ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

EQUIVALENT CONSUMPTION MINIMIZATION STRATEGY FOR PLUG-IN HYBRID ELECTRIC VEHICLES

M.Sc. THESIS

Furkan BİLGE

Department of Mechanical Engineering

Automotive Programme

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

ELEKTRİK PRİZİNDEN ŞARJ EDİLEBİLİR HİBRİT ELEKTRİKLİ ARAÇLAR İÇİN EŞDEĞER YAKIT TÜKETİMİ MİNİMİZASYONU STRATEJİSİ

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Furkan Bilge, a M.Sc. student of ITU Graduate School student ID 503181707, successfully defended the thesis entitled "EQUIVALENT CONSUMPTION MINIMIZATION STRATEGY FOR PLUG-IN HYBRID ELECTRIC VEHICLES", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 03 June 2022
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To my family,

FOREWORD

First of all, I would like to thank my family for their endless support during my study. Their encouragement helped me a lot to stay dedicated even in the hardest times we have been facing for the last two years.

Finally, I would like to thank my advisor Assis. Prof. Dr. Osman Taha Şen for his guidance and supportiveness. He broadened my horizon with his constructive feedbacks and made sure I was on the right track all the time.

June 2022

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ABBREVIATIONS

A-ECMS	: Adaptive Equivalent Consumption Minimization Strategy
AC	: Alternative Current
BEV	: Battery Electric Vehicle
BSFC	: Break Specific Fuel Consumption
CO2	: Carbon dioxide
CTUDC	: China Typical Urban Driving Cycle
DC	: Direct Current
DP	: Dynamic Programming
ECMS	: Equivalent Consumption Minimization Strategy
EM	: Electric Motor
EMS	: Energy Management Systems
FTP75	: Federal Test Procedure
FHEV	: Full Hybrid Electric Vehicle
GPS	: Global Positioning System
HDCD	: Hybrid Charge Depleting
HDCS	: Hybrid Charge Sustaining
HEV	: Hybrid Electric Vehicle
HV	: High Voltage
HWFET	: Highway Fuel Economy Test
ICE	: Internal Combustion Engine
ISG	: Integrated Starter Generator
MHEV	: Mild Hybrid Electric Vehicle
MPC	: Model Predictive Control
NEDC	: New European Driving Cycle
NOVC	: Non-Off Vehicle Charging
OCV	: Open Circuit Voltage
OVC	: Off-Vehicle Charging
PED	: Pure Electric Driving
PHEB	: Plug-in Hybrid Electric Busses
PHEV	: Plug-in Hybrid Electric Vehicle

PMR : Power Mass Ratio
SOC : State of Charge
WLTP : Worldwide Harmonized Light-Duty Vehicles Test Cycles
WOT : Wide Open Throttle

SYMBOLS

a_{des}	: Desired acceleration
a_{veh}	: Vehicle acceleration
A_f	: Front area of the vehicle
C_d	: Drag coefficient
Cap_{batt}	: Maximum battery capacity
g	: Gravitational acceleration
GR	: Gear ratio
I_{batt}	: Battery current
I_{total}	: Total inertia
m_f	: Summed fuel consumption of ICE
$m_{f,real}$	: Summed real fuel consumption in driving cycle
m_{veh}	: Vehicle mass
$\dot{m}_{f,eqv}$	: Instantaneous equivalent fuel consumption
$\dot{m}_{fuel}$	: Instantaneous actual fuel consumption of ICE
$\dot{m}_{ress}$	: Equivalent fuel consumption of energy storage system
n_{batt}	: Number of cells in the high voltage battery
P_{batt}	: Battery power
P_{ice}	: ICE power
P_{req}	: Power request from battery
Q_{lhv}	: Lower heating value of fuel
r_{wheel}	: Wheel radius
R_{aero}	: Aerodynamic resistance force
R_{ch}	: Battery internal resistance during charge
R_{disch}	: Battery internal resistance during discharge
R_{int}	: Battery internal resistance
R_{roll}	: Rolling resistance force
SOC_0	: Initial state of charge
SOC_{final}	: Final state of charge at the end of drive cycle
SOC_{max}	: Maximum permissible state of charge
SOC_{min}	: Minimum permissible state of charge

SOC_{target}	: Target state of charge
T_{em}	: Electric motor torque
T_{ice}	: Internal combustion engine torque
T_{loss}	: Inertia loss
T_{req}	: Requested torque
T_{wheel}	: Wheel torque
V_{batt}	: Battery voltage
V_{OC}	: Battery open circuit voltage
V_{veh}	: Vehicle velocity
α_{wheel}	: Wheel angular acceleration
α_{mot}	: ICE angular acceleration
η_{dsch}	: Discharging Efficiency
η_{em}	: Electric motor efficiency
η_{ch}	: Charging Efficiency
η_{ice}	: Engine efficiency
μ_{r}	: Rolling coefficient
ρ_{air}	: Density of air
ω_{em}	: Electric motor angular speed
ω_{wheel}	: Wheel angular velocity
γ	: Equivalence factor

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EQUIVALENT CONSUMPTION MINIMIZATION STRATEGY FOR PLUG-IN HYBRID ELECTRIC VEHICLES

SUMMARY

Greenhouse gases are the primary cause of climate change, because greenhouse gases prevent the turn back of the sunlight to the atmosphere and due to this reason, most of the heat that coming from the sun is absorbed by earth's surface and this heat warms the low atmosphere and earth's surface. Due to biggest cause of greenhouse gasses is carbon dioxide and main reason for carbon dioxide formation is transportation with one third rate, governments are taking measures to minimize carbon dioxide gas emissions in order to slow global warming especially for the transportation. Due to increasing vehicle number in the world, tight carbon dioxide emission regulations were introduced in 2021. These new standards present significant legal hurdles to the vehicle industry in terms of lowering exhaust emissions below a certain value.

At that point, hybrid electric vehicles play a critical role to achieving this goal for OEMs. Most of the vehicle manufacturer must invest hybrid technologies to be able to sell their products to the market. Hybrid electric vehicles have an electric motor and battery package in addition to a conventional internal combustion engine, which is utilized to reduce fuel consumption and consequently carbon dioxide emissions by employing the electric engine in areas where the internal combustion engine efficiency is too low. Generally, in the urban driving where the start and stop activations are too much, electric motors can handle the start the internal combustion engine and provide traction for overcome the necessary inertial forces. They also provide additional torque in transient maneuvers where fast torque build is necessary for better acceleration and allow pure electric drive where just electric motor is used as a traction source depending on the battery and electric motor power capacity. They can be categorized into four classes based on components and degree of hybridization which consist of micro hybrid, mild hybrid, full hybrid (FHEV) and plug-in hybrid (PHEV). As main topologies, they are splitted 3 main parts depending on the power flow in the powertrain of vehicle: series hybrid, parallel hybrid and power-split hybrid.

In terms of operational strategy on the hybrid vehicle, for getting the best fuel economy which means lowest carbon dioxide, it's critical to run the internal combustion engine and electric motor as efficiently as possible. As a result, the topic of energy management and energy optimization have become a major focus in the automotive industry. There are two main types of energy management strategies; rule-based and optimization based. Rule based techniques use heuristics methods, as well as previous experiences and vehicle data or test data, to build a set of rules for managing an operating strategy. On the optimization-based side, there are main 2 categories exist: global optimization and real time optimization. If the driving cycle characteristics are known, global optimization methods give satisfying results for energy management. Global optimization is an area of applied mathematics and numerical analysis that searches to locate the global minimum and maximum of a function and it is commonly referred to as a minimization problem. Dynamic programming and genetic algorithm

are the most common global optimization methods used for energy management side. But in the real life, due to it is hard to detect or understand the cycle characteristic previously, generally real time optimization methods are preferred.

The most utilized instantaneous optimization method for this purpose is the equivalent consumption minimization strategy (ECMS). The main logic behind ECMS is to convert energy consumption of electric equipment into fuel consumption using an equivalent factor (EF), which is then added to the engine's real fuel consumption to produce the equivalent total virtual fuel consumption at any given time. The minimum energy distribution of HEVs is solved using the equivalent fuel consumption as the goal function. Due to ECMS uses a static equivalent for the energy management systems, it is so crucial to select the correct factor in sensible way, otherwise, either excessive battery consumption is seen or ICE works too much and causes too high fuel consumption. Especially for the plug-in hybrid vehicles which have high voltage battery package with the high battery capacity, it is critical to keep the state of charge above a certain threshold for the battery health. Although ECMS uses a static value, with the correct selection of equivalent factor, it gives satisfying results in terms of decreasing the fuel consumption and carbon dioxide.

In this thesis, a P2 plug-in hybrid electric vehicle model was created in MATLAB Simulink tool including both internal combustion engine and electric motor with high voltage battery system. According to the regulation for plug-in hybrid electric vehicle, charge depleting and charge sustaining tests were performed on the vehicle model. For the energy management side, ECMS algorithm was implemented to plug-in hybrid electric vehicle model as a controller for the torque distribution between ICE and EM. Then the plug-in hybrid electric vehicle model has been converted conventional internal combustion engine model taking into the account the weight decreased origined from high voltage battery and electrified powertrain to be fair for fuel comparison. Plug-in hybrid model with the ECMS energy management system has been analyzed in WLTP Class 3b and the results showed that, with the optimum static equivalent factor selection, fuel consumption has been decreased about 29.10%. And also, in charge depleting test, in 6 times back-to-back WLTP tests, 98.88 km electric range was obtained where only EM has been used as traction source. Additionally, after the charge depleting test, during the confirmation cycle where the electric drive is switched off and ICE is activated, charge state of HV battery was kept as expected over a certain threshold. Details of ECMS code is given in the appendices section.

ELEKTRİK PRİZİNDEN ŞARJ EDİLEBİLİR HİBRİT ELEKTRİKLİ ARAÇLAR İÇİN EŞDEĞER YAKIT TÜKETİMİ MİNİMİZASYONU STRATEJİSİ

ÖZET

Sera gazları iklim değişikliğinin birincil nedenidir, çünkü sera gazları güneş ışığının atmosfere geri dönüşünü engeller ve bu nedenle güneşten gelen ısının büyük bir kısmı dünya yüzeyi tarafından emilir ve bu ısı düşük atmosferi ve dünya yüzeyini ısıtır. Sera gazlarının en büyük nedeninin karbondioksit olması ve karbondioksit oluşumunun ana nedeninin üçte bir oranında ulaşım olması nedeniyle, hükümetler küresel ısınmayı yavaşlatmak için özellikle ulaşımda karbondioksit gazı emisyonlarını en aza indirecek önlemler alıyor. Dünyada artan araç sayısı nedeniyle 2021 yılında sıkı karbondioksit emisyonu düzenlemeleri uygulamaya konuldu. Bu yeni standartlar, egzoz emisyonlarını belirli bir değerin altına düşürme konusunda otomobil endüstrisine önemli yasal engeller getiriyor.

Bu noktada, araç üretici firmalar için bu hedefe ulaşmada hibrit elektrikli araçlar kritik bir rol oynamaktadır. Araç üreticileri adına, ürünlerini yasalara ve emisyon normlarına uygun bir şekilde pazara satabilmek için hibrit ve elektrikli araç teknolojilerine yatırım yapmak durumu kaçınılmaz olacaktır. Hibrit elektrikli araçlar, içten yanmalı motor çalışma veriminin çok düşük olduğu alanlarda, elektrik motorunun kullanılarak yakıt tüketimini ve dolayısıyla karbondioksit salınımını azaltmak için kullanılan, geleneksel içten yanmalı motora ve ek olarak bir elektrik motoru ve batarya grubuna sahip araç tipidir. Özellikle dur kalk manevralarının fazla olduğu şehir içi sürüşlerde, elektrik motorları içten yanmalı motorların ilk kalkış anı için gerekli olan atalet kuvvetlerinin üstesinden gelmek için çekiş sağlayarak içten yanmalı motorun harekete geçmesini sağlayabilir. Ayrıca, elektrik motorları sürücünün daha hızlı bir şekilde hızlanma isteğinin olduğu durumlarda ek tork sağlarlar ve hibrit elektrikli araç üzerinde kullanılan batarya grubunun ve elektrik motorunun güç kapasitesine bağlı olarak, çekiş kaynağı olarak sadece elektrik motorunun kullanıldığı elektrikli sürüş modunun kullanılabilmesine olanak sağlarlar. Hibrit elektrikli araçlar, araç üzerinde kullanılan bileşenlerine ve hibridizasyon derecelerine göre, mikro hibrit, hafif hibrit, tam hibrit ve prizden şarj edilebilir hibrit olmak üzere dört sınıfa ayrılabilirler. Ana topolojiler olarak ise aktarma organı üzerindeki güç akışına göre, seri hibrit, paralel hibrit ve çift modlu hibrit olmak üzere 3 ana gruba ayrılırlar.

Mikro hibrit araçlar, düşük güç oranına sahip elektrik motorunu bünyesinde barındırdılar. Düşük güçlü elektrik motoru dur-kalk gibi manevralarda içten yanmalı motorun ataletini yenip, motoru tekrar çalıştırmak için kullanılmaktadır. Dur-kalk sistemi ise, araç durgun halde iken içten yanmalı motorun boşta çalışma süresini azaltılarak, yakıt tüketimi ve zehirli emisyon gazı salınımını azaltmak için tasarlanan bir sistemdir. Hafif hibrit araçlar, sürücünün ani hızlanma isteği ya da anlık olarak yüksek tork talep durumlarında, gerekli olan tork ihtiyacını içten yanmalı motor ile birlikte sağlayabilecek kapasitede elektrik motoruna sahip olan araç tipidir. Bu şekilde

tüm tork içten yanmalı motordan talep edilmeyecek ve içten yanmalı motor, olabilecek en verimli noktada çalıştırılarak, yakıt tüketimin azalımı sağlanacaktır. Mikro ve yarı hibrit araçlarda tamamen elektrikli sürüş modu yoktur. Tam hibrit araçlar, yüksek kapasite batarya ve yüksek torklu elektrik motor sayesinde kısa mesafelerde, içten yanmalı motorun kullanılmadığı ve aracın tüm çekiş ihtiyacının sadece elektrik motoru tarafından karşılandığı elektrikli sürüş modunu mümkün kılmaktadır. Özellikle içten yanmalı motorun veriminin düşük olduğu düşük hız bölgelerinde, tork ihtiyacı tamamen elektrikli motor ile sağlanır ve bu sayede emisyon salınımı engellenir. Elektrik prizinden şarj edilebilir hibrit elektrikli araçlar ise tam hibrit araçlar ile aynı fonksiyonlara sahiptir. Şebekeden şarj edilebilmeleri sayesinde, tam dolu bir yüksek voltajlı batarya grubu sayesinde, içten yanmalı motor hiç çalışmadan sadece elektrikli sürüş modu ile 100 km'nin üzerine ulaşabilen menzilleri kat edebilirler.

Seri hibrit araçlarda, içten yanmalı motorun tek görevi, jeneratör vasıtasıyla sürekli olarak yüksek voltajlı batarya grubunun doldurulmasını sağlamaktır. Bataryadaki enerji ise, elektrik motoru tarafından aracın çekişi için kullanılmaktadır. Seri hibrit araç konfigürasyonu günümüzde genellikle menzil arttırıcı olarak kullanılmaktadır. Paralel hibrit araç mimarisinde, tekerlekler aktarma organları vasıtasıyla hem içten yanmalı motora hem de elektrik motoruna mekanik olarak bağlıdır ve her ikisinden de çekiş için tahrik sağlanabilir. Aracın frenlemesi sırasında, elektrik motoru jeneratör modunda çalışıp manyetik olarak frenleme yapabilmesi sayesinde, frenleme enerjisiyle ürettiği elektrik enerjisini bataryaya aktararak bataryanın dolmasını sağlar. Elektrik motorunun aktarma organları üzerindeki yerleşim konumuna bağlı olarak P0, P1, P2, P3 ve P4 adı verilen farklı paralel hibrit konfigürasyonları ortaya çıkmaktadır. Çift modlu hibrit mimarisinde ise, kullanılan planet dişli mekanizması sayesinde araç tahriği sadece içten yanmalı motor, sadece elektrik motoru ya da her ikisi ile birlikte sağlanabilmektedir.

