission intensity of the electricity production is only reported for each different region in databases such as in GREET, ecoinvent, or other sources, it is what was used for this thesis. As the importance of marginal mix was understood by the research group during progression of this thesis, it was considered for life cycle analysis of fellow members that joined the group later and continued their work as a future work of this current thesis.[209] Also, the work done during the research stay on fuel cell buses evaluation kept this in mind and the marginal emissions as well as cost has been considered in those studies. Thus, it can be said that this area has already been adopted as future work by the research group and will also be implemented in future studies to keep into account this important variation for both the emissions as well as the cost of electricity generation.

6.4.3 More focus on vehicle cycle

As majority of emissions from the ICEVs are from the use phase emissions, the emphasis in this thesis has been given to the well-to-wheel cycle. It was found that EVs with a clean electricity emission intensity can provide around zero emissions during use phase, it will still however have emissions from its production phase. Hence, the 2050 target to become climate neutral and have net zero emissions, will still not be achieved until the emissions from the vehicle manufacturing is reduced. In the current research work the emissions from the battery manufacturing was also evaluated to see the impact of electricity consumption on the battery production. However, there are several other parameters to be considered for the emissions from the vehicle manufacturing, the influence of the raw materials used for battery and vehicle manufacturing, technology development, technology scaling, etc.

These parameters have been considered during the research work performed at KAUST during the research stay for different kind of buses in terms of the emissions associated with it as well as the cost. This is very important specially for the auto makers as despite switching to producing only the electric vehicles in the future it still needs to focus on reducing the emissions further. This is because when considered from the perspective of the Science Based Targets Initiative (SBTi), all the emissions from the scope 1, 2 and 3 emissions need to be considered. The processes involved in the Scope 1, 2 and 3 are very tough to be decarbonised and so a strict monitoring and strategies needs to be employed to become carbon neutral in the future. Hence, a lot of related studies to be done on the vehicle cycle other than the use phase as well for meeting the 2050 emission targets in the future. A description of the scope 1, 2 and 3 emissions as defined by the United States Environmental Protection Agency is shown in Figure 6–1.

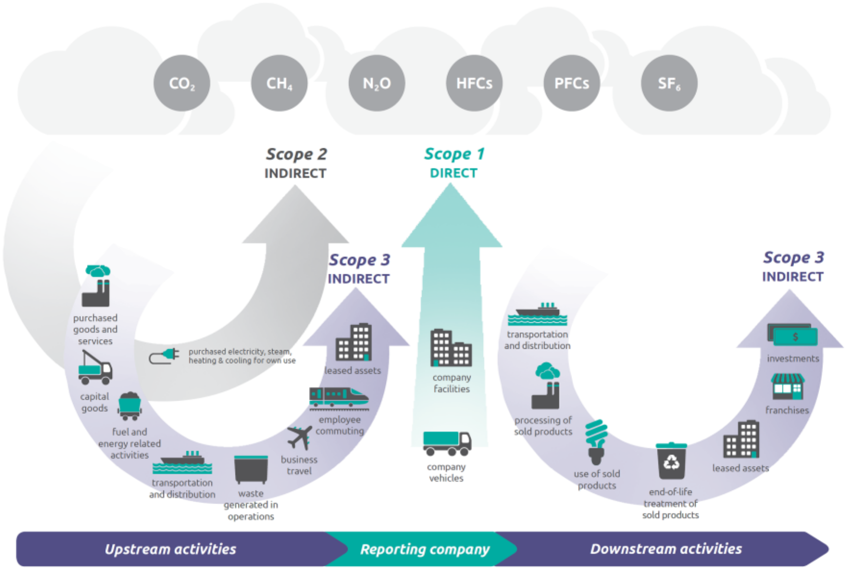


Figure 6–1: EPA's definition of Scope 1, 2 and 3 emissions. (Adapted from [210]*)*