Hibrit araçta operasyonel strateji açısından, en düşük karbondioksit salınımı anlamına gelen en düşük yakıt ekonomisini elde etmek için içten yanmalı motorun ve elektrik motorunun mümkün olduğunca verimli bir şekilde çalıştırılması kritik öneme sahiptir. Bundan dolayı, enerji yönetimi ve enerji optimizasyonu konusu otomotiv endüstrisinde önemli bir odak noktası haline gelmiştir. Temelde kullanılan iki ana enerji yönetimi stratejisi türü vardır; kural tabanlı ve optimizasyon tabanlı. Kural tabanlı teknikler, enerji dağılım stratejisini yönetmek için bir dizi kural oluşturmak için buluşsal yöntemlerin yanı sıra, önceki deneyimleri ve araç verilerini veya test verilerini kullanır. Optimizasyon tabanlı tarafta ise, ana 2 kategori vardır; global optimizasyon ve gerçek zamanlı optimizasyon. Eğer ki sürüş çevrimi özellikleri biliniyorsa, global optimizasyon yöntemleri enerji yönetimi için tatmin edici sonuçlar verir. Global optimizasyon ise, bir fonksiyonun global minimum ve maksimumunu bulmaya çalışan bir uygulamalı matematik ve sayısal analiz alanıdır ve genellikle minimizasyon problemi olarak adlandırılır. Dinamik programlama ve genetik algoritma, enerji yönetimi tarafında kullanılan en yaygın küresel optimizasyon yöntemleridir. Ancak gerçek hayatta çevrim karakteristiğinin önceden tespit edilmesi veya anlaşılması zor olduğundan, genellikle gerçek zamanlı optimizasyon yöntemleri tercih edilmektedir.

Bu amaçla seçilen ve en yaygın olarak kullanılan gerçek zamanlı optimizasyon yöntemi eşdeğer tüketim minimizasyon stratejisidir (ECMS). Bu stratejinin arkasındaki ana mantık, bir eşdeğer faktörü vasıtasıyla, batarya kullanım enerjisinin sanal yakıt tüketimine çevrilmesini sağlamak ve bunun ile içten yanmalı motorun gerçek yakıt tüketimin toplanıp, herhangi bir zamanda eşdeğer toplam sanal yakıt tüketimini hesaplamaktır. Hibrit elektrikli araçların enerji yönetimi, maliyet fonksiyonu olarak eşdeğer yakıt tüketiminin seçilmesi ve bu maliyetin minimize edilmesi amacıyla yapılır. Bu stratejide, enerji yönetim sistemleri için statik bir eşdeğer faktörü kullandığından, doğru faktörün mantıklı bir şekilde seçilmesi çok önemlidir, aksi takdirde ya aşırı batarya tüketimi görülür ya da içten yanmalı motor çok fazla çalışır ve gerçek yüksek yakıt tüketimine neden olur. Özellikle elektrik prizinden şarj edilebilir hibrit elektrikli araçlarda, şarj durumunun belirli bir eşiğin üzerinde tutulması batarya sağlığı açısından kritik önem taşımaktadır. Eşdeğer tüketim minimizasyon stratejisi, statik bir eşdeğer faktörü kullanmasına rağmen eşdeğer faktörün doğru seçimi ile yakıt tüketimini ve karbondioksiti azaltmak açısından tatmin edici sonuçlar vermektedir.

Bu tezde, MATLAB Simulink uygulamasında hem içten yanmalı motor hem de yüksek gerilimli batarya grubu ve yüksek güç kapasiteli elektrik motoru içeren, P2 mimarisinde, elektrik prizinden şarj edilebilir hibrit elektrikli araç modeli oluşturulmuştur. Hibrit elektrikli araç yönetmeliğine göre belirlenen şarj tüketim (charge depleting) ve şarj koruma (charge sustaining) testlerinin, araç modeli üzerinde simülasyonları yapılmıştır. Enerji yönetimi tarafında, içten yanmalı motor ve elektrik motoru arasındaki tork dağılımı için bir kontrolör olarak çalışan eşdeğer yakıt tüketimi minimizasyon stratejisi algoritması eklenmiştir. Ardından hibrit elektrikli araç modeli, yakıt karşılaştırması açısından adil olması açısında yüksek voltajlı batarya ve elektrikli aktarma organlarından kaynaklanan ağırlık azalması dikkate alınarak konvansiyonel içten yanmalı motor modeline dönüştürülmüştür. Eşdeğer yakıt tüketim minimizasyon stratejisi enerji yönetim sistemine sahip hibrit araç modeli, hafif Taşıtlar için dünya genelinde uyumlu test prosedürü (WLTP) tip 3b testiyle analiz edilmiş ve sonuçlar optimum statik eşdeğer faktör seçimi ile yakıt tüketiminin yaklaşık %29,10 oranında azaldığını göstermiştir. Ayrıca, şarj tüketim testinde, 6 kez arka arkaya koşulan tip 3b testlerinde, çekiş kaynağı olarak sadece elektrik motorunun kullanıldığı sürüş modunda, 98,88 km elektrikli sürüş menzili elde edilmiştir. Ek olarak, şarj tüketim testinin ardından, elektrikli sürüş modunun devre dışı kaldığı ve içten yanmalı motorun etkinleştirildiği onay döngüsü testi sırasında, yüksek voltajlı akünün şarj durumu, beklendiği gibi belirli bir eşiğin üzerinde tutulmuştur. MATLAB kodunun detayları ekler bölümünde verilmiştir.

1. INTRODUCTION

Today, with the increase of human population and the effect of developing industry, the use of fossil fuels has also increased. Accordingly, greenhouse gases emitted into the atmosphere also triggered global warming and caused the atmosphere to warm up. In Figure 1.1 below, the percentage of gases that have the greatest greenhouse effect in the atmosphere (left) and the sources of CO_2 gas, which has the largest share, are shown (right).

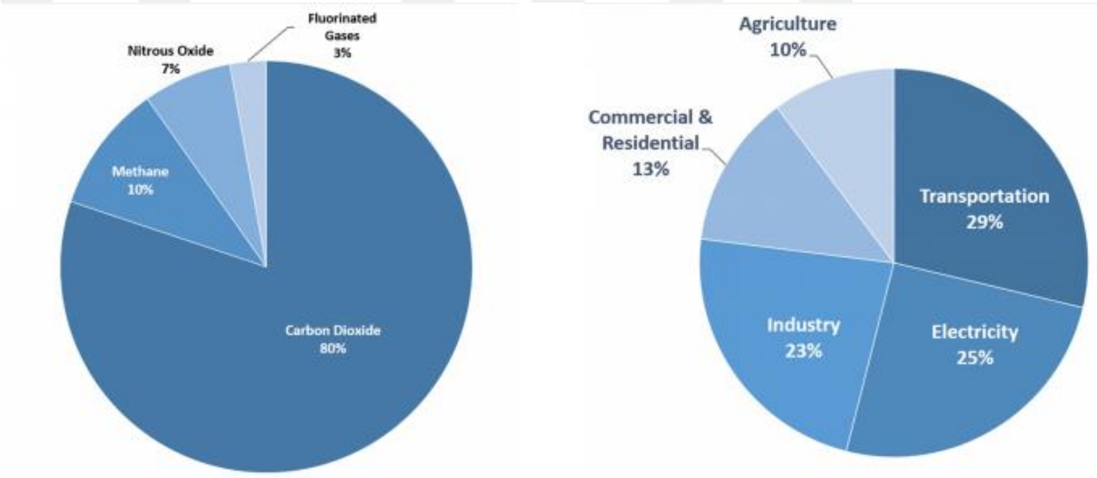


Figure 1.1: US Environmental Protection Agency greenhouse gas source 2019 [1].

As seen in Figure 1.1, the gas that contributes the most to the formation of greenhouse gas in the atmosphere is CO_2 with 80% rate. CO_2 gas (carbon dioxide) is a colorless gas with a slightly pungent odor and a sour taste. The presence of CO_2 gas in the atmosphere prevents some of the radiant energy that the Earth receives from returning to space, thus producing the so-called greenhouse effect. Although CO_2 gas is a harmful gas for human health, transportation is the main cause of CO_2 production with a rate of 29%, followed by industrial production with 23%, electricity production with 25%, and agricultural production with 10%.

On the other hand, the CO_2 production situation in Europe converges to the values in America. As can be seen in Figure 1.2, while the energy industry leads the way in CO_2

emissions with 28.0%, it is followed by energy sources that cause non-transport fuel consumption with 25.5%, and transportation with 24.6%.

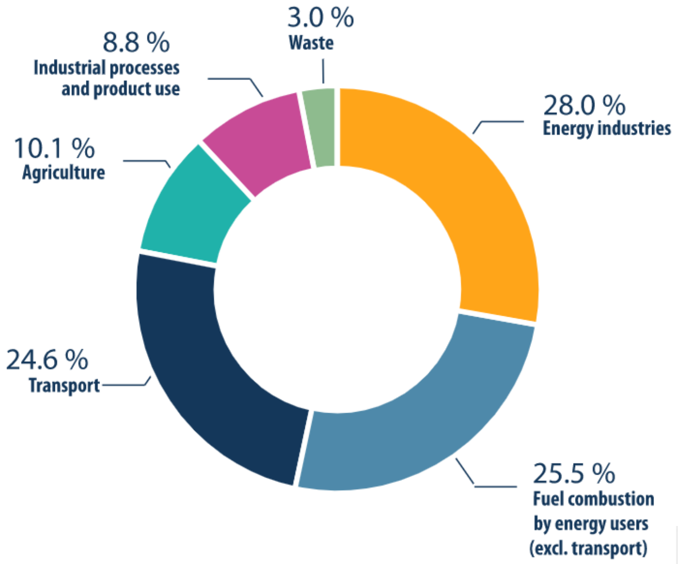


Figure 1.2 : European greenhouse gas emissions emission percentages 2018 [2].

When transportation, which draw attention with its high percentages in both Europe and America, is divided into percentages, road transportation takes the lead with 72.1%, followed by maritime transportation with 13.6% and aviation with 13.3%. railway transportation and other types of transportation cause greenhouse gas emissions with a rate of 0.5%. Details are shown in Figure 1.3.

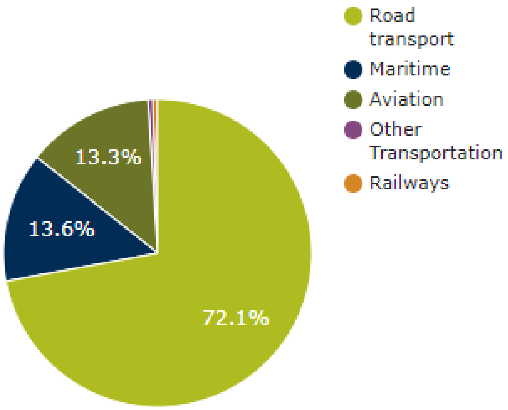


Figure 1.3 : Distribution of transport modes in greenhouse gas production in EU [3].

As it can be seen in Figure 1.4, road transportation is mostly composed of passenger and light commercial vehicles with 43.7%, heavy commercial trucks with 18.9%, light commercial vans with 8.5% and 0.9% consists of motorcycles.

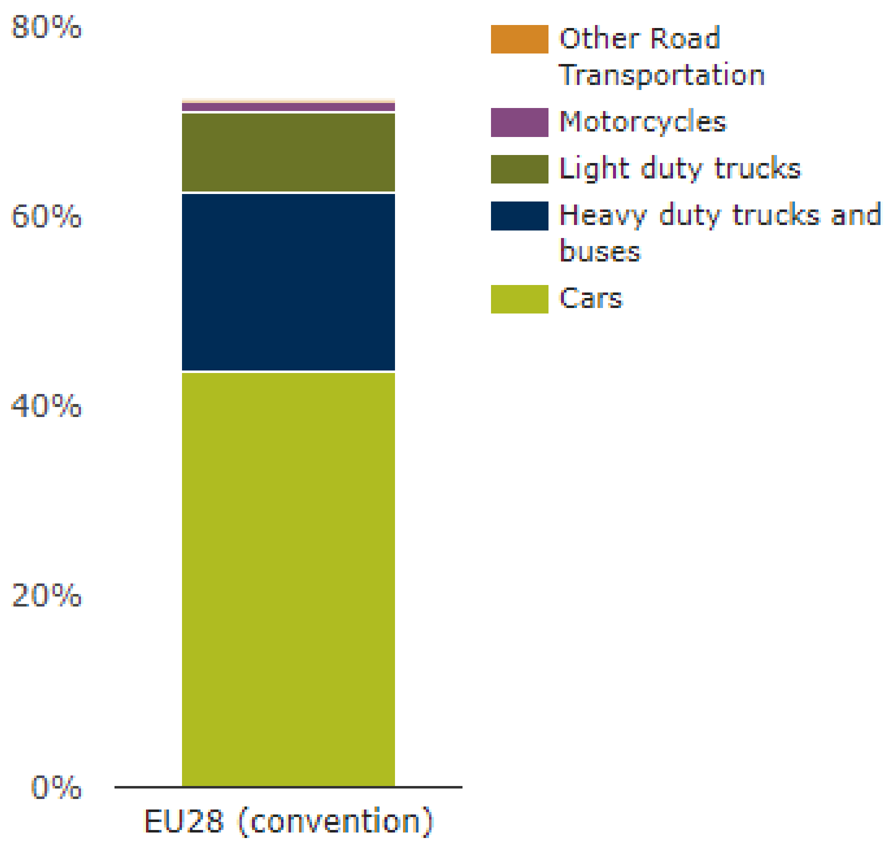


Figure 1.4 : Distributions of road transport rates in greenhouse production [3].

As it can be understood from the above figures, vehicles have really big effect on greenhouse gas emissions and global warming, so the regulations for reducing greenhouse gases and pollutant emissions are becoming more critical. The average values change over years are shown in Figure 1.5.

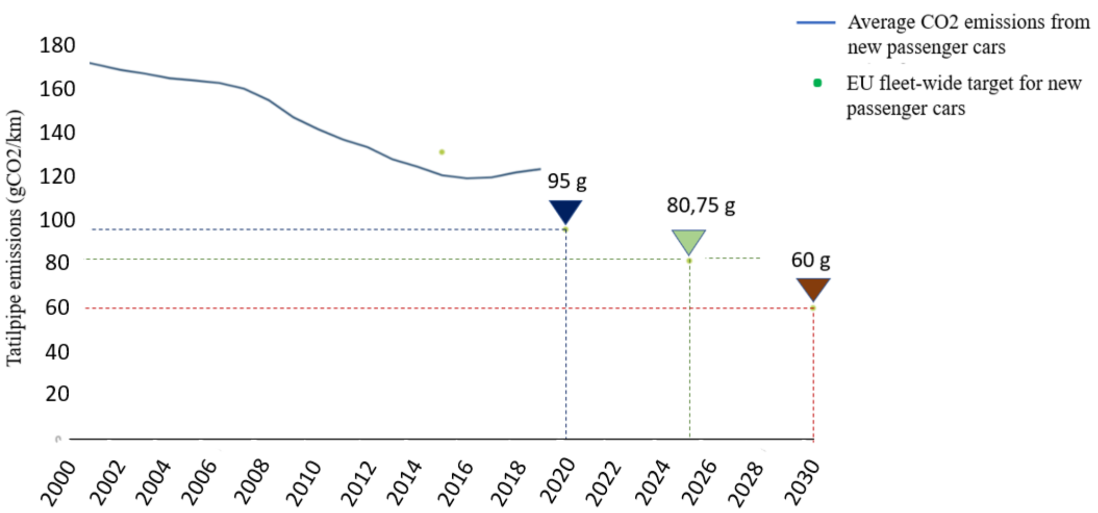


Figure 1.5 : Average carbon dioxide emissions from new passenger cars [4].

The current light vehicle fleet CO2 emissions objectives, which were agreed in 2018 after much controversy, ask for a 15% decrease in 2025 from the 2021 standard of 95 grams per kilometer, and a 37.5 percent reduction by 2030. To accomplish those goals, automakers have been actively investing in electrification, launching dozens of new full-electric and plug-in hybrid vehicles since January 2020 [5].