6.4.4 Evaluate other e-fuels and biofuels

In the current study, the focus was given to the comparison of several powertrain options with the conventional ICEV to see their potential for decarbonisation. However, there are several ways to decarbonise the ICEV itself, the primary one is using clean fuels. The reason as to why the ICEV is carbon intensive is because the fuels or the energy carrier it uses is carbon intensive. If a clean fuel with lower carbon intensity is used, it can be made environmentally friendly. This is possible using biofuels and synthetically produced e-fuels. Although OMEx, an e-fuel, has been considered in this study, there can be several other fuel options that may be evaluated for such life cycle analysis. The scalability of such fuels may be an issue but the best way to produce them in large quantities must be used in transportation sectors that are hard to electrify. The fact that these fuels are renewable and mainly uses waste CO_2 from the atmosphere for its production, makes them carbon negative on the well-to-tank basis. Thus, the emissions from the tank-to-wheel phase are offset by the negative WTT phase and makes the fuels carbon neutral or even carbon negative in few cases.

As, concluded from this thesis, hybrid vehicles can be a very effective option for the future to decarbonise transportation, it is important to develop and evaluate such cleaner fuel options for the hybrid vehicles. During the research stay at KAUST e-Fischer Tropsch diesel was used as an alternative e-fuel as well. However, there are several other options as well that can be evaluated for its usage in the ICEVs as well as HEVs. In future these fuels needs holistic scientific and economic evaluations to gain the much needed support from the government and the industry for their development and application. The use of these cleaner fuels, especially the ones that are drop-in fuels are an easy way to decarbonise the transportation sector without the need of producing new vehicles and developing additional infrastructure. Through life cycle analysis as done in this thesis a strong base can be developed to show that the use of such fuels can be a potential way to reach future targets and ensure sustainable transportation.

6.4.5 Impact assessment using other emissions

As mentioned in the introductory chapters, the emissions from the transportation sectors have several impacts on the environment. However, the government and the policy makers globally have been focussing on the CO_2 emissions only and not giving similar importance to other emissions. These emissions have varied impact on the environment, such as global warming, acidification, eutrophication, etc. Even for the global warming impact it's not just CO_2 but also methane, nitrous oxide as well as fluoride gases, that have contributions. Similarly, the impact data of other gases are required which at times are quite difficult to get. As the current emissions legislations focuses on the CO_2 emission reduction from the tailpipe with an initiative for decarbonisation, the focus of this thesis has been to address that and so the impact calculations are not done. However, for the well-being of the environment in totality, it is important to do such evaluations and see what else impact the transportation sector have other than the emission of GHGs. Figure 6–2 shows the share of emissions for global warming impact or global greenhouse gas emissions calculation.

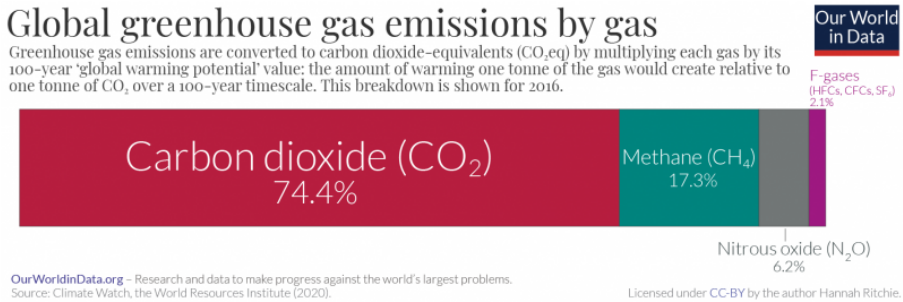


Figure 6–2: Share of different gases contributing towards global greenhouse gas emissions. (Adapted from [211]*)*

Furthermore, it is important to calculate these impacts as in case of the electric vehicles, although they don't have CO_2 emissions as high as in the ICEVs, SOx emissions are higher. These emissions are mainly related to the battery manufacturing process which also leads to water depletion and thus is harmful for both, the lithosphere and hydrosphere. Moreover, the battery manufacturing impacts to resource depletion on earth which is also harmful to the life on earth. Therefore, for a sustainable transition of the transportation sector all the impacts need to be assessed to stay aware of the impact it will have on life on our planet. Hence, for future life cycle studies, the research group is going to include impact assessments as much as possible, based on the data availability. This has been done during the research stay at KAUST and will be continued in future by the research group.

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