In this way, for reducing fleet average CO2 values, the electrification and hybridization is crucial for OEMs for satisfying the emission regulations that becomes more or more strict. Hybrid electric vehicles (HEVs) can be thought as a transition stage from pure internal combustion engines (ICEs) to full electric vehicles, because in HEVs both ICE and electric motor (EM) exists, and main target is operating both in the optimum efficiency. It is clear that, using hybrid electric vehicles or battery electric vehicles will reduce emissions due to better operating strategies in certain amount but on the other hand, the powertrain structure will be more complex with additional hybrid component weights. Technical details of the powertrain structures are explained in next section.

For CO2 emissions, battery electric vehicles cause zero tail-pipe emissions during their on-road operations, but all life cycle CO2 must be taken into account. As can be seen in Figure 1.6, well to tank is mostly related with source of the electricity that is used as a traction source in BEVs. Also, vehicle production energy that is used for manufacturing the components of EV has taken into account. But, during their operations they cause zero tailpipe emission. In optimization studies, the source of electricity is generally not taken into account, more focus is on lifecycle CO2 emission.

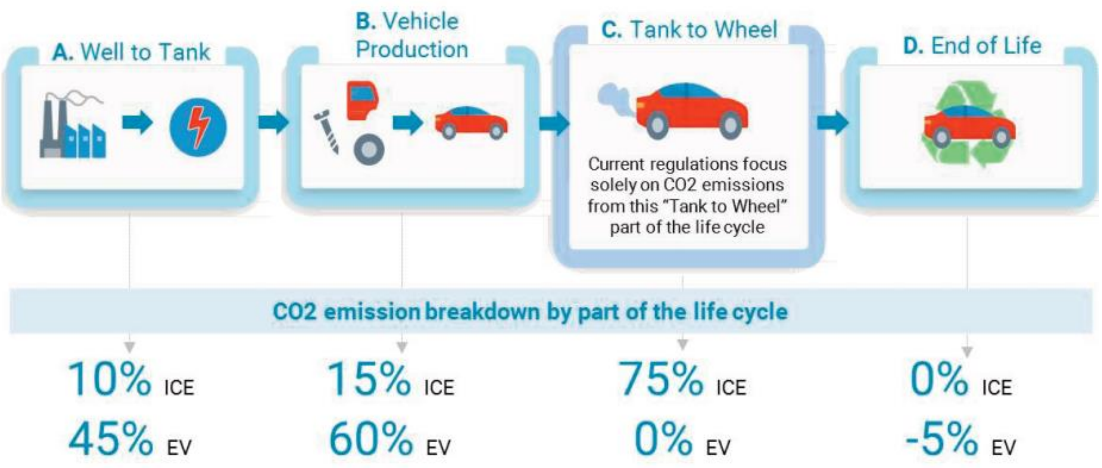


Figure 1.6 : CO2 life cycle comparison between EV and ICE vehicles [6].

1.1 Purpose of Thesis

Energy management strategy plays a crucial part in achieving the best fuel economy feasible under a variety of driving scenarios. The main goal of this thesis is to find optimum torque split behaviour in a World Harmonized Light-Duty Vehicle Test Procedure (WLTP) with changing initial state of charge (SOC) of a high voltage (HV) plug-in hybrid electric vehicle to obtain optimum fuel consumption with satisfying the target state of charge. For optimum torque split, equivalent consumption minimization strategy (ECMS) energy management approach is used.

For a basic vehicle dynamic structure, a plug-in hybrid electric vehicle is modelled on MATLAB/Simulink. After lots of iterations, optimum equivalent factor is defined for changing state of charge conditions.

1.2 Literature Review

For the energy management system of a hybrid electric vehicle, there are various controller algorithm solutions available in the literature. These can be divided two main categories like as Offline Energy Management Systems (EMSs) and Online Energy Management Systems (EMSs).

When compared to online globally optimized energy management systems, offline EMSs are based on pre-defining a series of control rules to determine the power split, but they can not accomplish optimal power allocation. Online EMSs, on the other hand, are based on local optimization and causality, and compatible to be used in real time control. Instantaneous optimization for EMSs, for example, can reduce instantaneous fuel usage at each instant without knowing the complete driving cycle in advance and only achieve local optimal outcomes [7].

Offline EMSs can be categorized into two main subgroups: rule based and global optimization-based EMSs. Also rule based EMSs can be splitted two subgroups: deterministic rule-based EMSs and fuzzy logic-based EMSs [7].

Deterministic rule-based system strategies can be created by combining expert knowledge with real world data. Rule based systems, in instance, can be developed using rule learning algorithms, which might be on statistical heuristics or random basis [8].

Hofman et al. used simple rule-based energy management system to find optimal control power flow through throttle valve for a given power demand for minimizing the fuel consumption. They used 1.6-liter SI engine break specific fuel consumption (bsfc) map as shown in Figure 1.7 to detect optimal operation line for minimum fuel consumption.

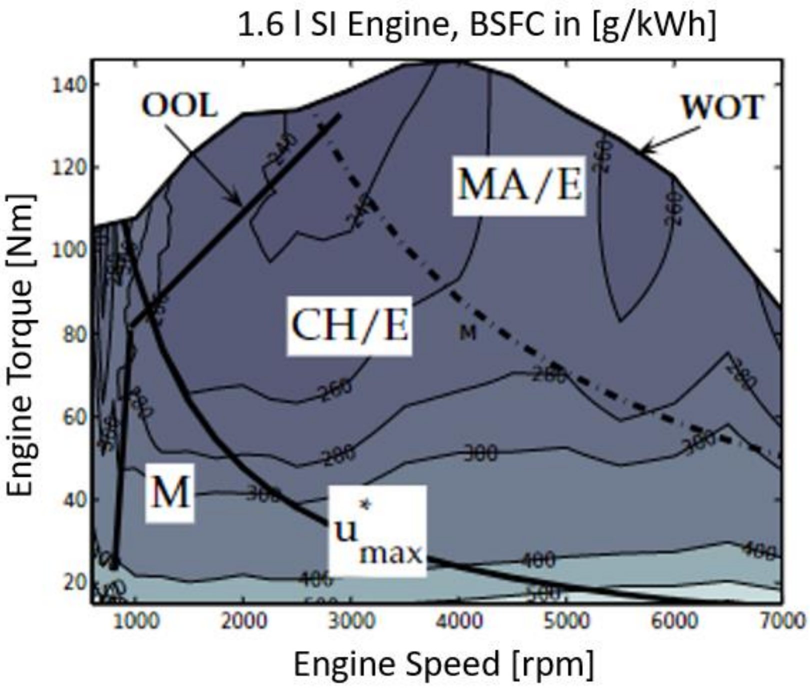


Figure 1.7 : Contour plot of BSFC as a function of the engine output torque and speed [9].

OOL means optimal operation line for minimum bsfc, WOT means wide-open throttle. Their simulation results showed that, with rule-based approach, they made 26.10% fuel saving compared to baseline fuel consumption [9].

Fuzzy logic that is based on fuzzy rule-based control strategies, is introduced in 1965 with the proposal of fuzzy set theory by scientist L. Zadeh [10]. In technical background, compared to rule-based logic, the truth value of variables in fuzzy logic can be any real number between o and 1, which means a type that allows many valued logics.

In 2015, Z. Tareq et al. made a study on energy management system for a hybrid electric vehicle based fuzzy logic. Due to restriction of limited lifetime and cost of the battery, they used a supercapacitor to feed the battery and designed a fuzzy logic controller for the energy management system between supercapacitor and battery [11]. In the Figure 1.8, the basic structure of the model in the study is shown.

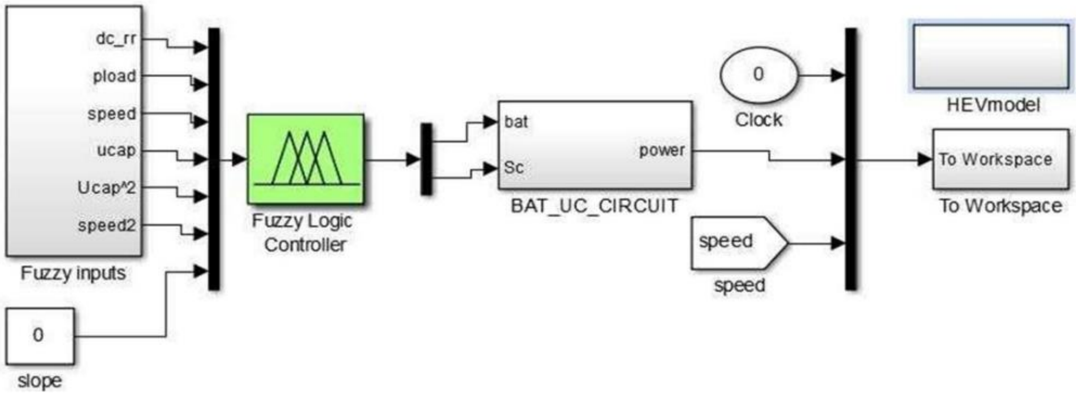


Figure 1.8 : Model of fuzzy logic controller for hybrid electric vehicle [11].

In the model setup, output voltage of hybrid source error (dc_rr), load power (pload), speed, supercapacitor voltage(ucap), maximum value of speed (speed2), maximum value of supercapacitor voltage (Ucap^2) and slope is given as inputs. The output variables in the study would be the selection of power either supercapacitor or battery depending on certain conditions [11]. Also in Figure 1.9, fuzzy rules for the controller are given.

	Fuzzy rules
1	*If (dc_r is pos_L) then (Pbat is neg_L)(Psc is zero)(1)*
2	*If (dc_r is pos_S) then (Pbat is neg_S)(Psc is zero)(0.5)*
3	*If (dc_r is zero) then (Pbat is zero)(Psc is zero)(1)*
4	*If (dc_r is neg_S) and (Sc is not Over) then (Pbat is zero)(Psc is pos_S)(1)*
5	*If (dc_r is neg_L) and (Sc is not Over) then (Pbat is zero)(Psc is pos_L)(1)*
6	*If (dc_r is neg_S) and (Sc is Over) then (Pbat is pos_S)(Psc is zero)(0.51)*
7	*If (dc_r is neg_L) and (Sc is Over) then (Pbat is pos_L)(Psc is zero)(1)*
8	*If (P_load is large) and (Sc is not Under) then (Pbat is zero)(Psc is neg_L)(1)*
9	*If (P_load is small) and (speed is high) and (Sc is not Under) and (slope is not up) then (Pbat is zero)(Psc is neg_S)(0.25)*
10	*If (P_load is neg-zero) and (speed is low) and (Sc is not Under) and (slope is not up) then (Pbat is zero)(Psc is neg_S)(0.05)*

Figure 1.9 : Model of fuzzy logic controller for hybrid electric vehicle [11].

According to simulation results, the fuzzy logic controller which is designed to manage energy flow between battery and supercapacitor energy storage devices is performing as expected with the power feed from either battery or supercapacitor providing sufficient power to the load [11].

Global optimization is an area of applied mathematics and numerical analysis that seeks to locate the global minimum and maximum of a function or a group of functions on a specified set. It is commonly referred to as a minimization problem. Global optimization method in energy management system is mostly used for minimization strategy to reduce fuel consumption as well [12]. Dynamic programming and genetic algorithm are the most common global optimization methods used for energy management side.

In 2013, H. Tang et al. developed an energy management system strategy logic for plug-in series parallel hybrid electric bus by using dynamic programming. The basic components on the powertrain are shown in Figure 1.10. A torsion damper connects the ISG to the engine. Between the ISG motor and the main drive motor, there is an on-off mode clutch. When the mode clutch is in the "ON" position, ePHEB operates in parallel mode or engine-only mode, with the diesel engine, ISG motor, and main drive motor mechanically driving the wheel.

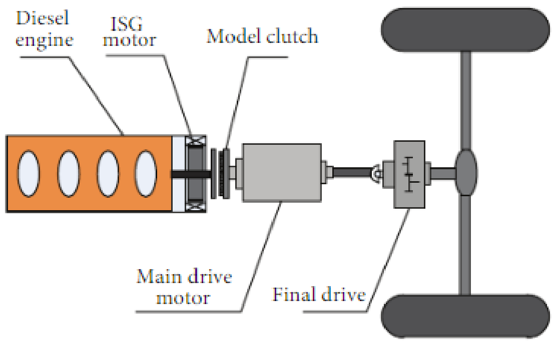


Figure 1.10 : Plug-in series PHEB powertrain configuration [13].

The aim of dynamic programming is to find the best control for each stage in order to minimize the cost function - fuel consumption - across the entire driving cycles. They made determination for the appropriate SOC increment, and the optimal control of a long driving distance of a specific driving cycle is replaced with the optimal control of one driving cycle, which significantly reduces computational time while maintaining precision. In the Figure 1.11, flow chart for solving the dynamic programming problem backward is shown.

According to the simulation results, empirical fuel consumption of the prototype diesel bus is 43L/100 km in the CTUDC cycle and the optimized model with dynamic programming shows 19.90L/100 km, with the additional 11.61 kWh/100 km electrical consumption. In the case that if just pure fuel consumption is taken into account, fuel consumption is reduced by 53.7%. It is clear that dynamic programming improves fuel economy dramatically [13].

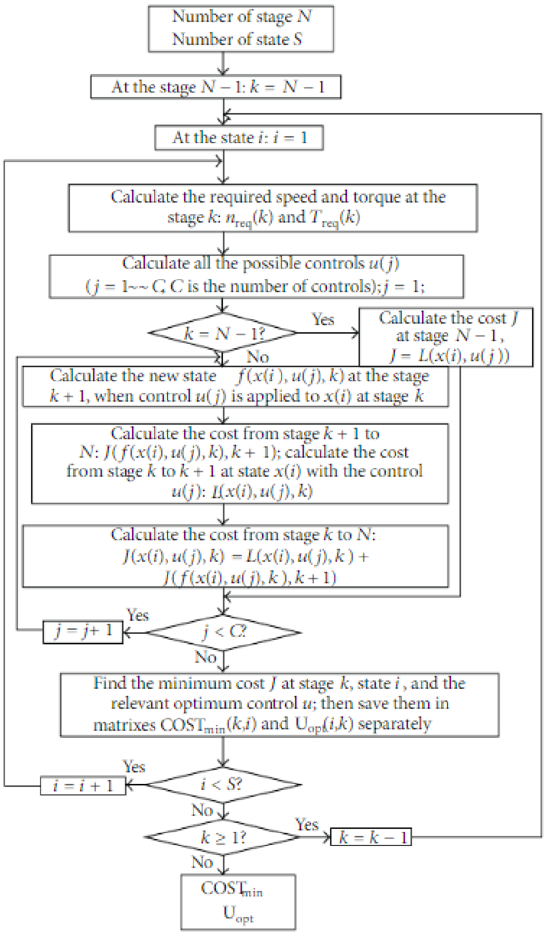


Figure 1.11 : The flow chart of DP problem backward [13].

The genetic algorithm is a method based on natural selection, the mechanism that drives biological evolution, for addressing both limited and unconstrained optimization problems. A population of individual solutions is repeatedly modified by the genetic algorithm. The genetic algorithm selects individuals from the present population to be parents at each phase and uses them to generate the following generation's children. The population "evolves" toward an optimal solution over generations. The genetic algorithm can be used to handle a number of optimization problems that aren't well suited for traditional optimization techniques, such as issues with discontinuous, nondifferentiable, stochastic, or highly nonlinear objective functions [14].

In 2015, J. Nellen et al. made a study about genetic algorithm-based energy management in PHEVs. In the study, the main objective is to define torque split between the ICE and EM. Due to this reason, they used genetic algorithm for the optimization of variable tuning to minimize the weighted sum of functions that makes evaluation for the fuel consumption, the battery state of charge and drivability aspects [15]. The basic algorithm of genetic algorithm is shown in below Figure 1.12.

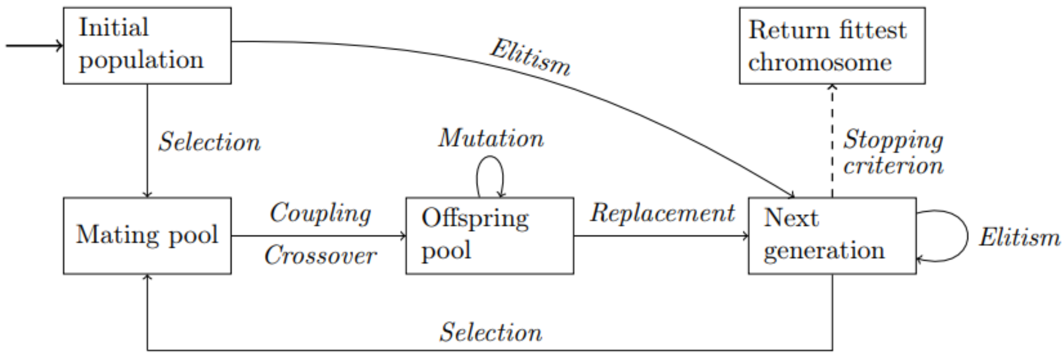


Figure 1.12 : Schematic workflow of a genetic algorithm [15].

Employing a MATLAB/Simulink model including the vehicle dynamics, GA-based control approach is examined using 2-point-crossover and uniform mutation, and compared it to other control strategies. As comparison driving cycles, NEDC (New European Driving Cycle), FTP 75 and the HWFET of the standard driving cycles are used. According to the simulation results, in black and blue bold print, the lowest and greatest fuel consumption statistics are emphasized. In NEDC, genetic algorithm-based result 1.8% better than the best considered reference strategy, on FTP75 side, the improvement rate is about 1.35% and on HWFET side it is about 0.85%, the values are shown in Table 1.1 [15].

Table 1.1 : Fuel consumption and SOC comparison for different strategies [15].

	NEDC		FTP-75		HWFET	
Strategy	Fuel cons.	*SoC*	Fuel cons.	*SoC*	Fuel cons.	*SoC*
ICE	**428.101**	0.7000	**727.606**	0.7000	**379.841**	0.7000
EM	392.686	0.6246	593.519	0.5336	360.903	0.5805
RDP	387.081	0.6246	591.783	0.5614	350.621	0.5807
ADP	388.726	0.6245	589.266	0.5336	352.513	0.5805
A-ECMS	390.239	0.6246	592.168	0.5442	356.356	0.5806
T-ECMS	391.641	0.6246	592.514	0.5335	358.858	0.5805
GA_{best}	**380.123**	0.6263	**581.001**	0.5398	**347.776**	0.5789

As explained in the previous section, contrary to offline energy management systems, online energy management systems can handle instantaneous optimization at each instant without knowing the complete driving cycle in advance and only achieve local optimal outcomes. Online EMSs can be divided 2 main features, instantaneous optimization-based EMSs and predictive EMSs. Instantaneous methods can be categorized like equivalent consumption minimization strategy (ECMS) and adaptive equivalent consumption minimization strategy (A-ECMS). On the predictive side, the most common used method is model predictive control (MPC). In this thesis, in the chapter 4, details of ECMS methodology are given, so main focus in this chapter are the other methods.

A-ECMS is introduced in 2005 by G. Rizzoni et al. for real-time energy management system for hybrid electric vehicle. In this study, the main parameter of ECMS methodology equivalent factor is estimated by framework an on-the-fly algorithm for changing driving conditions as shown in Figure 1.13. The main target to periodically refresh the equivalent factor according to the driving conditions. They used MATLAB/Simulink for calculating the needed torque to overcome instant resistance forces for changing conditions [16].

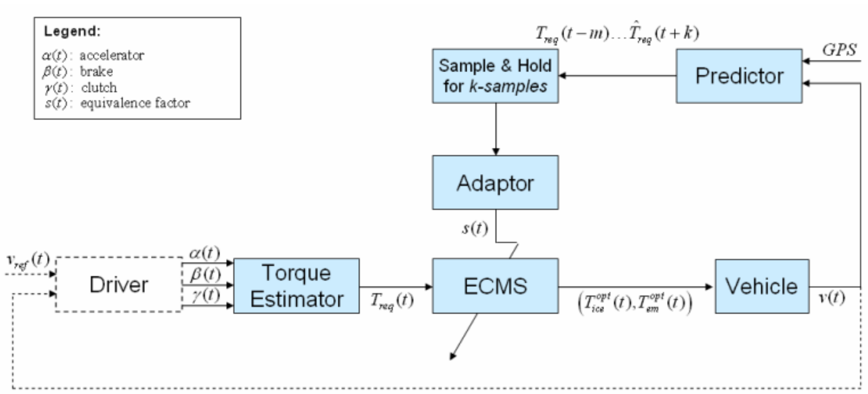


Figure 1.13 : Control block diagram of the A-ECMS [16].

Basic ECMS strategy involves calculating the instantaneous cost function as a sum of the fuel consumption and an equivalent fuel consumption due to the SOC change. The instantaneous cost function, according to approach, is the total of the fuel consumption from ICE and an equivalent fuel consumption connected to the use of the EM. The logical controller creates the current mission by combining historical and expected vehicle speed and GPS data, and then finds the control settings that optimize fuel usage while keeping the charge sustainability restriction in mind and this logic in named as A-ECMS [16]. According to their study, for different kind of driving cycles, fuel economy improvement is shown in the Table 1.2. Also, the results are compared with dynamic programming and ECMS methodology results that conducted on the same vehicle dynamic model.

Table 1.2 : Simulation results comparison for different driving cycles [16].

Driving Cycle	Pure thermal mpg	DP mpg	DP Improv.	ECMS opt mpg	ECMS opt Improv.	A-ECMS mpg	A-ECMS Improv.
FUDS	22.1	25.7	16.4%	25.7	16.3%	25.5	15.5%
FHDS	24.8	26.0	4.9%	25.8	4.1%	25.8	3.9%
ECE	20.8	24.5	18.2%	24.5	18.0%	24.5	17.9%
EUDC	23.3	24.8	6.3%	24.7	6.2%	24.7	6.1%
NEDC	22.2	24.5	10.7%	24.5	10.7%	24.4	10.1%
JP1015	21.0	25.2	20.1%	25.1	19.8%	24.8	18.2%

Model predictive control (MPC) makes predictions about the system's future behavior using a model of the system. MPC features a preview feature that allows it to incorporate future reference data into the control issue in order to improve controller perform [17].

In 2015, J. Zang et al. made a study regarding a model predictive control-based energy management system for a plug-in hybrid electric vehicle using multi-step Markov prediction method. They used dynamic programming to solve the optimization problem in the prediction horizon. The main focus on the fuel economy while electric consumption is more efficient than the fuel consumption and due to this reason, they defined a cost function including penalty coefficient, which changes depending on deviation from target SOC under the Figure 1.14 system constraints [18].

$$\begin{cases} n_{e\text{-min}} \le n_e(k) \le n_{e\text{-max}} \\ T_{e\text{-min}}\left(n_e(k)\right) \le T_e(k) \le T_{e\text{-max}}\left(n_e(k)\right) \\ T_{ISG\text{-min}}\left(n_{ISG}(k), \mathrm{SOC}(k)\right) \le T_{ISG}(k) \le T_{ISG\text{-max}}\left(n_{ISG}(k), \mathrm{SOC}(k)\right) \\ T_{m\text{-min}}\left(n_m(k), \mathrm{SOC}(k)\right) \le T_m(k) \le T_{m\text{-max}}\left(n_m(k), \mathrm{SOC}(k)\right) \\ \mathrm{SOC}_{\min}(k) \le \mathrm{SOC}(k) \le \mathrm{SOC}_{\max}(k) \\ n_m(k) = n_e(k) = n_{ISG}(k) \quad \text{if} \quad clutch = 1 \\ n_e(k) = n_{ISG}(k) \quad \text{if} \quad clutch = 0 \\ T_e(k) + T_{ISG}(k) = 0 \quad \text{if} \quad clutch = 0 \end{cases}$$

Figure 1.14 : The constraints of system variables [18].

According to their simulation results, they have run a simulation around 180 km with repeating 31 consecutive Chinese typical urban drive cycle with the 65% maximum weight of vehicle and although the MPC strategy does not achieve best fuel efficiency, it does improve fuel economy by around 10% over the pure electric driving, hybrid charge depleting and hybrid charge sustaining combination strategy (PED+HDCD+HDCS) [18].

2. GENERAL INFORMATION ABOUT HYBRID ELECTRIC VEHICLES

Hybrid electric vehicles have an internal combustion engine that is paired with an electric motor. As a result, the vehicle satisfies the principle of high efficiency without the use of external power. The electric motor is connected in series or parallel to the internal combustion engine in this system, which is the foundation of hybrid technology. The system's hybrid power regulator connects the battery and the electric motor, providing the vehicle's electricity traction system and regeneration system as well. The essential energy that is used for traction is stored in a high-voltage lithium-ion battery. During braking or deceleration, regeneration recovers some of the energy lost during deceleration, which is then stored in the lithium-ion battery. The roots of hybrid engine technology can be traced all the way back to 1902. Ferdinand Porsche invented a gasoline-electric engine for the first time in 1902 and designed first hybrid vehicle like shown in below Figure 2.1. This vehicle is also known as mixte-wagen [19].

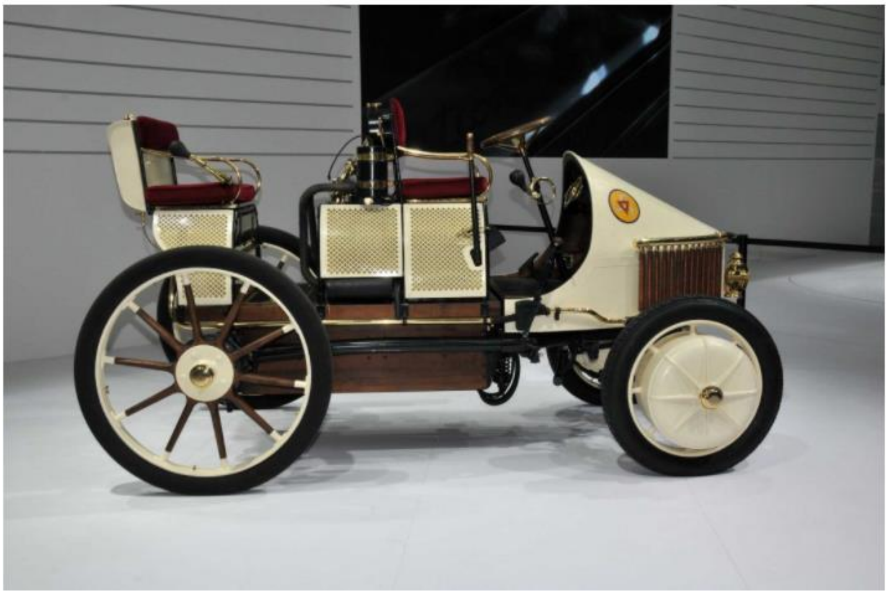


Figure 2.1 : The first hybrid vehicle “Mixte-Wagen” in the history 1902 [20].

Following that, in collaboration with an Austrian wagon manufacturer, a vehicle engine was developed that converges to today's hybrid technology by adding an electric motor, generator, and battery to a 4-cylinder Daimler engine [20]. Today most of the market sales share belongs to HEVs after conventional engines.

As it can be seen in Figure 2.2, hybrid electric vehicles accounted for 18.4% of total passenger car sales in the EU in the first quarter of 2021. Battery-electric vehicles accounted for 5.7% of all new auto registrations in the first quarter, while plug-in hybrids accounted for 8.2% of EU registrations. Traditional fossil-fuel cars continued to lose ground in the European Union, even though gasoline and diesel still accounted for 65.4% of total vehicle sales.

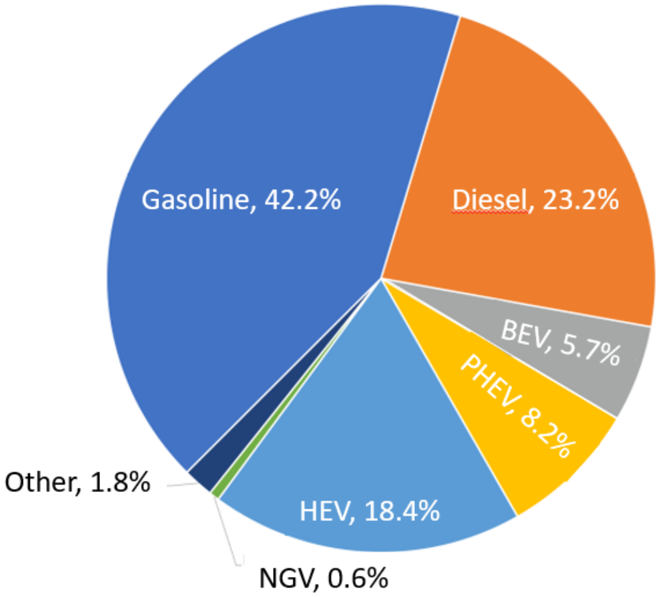


Figure 2.2 : New passenger cars by fuel type in the EU, Q1 2021 [21].

As it can be seen in Figure 2.3, hybrid electric vehicles (HEVs) remained the largest volume category of alternatively powered passenger cars in the EU, with 469,784 units registered from January to March 2021 (an increase of 101.6% compared to the same period last year).

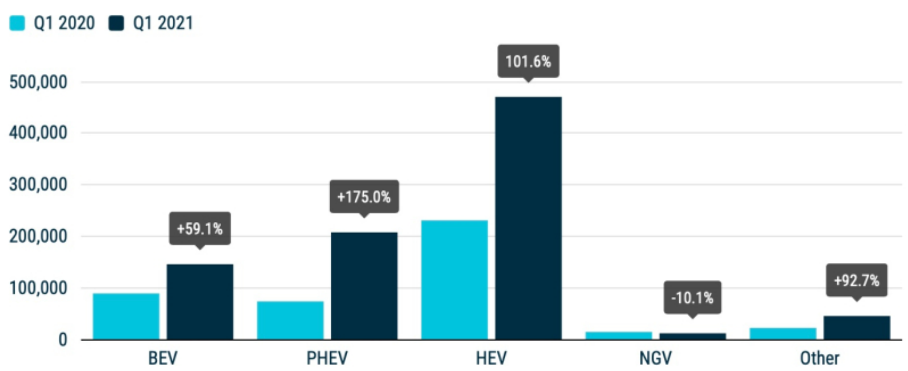


Figure 2.3 : New passenger car registrations in the EU by alternative fuel type [22].

2.1 Hybrid Electric Vehicle Components

In this section, the key components of a hybrid vehicle are explained briefly. As the main components, hybrid electric vehicles consist of internal combustion engine (ICE), electric motor, DC-DC converter, traction battery pack, exhaust system, fuel tank, power electronics controller, thermal system (cooling) and transmission. All the components are shown in Figure 2.4 together.

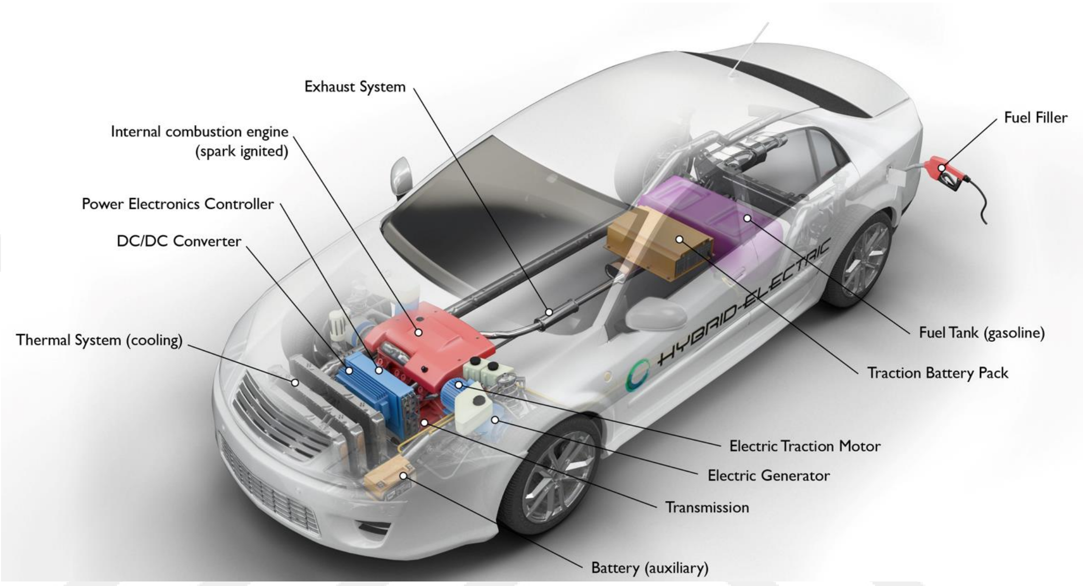


Figure 2.4 : Key components of hybrid electric vehicle [23].

2.1.1 Internal combustion engine

In this setup, gasoline fuel is injected into either the intake manifold or the combustion chamber, where it is mixed with air before being ignited by a spark from a spark plug. Internal combustion engine causes pollutant emission gaseous and CO2 which leads to greenhouse effect in earth. Main target with hybridization is to provide better ICE efficiency during its working lifetime for decreasing drive off emissions and fuel consumption.

2.1.2 Electric motor

Electric motor provides traction to the vehicle's wheels and drives the vehicle with the help of the traction battery pack. In some electric motors, electric motor works as a generator and during braking maneuvers, generates electricity from the revolving wheels and transfers it to the traction battery pack. This case is named as recuperation in the automotive nomenclature.

2.1.3 DC-DC converter

This device converts higher-voltage DC power from the traction battery pack to lower-voltage DC electricity required to power vehicle accessories and recharge the auxiliary battery.

2.1.4 Traction battery pack

Electricity is stored here for using by the electric traction motor. During recuperation, it is charged by the electric motor which is working as a generator mode. In plug-in hybrid vehicles, it is possible to charge it from external electric source.

2.1.5 Exhaust system

The exhaust system is responsible for transferring the exhaust gases from the engine out to the tailpipe. A three-way catalyst is used in the exhaust system to reduce tailpipe emissions. Also, it includes particle filter which is grabbing the unburned fuel particles (soot) to reduce particulate number and particulate mass emissions.

2.1.6 Fuel tank

This tank stores fuel in the tank the car until the engine needs it.

2.1.7 Power electronics controller

This unit controls the speed of the electric traction motor and the torque by managing the flow of electrical energy supplied by the traction battery. This component can be named as inverter in some applications.

2.1.8 Thermal system cooling

This system keeps the internal combustion engine, electric motor, power electronics, traction battery and other components within a safe operating temperature range. Especially in hybrid electric vehicles, it is so critical to provide available temperature ranges for providing better battery performance.

2.1.9 Transmission

To give a motion to the wheels, the transmission transmits mechanical power from the engine and/or electric traction motor. In battery electric vehicles, due to wide range torque band of electric motor, 1 or 2 different gears are used. This provides a total mass decrease in weight in electric vehicles but, the mass effect of high voltage battery and powerful electric machine in electric vehicles must be taken into the account.

2.2 Hybrid Electric Vehicle Types

A hybrid electric vehicle can be splitted in to 4 main hybrid types consist of Micro Hybrid, Mild Hybrid, Full and Plug-in hybrid. The type of hybridization is defined regarding the functions that vehicles have capability to do them. A hybrid electric vehicle can perform at least one or more of the following functions [24].

- Engine Stop/Start
- Electronic Torque Assistance
- Energy Recuperation (regenerative braking)
- Electric Driving
- Battery Charging (during driving)
- Battery Charging (from the grid)

2.2.1 Engine stop/start

The stop/start (S&S) function turns off the internal combustion engine when the vehicle is motionless, without the driver's interaction (through the ignition key). This feature lowers the vehicles over all fuel consumption. The engine is automatically restarted when the driver indicates that he or she wants to drive (clutch pedal pressed or brake pedal released).

Most vehicles with an idle stop/start function also contain an energy management function that optimizes the use of low voltage (12V) battery energy. The major role of the low voltage battery in a traditional ICE car with no energy management is to generate the electrical energy required for the engine to start. The alternator (generator), which is placing a load torque on the engine, supplies the electrical energy for all the electrical consumers after the engine has started.

Even though the engine is running, the battery sends electrical energy to the consumers if the car has an energy management function. As a result, the alternator does not need to produce electrical energy, its load torque is almost zero, and fuel consumption is reduced. Further, the battery is recharged when the engine is working in the most fuel-efficient points or when the vehicle is braking (through energy recuperation).

2.2.2 Electric torque assistance

The electric motor can supply more torque to the wheel, enhancing the powertrain's overall torque responsiveness. When the driver depresses the accelerator pedal, the powertrain is asked to provide additional torque. In order to deliver the desired torque, an internal combustion engine (particularly a diesel) has a certain delay. The internal combustion engine's torque response delay is caused by a number of factors [24].

- The mechanical inertia of the moving parts
- The inertia of the air in the intake manifold
- The torque restriction (to prevent smoke in the exhaust)

The electric motor can assist the powertrain in these situations, known as torque transients (load point shifting operating point), by delivering additional torque to compensate for the engine torque response delay. The function is named as torque filling.

The maximum torque capability of an internal combustion engine is determined by the engine speed. The maximum overall torque of the powertrain is enhanced by adding the electric motor torque to the engine torque (positive offset). This function is called torque boost and can be supplied only for a short duration of time (order of seconds) due to battery depletion constraints. Mild hybrid electric vehicles (MHEV), full hybrid electric vehicles (FHEV), and plug-in hybrid electric vehicles (PHEV) typically provide electric torque assistance (PHEV).

2.2.3 Energy recuperation

When the driver presses the brake pedal, the vehicle must slow down. In these cases, in order to reduce the vehicle speed, braking torque is needed at the wheels. There are numerous techniques to achieve the total needed braking torque at the wheels:

- Only with the mechanical brakes (hydraulic brakes)
- Additional powertrain braking at wheel level

When the driver request brake on a vehicle with a conventional powertrain, merely on internal combustion engine side, the fuel injection is interrupted (fuel-cut off) and the engine overruns (engine braking). The overall torque losses of the engine (friction torque + pumping losses + auxiliary devices) are equal to the amount of engine brake.

But in the case when the driver request braking on hybrid electric vehicle, a negative torque can be requested from the electric motor, enhancing the powertrain's braking performance. During vehicle braking, the electric machine in all hybrids electric vehicles is in generator mode. The vehicle's kinetic energy rotates the generator's rotor, overcoming its negative torque, and electrical energy is produced. The amount of electrical energy generated during braking (recuperation/regeneration) depends on the power of the electrical motor.

2.2.4 Electric driving

The vehicle can be driven in electric mode if the electric motor is powerful enough (EV). The internal combustion engine is turned off in this mode, and the electric motor provides all the torque required for vehicle propulsion. Due to the limited energy available in the battery in full hybrid electric vehicles, the electric mode is only available up to vehicle speeds of 5–10 kph. The high voltage battery in plug-in hybrid electric vehicles has a greater capacity, allowing for EV mode up to speeds of 140 kph [25].

2.2.5 Battery charging during driving

To avoid irreversible harm, every battery has a minimum state of charge (SOC) that must be maintained. The theoretical amount of electrical energy accessible in the battery is represented by the state of charge. If a battery's SOC reaches 100 percent, it signifies that the maximum theoretical quantity of electrical energy that can be used has been reached. It is allowed to use 78 – 80 % of the theoretical maximum if the battery's minimum SOC is 20-22 %, this minimum rate is decided by the manufacturer [26]. The minimum SOC varies depending on the battery's size, power, and chemistry. In the Figure 2.5, minimum SOC battery function of hybrid electric vehicle is shown. It is clear that, in the plug-in hybrid vehicles, minimum allowed SOC is lower than the others due to its high voltage. If Wh or Ah capacity is taken into account, much more consumption is allowed due to longer electric driving range.

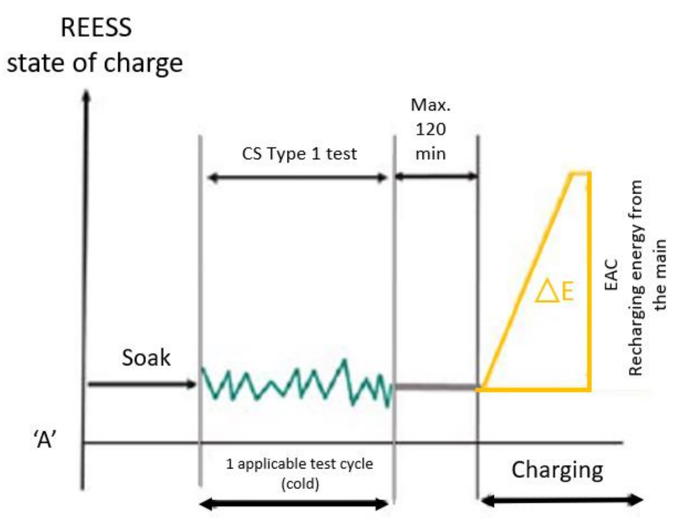
Type of hybrid electric vehicle	Micro (S&S)	Mild (MHEV)	Full (FHEV)	Plug-in (PHEV)
Minimum battery SOC [%]	80 … 90	40 … 60	30 … 50	10 … 20
Battery voltage [V]	12	48 / 160	200 – 300	300 – 400
Battery chemistry	lead-acid	lithium-ion / nickel – metal hydride	lithium-ion	lithium-ion

Figure 2.5 : Minimum SOC battery function of hybrid electric vehicles [24].

In any hybrid electric vehicle, regarding the battery SOC level, the driving mode is determined like in the following [27].

- Charge Depleting
- Charge Sustaining
- Charging

The electrical energy is accessible for usage after the battery is fully charged. The battery is in charge deplete mode in this situation. When the battery's SOC falls below a certain threshold, the internal combustion engine is responsible for charging the battery such that the SOC does not go below that threshold. The battery is in charge sustain mode in this situation. The kinetic energy of the vehicle is turned into electrical energy and stored in the battery when it brakes. The battery is in charging mode in this situation. Also, in the plug-in electric vehicles, it is so crucial to travel in pure electric driving mode without any ICE activation and especially in new hybrid cars, it is a key parameter to be compared. If electric range of a hybrid vehicle is enough for most people's everyday trip needs, it means there will be no CO2 emissions, at least as long as battery meets the targets [28]. In below Figure 2.6, example of type 1 charge depleting and charge sustaining tests are shown.



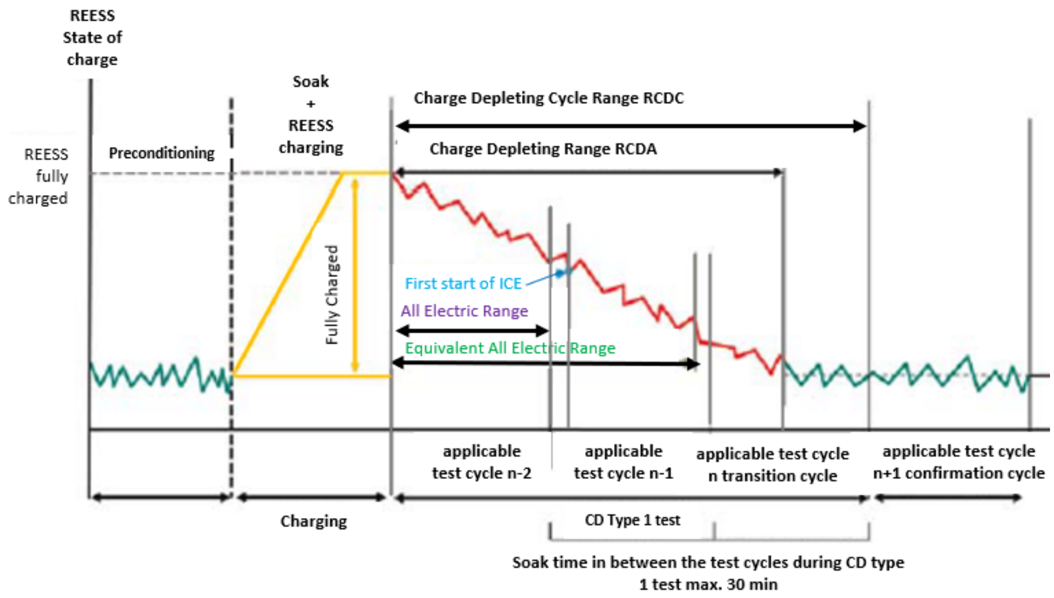


Figure 2.6 : Charge depleting type 1 test with subsequent charge-sustaining type 1 test [29].

2.2.6 Battery charging from grid

In terms of battery charging, the main difference between a full hybrid electric vehicle and a plug-in electric vehicle is that the PHEV may also be charged by plugging it into a power outlet. The location where the AC power is transformed; inside or outside the car, is the difference between AC and DC charging.

In the case of, the converter is integrated into the vehicle, it is referred to as an "onboard charger," but it's a converter. It converts AC to DC electricity before feeding it into the car's battery. Most chargers use AC power, which is the most prevalent charging option for electric vehicles today.

Unlike AC chargers, DC chargers have the converter built in into the device. That means it can supply power straight to the vehicle's battery, bypassing the onboard charger like shown in Figure 2.7. When it comes to EVs, DC chargers are bigger, faster, and an amazing development [30].

The charging curve is another significant distinction between AC and DC charging. The power going to an EV when using AC charging is a flat line (not much of a curve at all). This is owing to the onboard charger's small size, which can only accept a limited amount of power over a prolonged length of time. DC charging, on the other hand, results in a charging curve that degrades with time. This is because the EV's battery accepts a higher flow of power at first, but gradually requests less as it achieves full capacity [31].

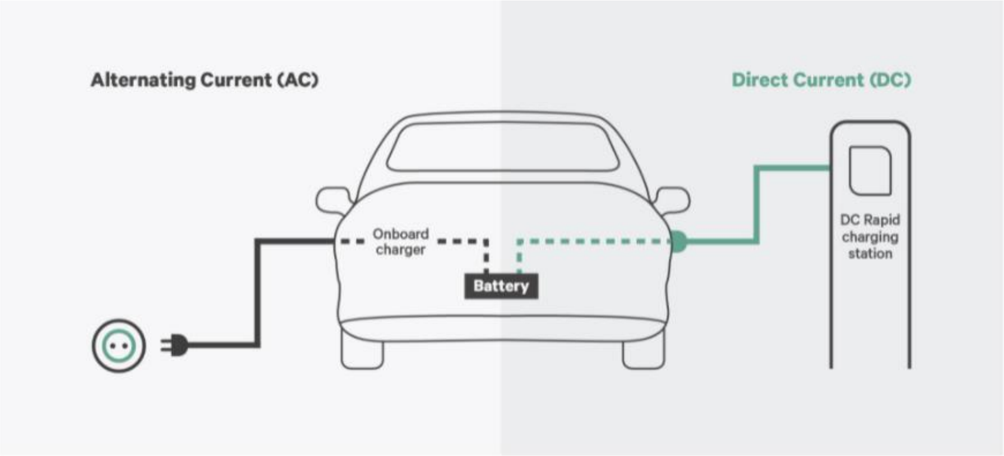


Figure 2.7 : AC and DC charger [30].

As a result, all the functions that already mentioned in previous section is summarized in the Figure 2.8. Micro hybrids have S&S, energy recuperation and LV battery charging functionalities while mild hybrid have additionally had electric torque assistance due to higher operating voltage. But in both of them, there is no pure electric driving. Full hybrid electric vehicles and plug-in electric vehicles includes lots of similarities like S&S, electric torque assistance, regenerative braking, battery charging but one of the big differences between them is pure electric driving range. Full hybrid electric vehicles use the electric drive functionality especially in low efficiency zones like drive-off phases or low speed driving region.

Functions	Type of hybrid electric vehicle			
	Micro (S&S)	Mild (MHEV)	Full (FHEV)	Plug-in (PHEV)
İdle stop/start	•	•	•	•
electric torque assistance fill and boost		•	•	•
energy recuperation regenerative braking	•	•	•	•
electric driving EV mode			•	•
battery charging during driving	•	•	•	•
battery charging from the grid				•

Figure 2.8 : Type of hybrid electric vehicles depending on their functionalities [24].

2.3 Hybrid Electric Vehicle Topologies

Regarding the design of the powertrain and allocation of electric motor, hybrid electric vehicles are splitted to 3 main categories: series hybrid, parallel hybrid and series-parallel (power-split) hybrid. In the following section, each hybrid types are explained in detail.

2.3.1 Series hybrid

The basic configuration of series hybrid is shown in Figure 2.9.

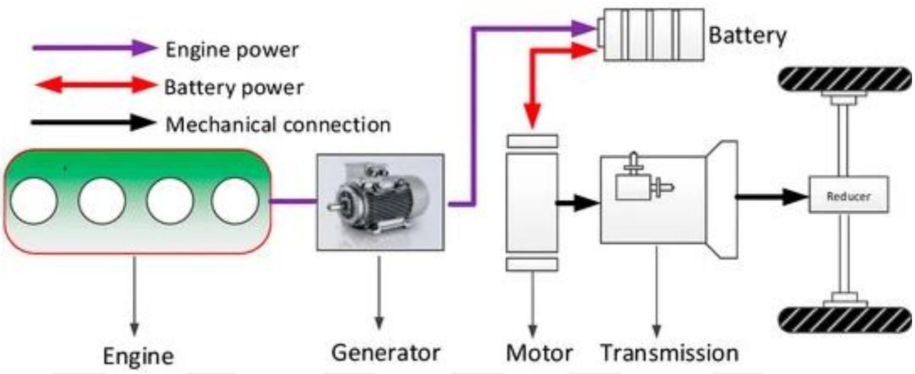


Figure 2.9 : Series hybrid configuration [32].

The simplest hybrid arrangement is a series drivetrain. The electric motor is the only source of power for the wheels in a series hybrid. The battery pack or a generator powered by a gasoline engine provides electric power to the motor. Electronic control unit calculates how much electricity comes from the battery and how much from the engine/generator. The battery pack is recharged by both the engine/generator and regenerative braking.

Frequent drive off and braking, where gasoline and diesel engines are inefficient, is the point where series hybrids are preferred. The electric control unit can decide to run the motor solely on the battery pack, conserving the engine for more economical situations.

In a series drivetrain, the engine is normally smaller because it only has to satisfy certain power demands; but on the other hand, the battery pack is frequently more powerful than in parallel hybrids to meet the remaining power demands. Because of the larger battery and motor, as well as the generator, series hybrids are more expensive than parallel hybrids [33].

2.3.2 Parallel hybrid

The basic configuration of parallel hybrid is shown in Figure 2.10.

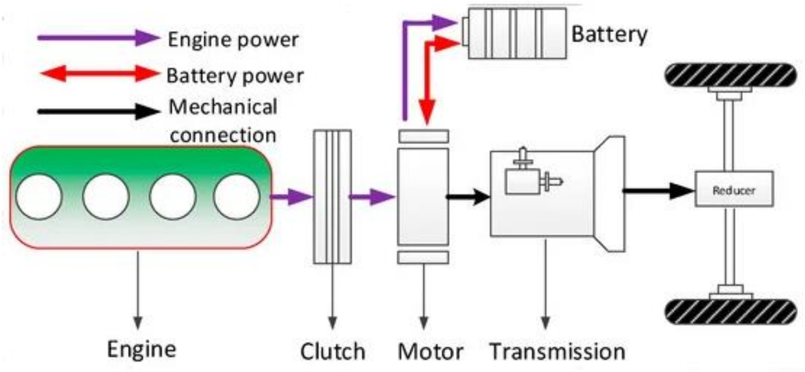


Figure 2.10 : Parallel hybrid configuration [32].

The engine and electric motor work together to provide the power that moves the wheels in vehicles with parallel hybrid drivetrains. Parallel hybrids have a smaller battery pack than series hybrids and rely on regenerative braking to keep the battery charged. Parallel hybrids use the motor as a generator for extra recharging when power demands are minimal, similar to how an alternator in a traditional vehicle does.

Due to the engine is directly connected to the wheels in parallel drivetrains, the inefficiency of transitioning mechanical power to electrical and back is reduced, resulting in higher highway efficiency for parallel hybrids.

Depending on the allocation position of electric motor on powertrain, different parallel configurations are occurred; P0, P1, P2, P3 and P4 as can be seen in figure 2.11. In the following sub-section, each of them is explained in detail.

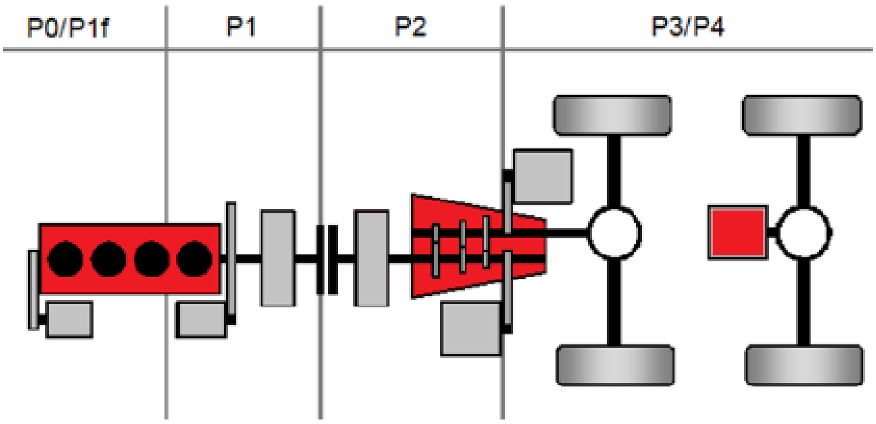


Figure 2.11 : Hybrid electric vehicle different powertrain configuration.

2.3.2.1 P0 configuration

In this hybrid configuration, also known as BiSG (Belt integrated Starter Generator), is the most cost-effective one because to the 48V system's little influence on the existing vehicle architecture.

There are two key cost drivers in a hybrid electric vehicle application: the influence on current powertrain components and the high voltage battery. The vehicle and transmission design should be kept the same as a conventional vehicle to reduce integration expenses. By replacing the 12V alternator with a 48V electric machine, the simplest approach to achieve the lowest cost is to integrate the 48V electric machine into the already existing engine accessories belt drive (generator).

The internal combustion engine (ICE) and the electric machine cannot be separated in the BiSG architecture; they are mechanically linked through the auxiliary belt. As a result, when the electric machine provides boost torque or recovers electrical energy, one of the disadvantages of this setup is that the engine friction torque will be a parasitic loss for the electric machine. Today, the P0 configuration is generally employed in 48V applications for features like stop-start, additive boost, and regenerative braking [34]. In Figure 2.12, simple architecture is shown.

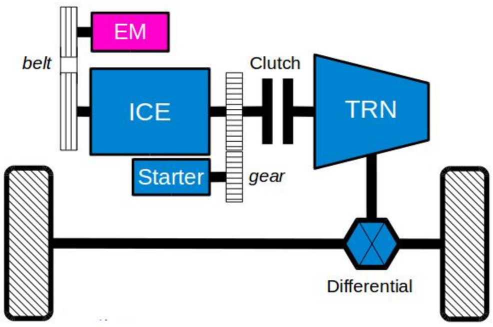


Figure 2.12 : P0 belt starter generator hybrid configuration [34].

2.3.2.2 P1 configuration

In the P1 configuration, the starting generator is positioned directly on the crankshaft, which converts the linear motion of pistons into rotary motion). Due to there is no belt drive, this architecture produces more torque than the P0 architecture, and it is more efficient because there are no belt losses. However, due to the lack of a torque/speed relationship between the crankshaft and the starter generator, one notable disadvantage of this method is that torque requirements can be high. Additionally, in P1 layout has more cost and greater influence on existing vehicle architecture, can be seen in Figure 2.13. As a result, vehicle manufacturers and system suppliers are not investing in the development of a crankshaft-mounted integrated starter generator solution for MHEVs [34].

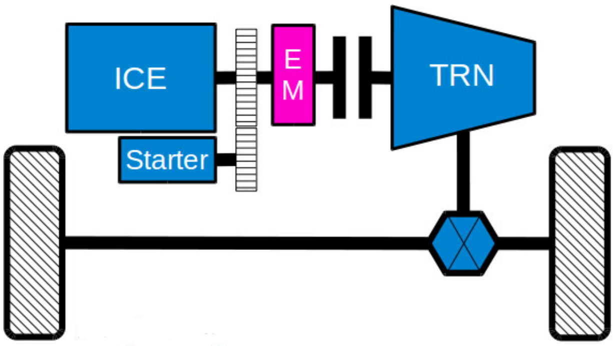


Figure 2.13 : P1 crankshaft integrated hybrid configuration [34].

2.3.2.3 P2 configuration

The P0 and P1 architectures are both installed on the engine side, without the possibility of mechanical disconnection. These layouts are not so efficient due to higher friction and torque losses and also ICE off, coasting recuperation is not allowed in these configurations. But on the other hand, in the P2, P3 and P4 hybrid layouts, electric machine is mounted input/output shaft of the gearbox (P2/P3 respectively), and system allows higher recuperation efficiencies and ability to provide hybrid functionalities thanks to mechanical disconnect (e.g., e-drive).

The P2 architecture, which is either built into the transmission on the input shaft or attached to the side, increases recuperation efficiency and electrical driving capabilities. The highest level of the above-mentioned benefits is obtained by mounting the solution on the output shaft (P3). The cost of integration is an evident disadvantage of the shaft mounted electrical machine [35]. As it can be seen in Figure 2.14 and 2.15, electric motor is mounted on input shaft side of transmission. It means, in this configuration, ICE off combinations are available like pure electric driving. In general applications, electric motor is more activated at the point where ICE is producing high pollutant emissions and CO2 depending on the SOC level of the battery.

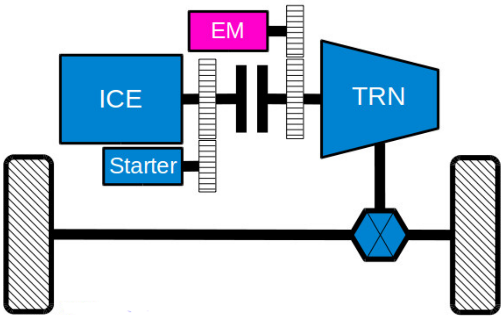


Figure 2.14 : P2 hybrid configurations – Side electric machine [34].

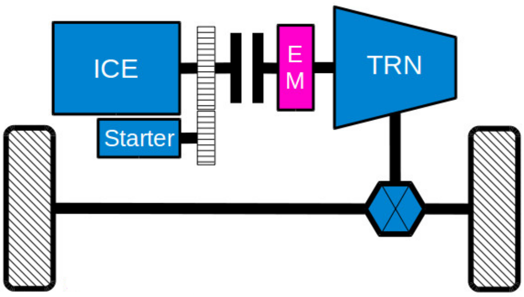


Figure 2.15 : P2 hybrid configurations – Integrated electric machine [34].

2.3.2.4 P3 configuration

In the P3 hybrid configuration, electric motor is mounted on the output shaft of the transmission. P3 and P4 configurations show lots of similarities in terms of hybrid driving so much more detailed information is given in P4 section. Basic P3 configuration is shown below Figure 2.16.

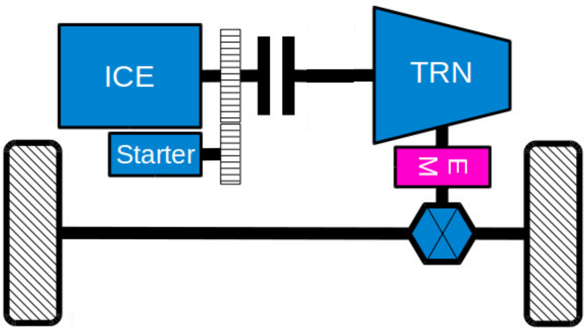


Figure 2.16 : P3 hybrid configuration [34].

2.3.2.5 P4 configuration

In P4 configuration shown in Figure 2.17, electric motor is mounted on the rear axle drive or wheel hubs. The P4 architecture enables the vehicle four-wheel drive feature, with an internal combustion engine driving the front axle and an electric motor driving the back axle. Highest energy recuperation potential is the key benefit of the P3 and P4 topology.

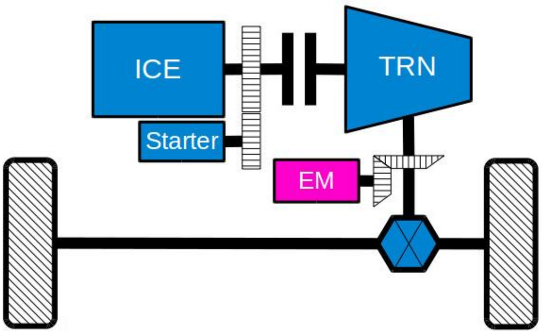


Figure 2.17 : P4 hybrid configuration [34].

2.3.3 Series parallel hybrid

The flexibility to operate as a series or parallel topology, which allows multiple operation modes and significantly improves overall efficiency under complex driving situations, is the most significant enhancement in the power-split architecture. Although the series path is often avoided due to its inefficiency, the fundamental benefit of this design is that the engine, generator, and motor speeds are all decoupled, providing for more control flexibility. The engine and two electric motors are connected to a power split device so that the power from the engine and the electric machines can be combined mechanically and electrically, permitting series and parallel operations as shown in Figure 2.18.

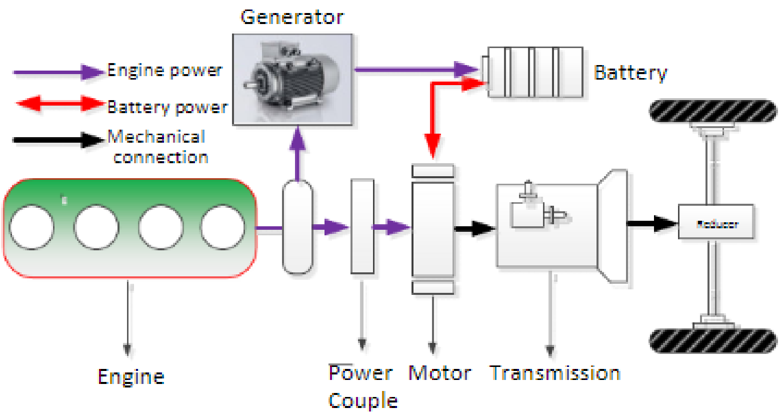


Figure 2.18 : Power split topology [34].

3. VEHICLE MODEL OF P2 PLUG-IN HYBRID ELECTRIC VEHICLE

In this thesis, P2 plug-in hybrid electric vehicle model is built in MATLAB Simulink tool. For the vehicle dynamic side, all the forces that acting on vehicle on lateral side are neglected. The model that calculates the total fuel consumption with ECMS methodology is shown in Figure 3.1. In the following section, sub-models are shown detailed.

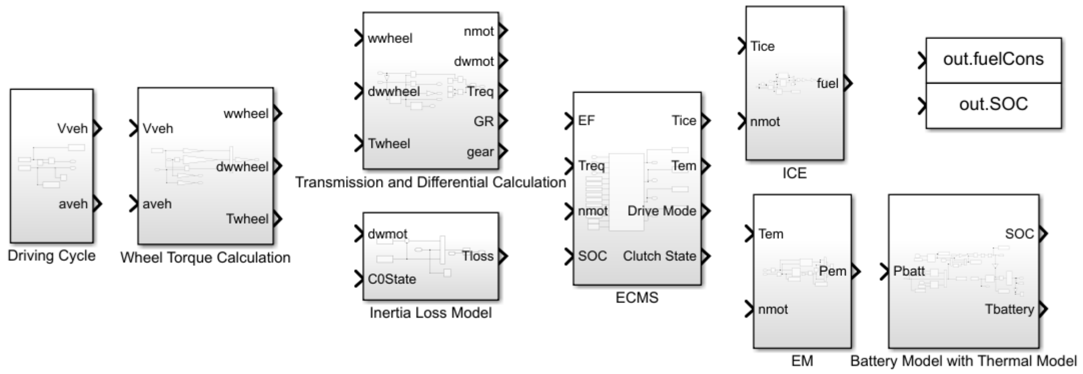


Figure 3.1 : P2 plug-in hybrid electric vehicle model.

3.1 Driving Cycle

For driving cycle section, vehicle speed and acceleration are given as inputs for any cycle that is requested to be run in the Simulink. All the related torque and loss calculations is done regarding these inputs. In the model, due to quasi static approach has been used, it is assumed that vehicle speed and acceleration has been followed without any error.

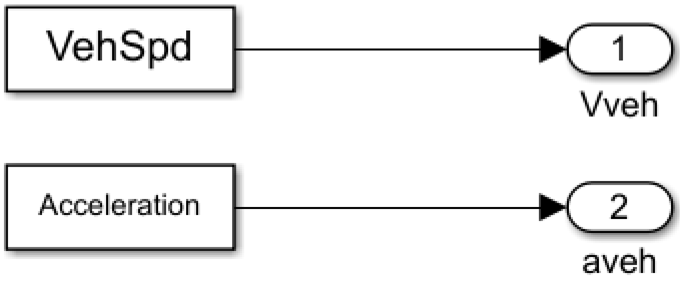


Figure 3.2 : Driving cycle inputs.

3.2 Wheel Torque Calculation

In this section, the torque value necessary for the traction at the wheel level, angular velocity and angular acceleration are calculated in the below Figure 3.3.

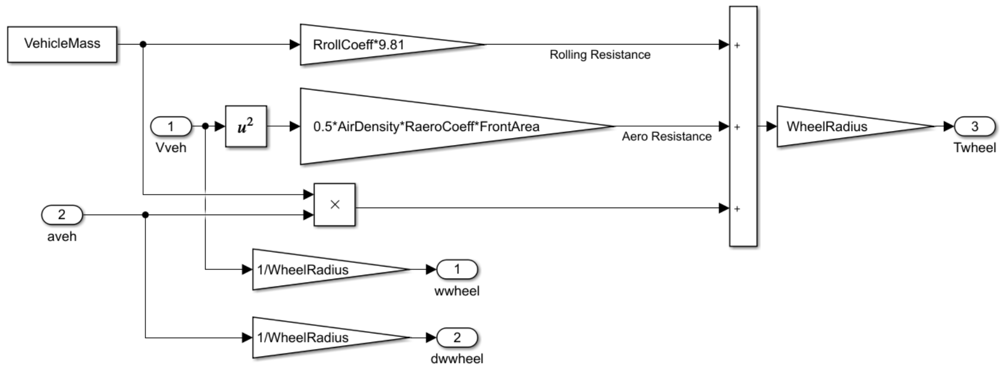


Figure 3.3 : Necessary torque on vehicle at wheel level.

For the torque calculation on wheel level, the below shown formula 3.1 is used:

$$T_{wheel} = (m_{vehicle}a_{desired} + R_{aero} + R_{rolling})*r_{wheel} \quad (3.1)$$

where $m_{vehicle}$ [kg] is the mass of the vehicle, $a_{desired}$ [m/s^2] is the desired acceleration, R_{aero} [N] is the aerodynamic resistance force, R_{roll} [N] is the rolling resistance force and r_{wheel} [m] is the wheel radius.

Aerodynamic resistance is found like in below formula 3.2:

$$R_{aero} = \frac{1}{2}\rho_{air}C_{drag}A_{front}{V_{Vehicle}}^2 \quad (3.2)$$

where ρ_{air} [kg/m3] is the density of air, C_{drag} [-] is the drag coefficient of the vehicle, A_{front} is the front area of the vehicle and V_{veh} [m/s] is the velocity of the vehicle.

Rolling resistance is found as following formula 3.3:

$$R_{roll} = \mu_r m_{vehicle} g \quad (3.3)$$

where μ_r [-] is the rolling coefficient and g [m/s^2] is the gravitational acceleration.

Angular velocity of the wheel is obtained with the following formula 3.4:

$$w_{wheel} = \frac{V_{veh}}{r_{wheel}} \quad (3.4)$$

Angular acceleration of the wheel is obtained with the following formula 3.5:

$$a_{wheel} = \frac{a_{veh}}{r_{wheel}} \tag{3.5}$$

3.3 Transmission and Differential Calculation

In this section, 9 speed automatic gearbox is used for the simulations. Gear shifts are just based on vehicle speed, due to main focus is on energy management system, gear shift strategies are considered in simple way. Also, due to reduce the powertrain calculation complexity, torque converter is not taken into account. The Simulink model can be seen in Figure 3.4.

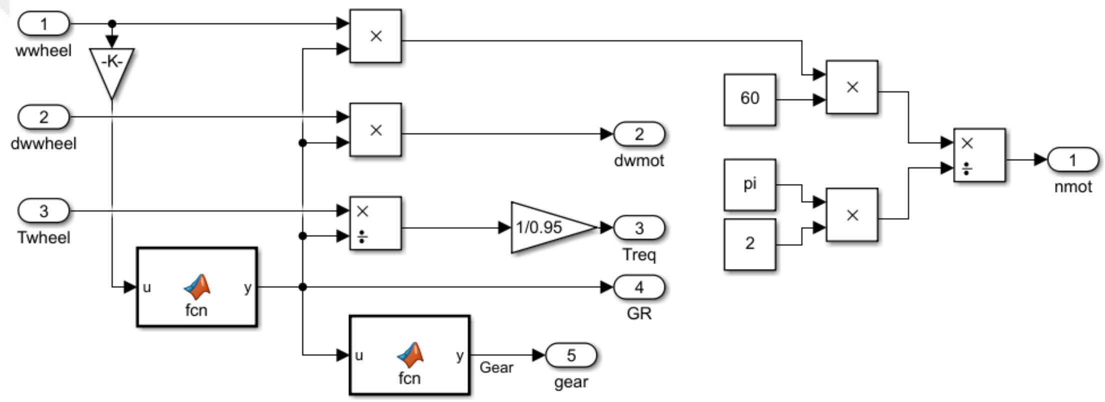


Figure 3.4 : Transmission and differential model.

In here, engine angular velocity is converted to rpm with using the formula 3.6.

Hereupon, engine speed [rpm] is used for ICE and EM speed calculations.

$$1\ rpm = \frac{2\pi}{60}\ rad/s \tag{3.6}$$

For total powertrain torque request, the following formula 3.7 is used:

$$T_{req} = \frac{T_{wheel}}{Gear\ Ratio} * \frac{1}{PTeff} \tag{3.7}$$

Powertrain efficiency is assumed as constant for all operating points and equals to 0.95. With this formula, powertrain level torque request is calculated. This value corresponds sum of EM and ICE torque value.

3.4 Inertia Loss Model

In this section, the loss that origined due to inertia of EM and ICE is calculated in Figure 3.5. In P2 configuration, the powertrain allows to pure e-drive, in this case C0 separation clutch is opened (it is working bitwise based, 0 is open, 1 is closed), ICE is disengaged, so ICE related inertia is not taken into account. On the other hand, if ICE and EM is activated at the same time, both inertia forces are calculated. The total torque loss is calculated as in formula

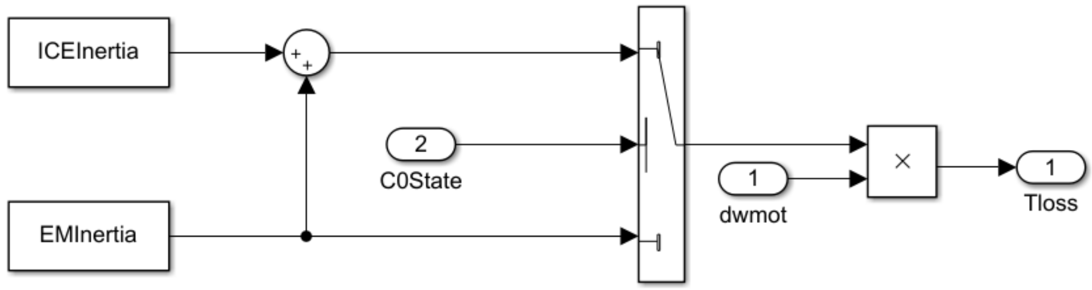


Figure 3.5 : Loss calculation for ICE and EM model.

$$T_{loss} = I_{total}\alpha_{mot} \tag{3.8}$$

where I_{total} [kgm^2] is the sum of inertia losses (ICE Inertia + Inertia) and α_{mot} is the [rad/s^2] is the angular acceleration of ICE and EM.

3.5 ECMS Structure

In this section, the algorithm of ECMS is implemented to vehicle model in MATLAB. Main inputs are like following; equivalent factor, total torque request that is calculated from the vehicle dynamic side using gear ratios, engine speed, SOC instant value for each simulation time, ICE full load table, ICE full load table speed breakpoints, ICE full load table torque breakpoints, ICE break specific fuel consumption map, electric motor efficiency map, electric motor efficiency map speed breakpoint, electric motor efficiency map torque breakpoint. Regarding the calculations inside the ECMS function, torque split is done with respect to fuel consumption cost function. Main outputs are torque request from ICE, torque request from EM, hybrid drive mode and clutch position. In this section, just the basic structure is shown but in the next section, more details about the algorithm are given. The code behind the logic is given in the Appendix A. In the Figure 3.6, the basic MATLAB function is shown.

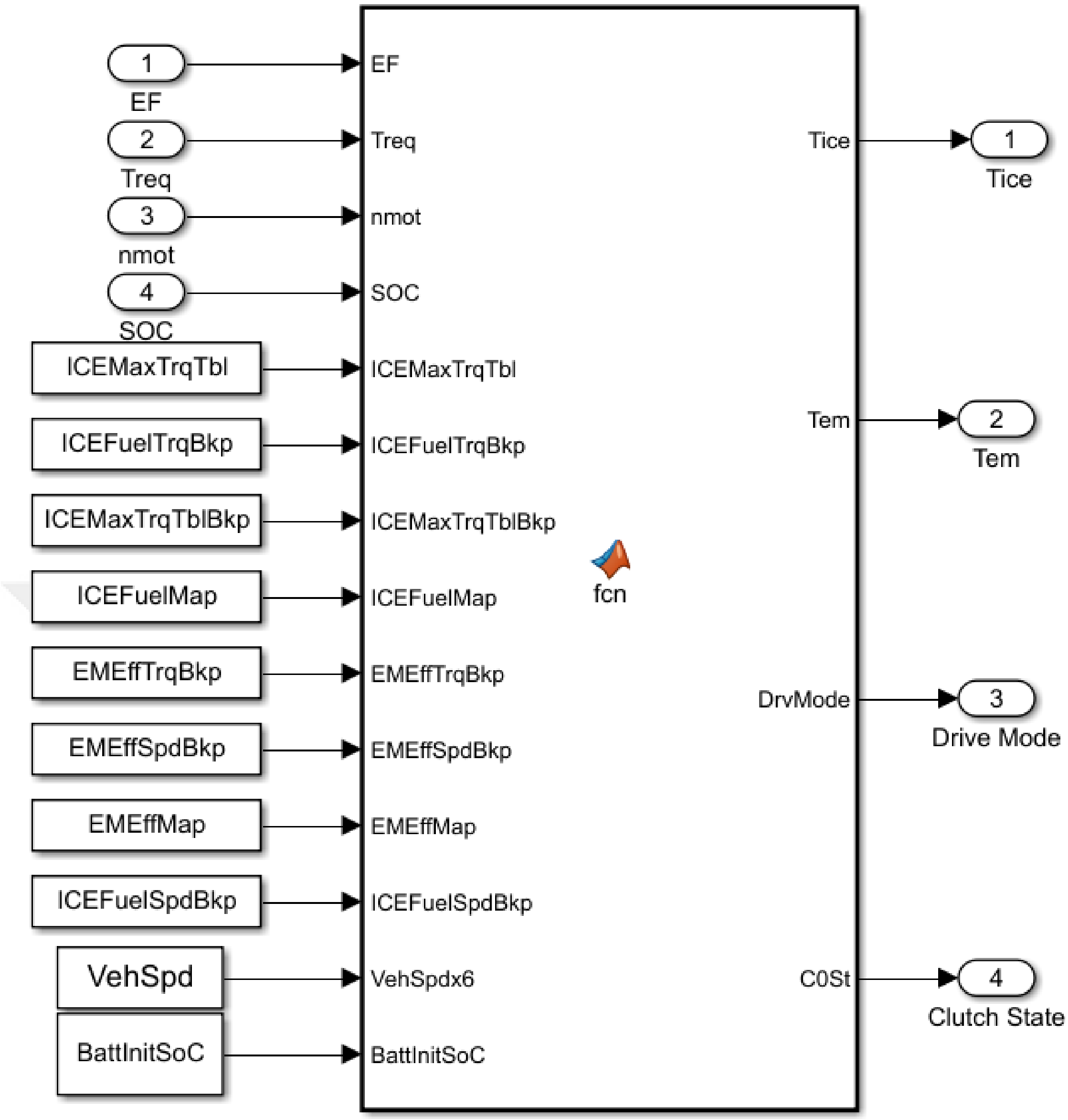


Figure 3.6 : Basic ECMS structure with its inputs and outputs in MATLAB.

In the ECMS algorithm, ICE torque request and EM torque request split is done using the cost function algorithm with equivalent factor to obtain minimum fuel consumption. For drive mode, in P2 hybrid structure, 5 different drive modes are used to simulate all available conditions on the vehicle.

3.5.1 Load point shifting – charging

In load point shifting - charging, both ICE and EM work, but EM is not used for traction. In the case that SOC goes below certain threshold that defined in the hybrid control unit, ICE produces more power and torque than the driver demand, and the difference between the produced and demanded is used for charging of high voltage battery. In this case, electric motor is used in generator mode, it charges the high voltage battery.

3.5.2 Hybrid discharging

In the hybrid discharging mode, both ICE and EM work at the same time and contrary to load point shifting – charging, EM is not used in generator mode, it is used for traction, so it consumes the high voltage battery. It is clear that, for that kind of discharging activation, the SOC level has to be higher than a certain threshold.

3.5.3 Start&stop

When the vehicle speed equals to “0” and ignition still on, ICE is switched off and electric motor works around 100 rpm to cool its components to increase efficiency for upcoming drive off.

3.5.4 Recuperation

In the recuperation, the working principle is similar with the load point shifting – charging, in both of them, EM is used in generator mode to charge the high voltage battery. But the main difference, under normal conditions, ICE is not activated during recuperation because, recuperation mostly activated during the braking and decelerations. If the recuperation efficiency on the wheel level increases, mechanical braking need that activated with hydraulic system reduces.

3.5.5 Pure electric drive mode

In the pure electric drive mode, just electric motor is used as traction source. For the vehicles that have big battery capacity, above a certain SOC threshold, electric drive mode is activated much more and electric range capacity is measured depending on how many meters driven on just with the electric motor. In this thesis study, especially for charge depleting test, when SOC of battery drops down to 13.9%, ICE is activated to keep the battery above a certain SOC threshold for battery health.

The last output of the ECMS model is clutch state. This clutch is named as separation clutch in the hybrid structures. This clutch working principle is similar with the clutch that is used in conventional vehicles. In P2 hybrid configuration, due to possibility of pure electric driving mode, ICE has to be disengaged from the powertrain and this is done thanks to K0 clutch. When the K0 clutch is opened (state 0), ICE is disengaged, in this case, the vehicle is driven just by electric motor, when the K0 clutch is closed (state 1), both EM and ICE work together.

3.6 Internal Combustion Engine Model

Internal combustion engine is modelled with a break specific fuel consumption map which use speed and torque as inputs. In here, for simulating the ICE working points like in real life, minimum torque request is saturated as 50 Nm to overcome frictional forces and the torque loss due to not modelled torque converter. On the other hand, for engine speed, the minimum speed is saturated to engine idle speed to make sure if the vehicle is running in the minimum available range. In Figure 3.7, the basic model is shown that created in MATLAB.

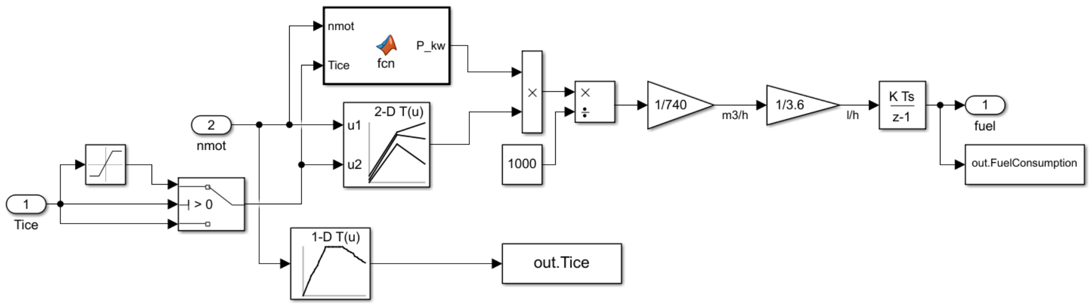


Figure 3.7 : Internal combustion engine model.

The break specific fuel consumption map calculates the total fuel consumption depending on actual ICE speed and ICE torque, in Figure 3.8, the break specific fuel consumption (BSFC) map shown.

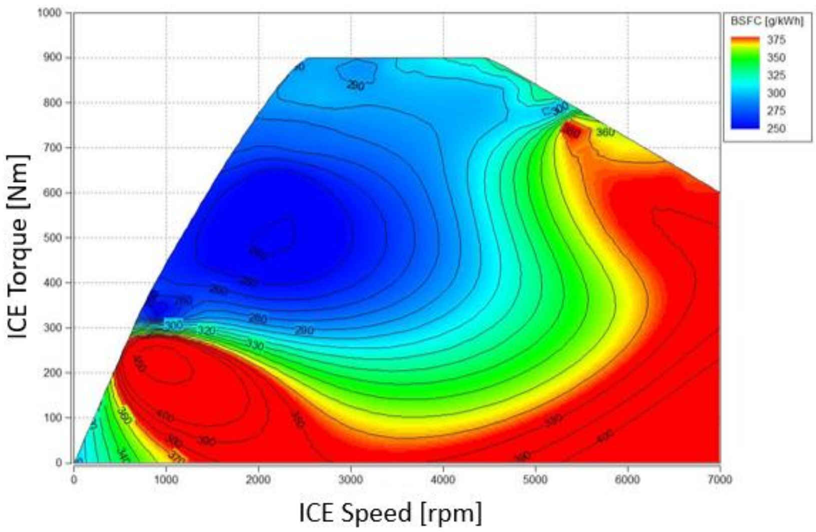


Figure 3.8 : Break specific fuel consumption (BSFC) map of ICE.

The boundaries of BSCF map in the torque axis is defined by characteristic of ICE full load curve. For each different speed, the maximum torque value that ICE can produce is different. In Figure 3.9, full load characteristic of ICE is given.

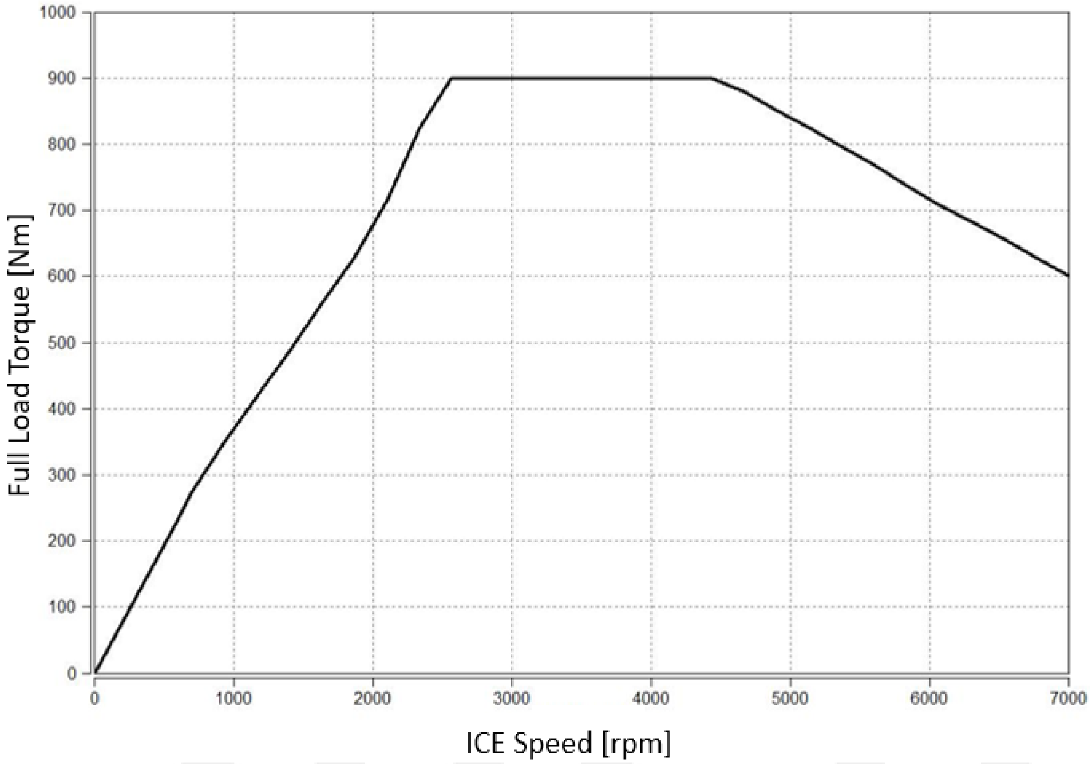


Figure 3.9 : Full load torque curve of ICE.

The total fuel consumption [l] is calculated in the following formula 3.9:

$$\text{Fuel consumption} = \int \frac{BSFC \ * P_{ICE}}{\rho_{fuel} \ * 3.6 * 1000} \tag{3.9}$$

where BSFC [g/kWh] is the instant fuel consumption value depending on ICE speed and ICE torque, P_{ICE} [kW] is the instant power of ICE depending on ICE speed and ICE torque, ρ_{fuel} [kg/m^3] is the density of the fuel. Other constants are used for unit conversion. If all instant values (second based) are integrated, total fuel consumption [l] is calculated.

Instant power of ICE [kW] is calculated in the following formula 3.10:

$$P_{ICE} = T_{ICE} * \frac{2\pi \, n_{ICE}}{60 * 1000} \tag{3.10}$$

where P_{ICE} [kW] is the instant fuel power value of ICE and n [rpm] is the ICE speed.

3.7 Electric Motor Model

Electric motor is modelled with an electric motor efficiency map which use speed and torque as inputs. In here, for simulating the electric motor working points like in real life, minimum torque request is saturated as -240 Nm due to hardware related limitations. On the other hand, for electric motor speed, the minimum speed is saturated to 500 rpm to cool its components when vehicle speed is “0”. In Figure 3.10, the basic model is shown that created in MATLAB.

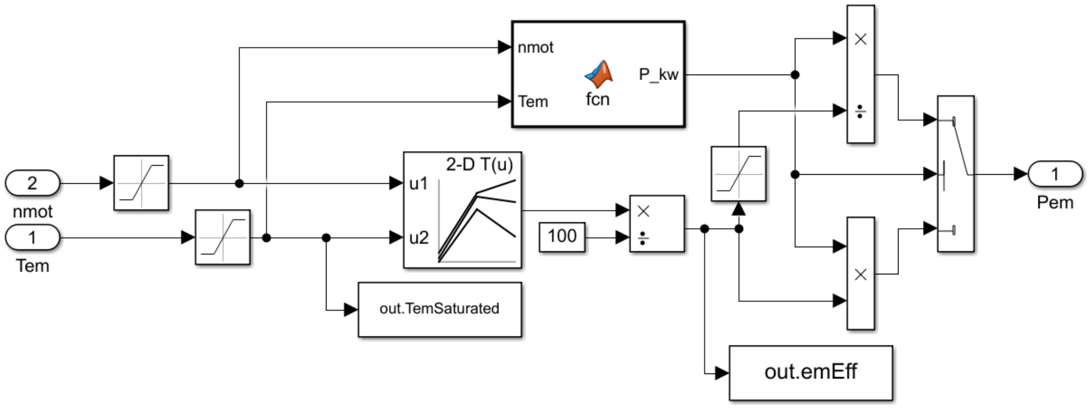


Figure 3.10 : Electric motor model.

In this block, depending on the electric motor speed, electric motor torque and the efficiency value of electric motor, total power that is necessary to produced by electric motor is calculated using the formula 3.11 and 3.12 depending on discharging ($T_{EM} \geq 0$) and charging ($T_{EM} < 0$) situations respectively:

$$P_{EM} = T_{EM} * \frac{2\pi\, n_{EM}}{60 * 1000 * \eta_{EM}} \;, T_{EM} \geq 0 \qquad (3.11)$$

$$P_{EM} = T_{EM} * \frac{2\pi\, n_{EM} * \eta_{EM}}{60 * 1000} \;, T_{EM} < 0 \qquad (3.12)$$

where P_{EM} [kW] is the instant electric motor power value depending on EM speed and EM torque, T_{EM} [Nm] is the instant torque value of EM, n_{EM} [rpm] is the speed of the EM and η_{EM} [-] is the efficiency value depending on EM speed and EM torque. It is clear that, this calculated power equals demanded value from the high voltage battery as well. For the battery related current and voltage calculations, as a total power demand, P_{EM} is used.

In the Figure 3.11, the details of the EM efficiency map are shown.

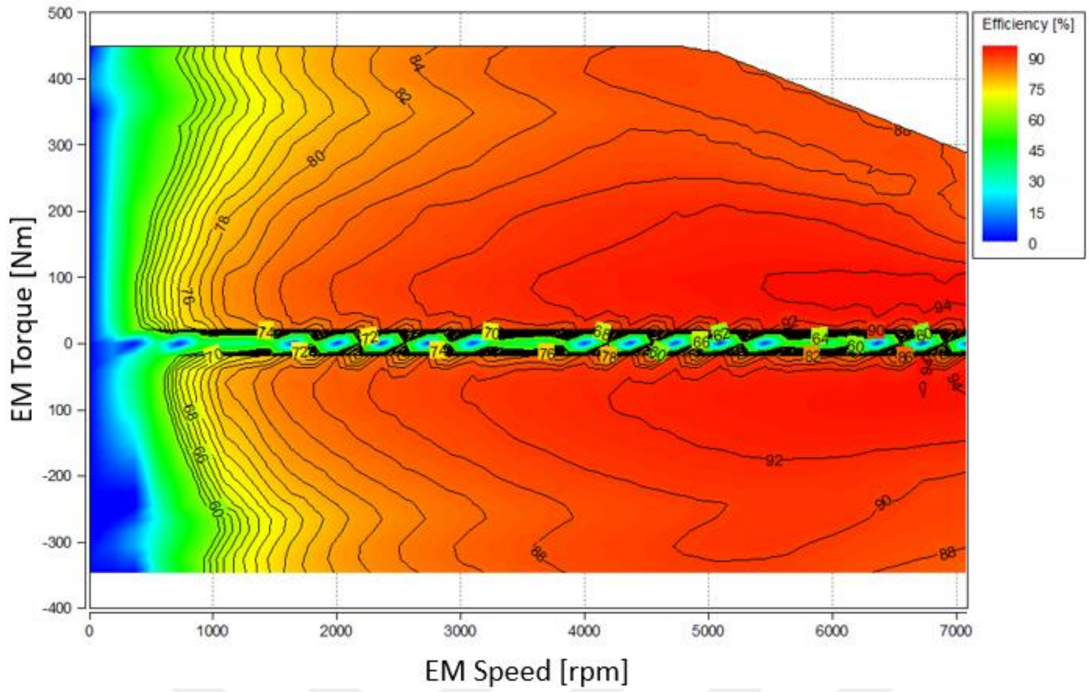


Figure 3.11 : Efficiency map of EM.

The boundaries of EM efficiency map in the torque axis are defined by characteristic of EM full load curve. For each different speed, the maximum torque value that EM can supply is different. In Figure 3.12, full load characteristic of ICE is given.

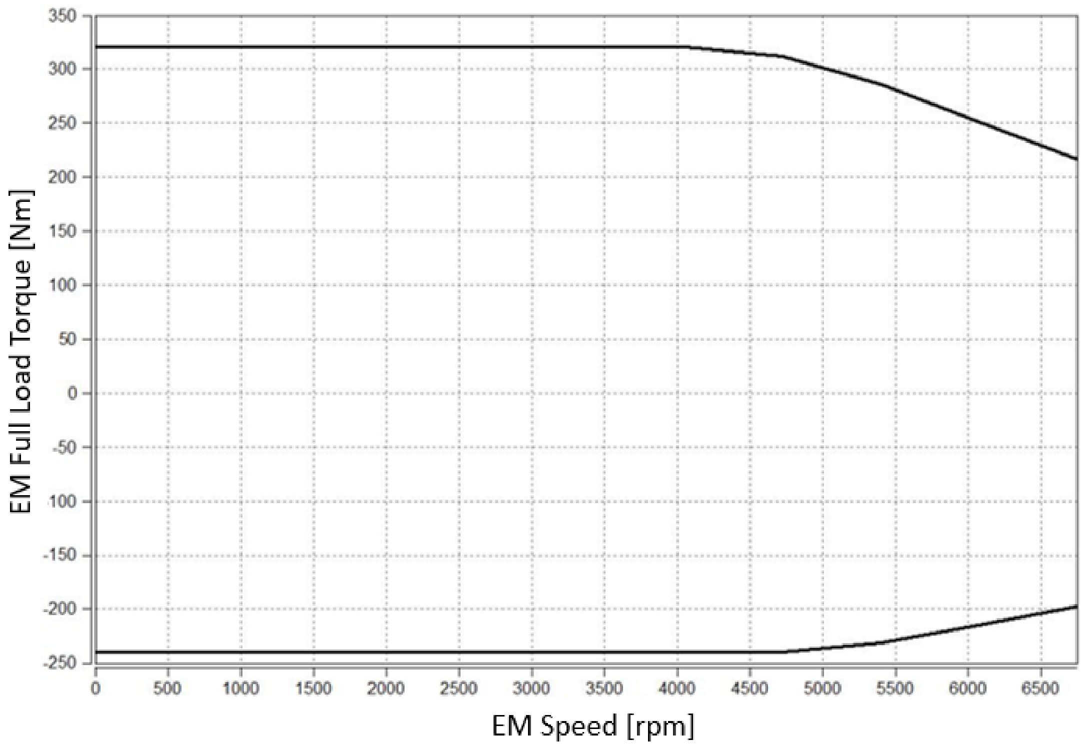


Figure 3.12 : Full load curve of EM.

3.8 High Voltage Battery Model

High voltage battery is modelled with battery equivalent circuit model which is used to estimate experimental impedance data using the distributed impedance elements, connected in series. This method is a good approach for the battery management applications such as battery state of charge estimation. In this thesis, internal resistances are considered to connected in series. The basic approach for the high voltage battery configuration is shown in Figure 3.13.

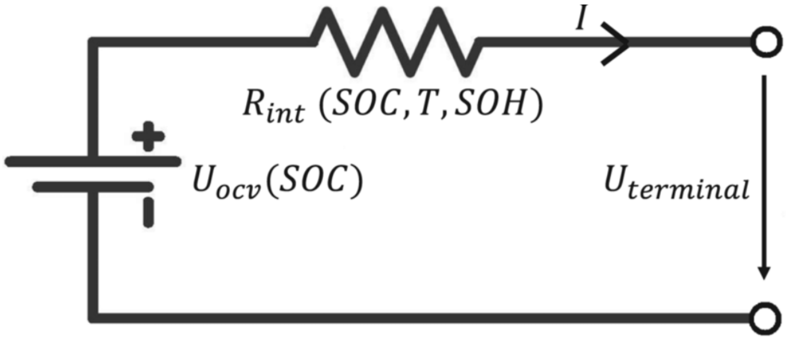


Figure 3.13 : Equivalent circuit modelling of the HV battery.

Total battery voltage is calculated using the formula 3.13:

$$V_{Bat} = V_{OC} + I_{Bat} * R_{int} \tag{3.13}$$

where V_{OC} [V] is the open voltage and R_{int} [Ohm] is the internal resistance of the battery and I_{Bat} [A] is the current flowing through the battery.

For the internal resistance, similar logic with the EM power calculation is used, depending on charging or discharging situation, different resistances characteristics are used like in the formula 3.14.

$$R_{int} = \begin{cases} R_{Disch}, P_{Bat} \geq 0 \\ R_{ch},\ P_{Bat} < 0 \end{cases} \tag{3.14}$$

Current flowing through the battery is calculated using the formula 3.15:

$$I_{Bat} = \frac{P_{Bat}}{V_{Bat}} \tag{3.15}$$

In this thesis, for the state of charge calculation, “Coulomb Counting” method which is a technique used to follow the SOC of a battery package is used. Details are shown in the formula 3.16:

$$SOC = SOC_i + \frac{\int_{t_0}^{t} i_{Bat}\, dt}{C_{Bat} * 3600} \tag{3.16}$$

where SOC_i [-] is the initial state of charge value and C_{Bat} [Ah] is the maximum capacity of the high voltage battery. The high voltage battery model that created in MATLAB shown in the Figure 3.14.

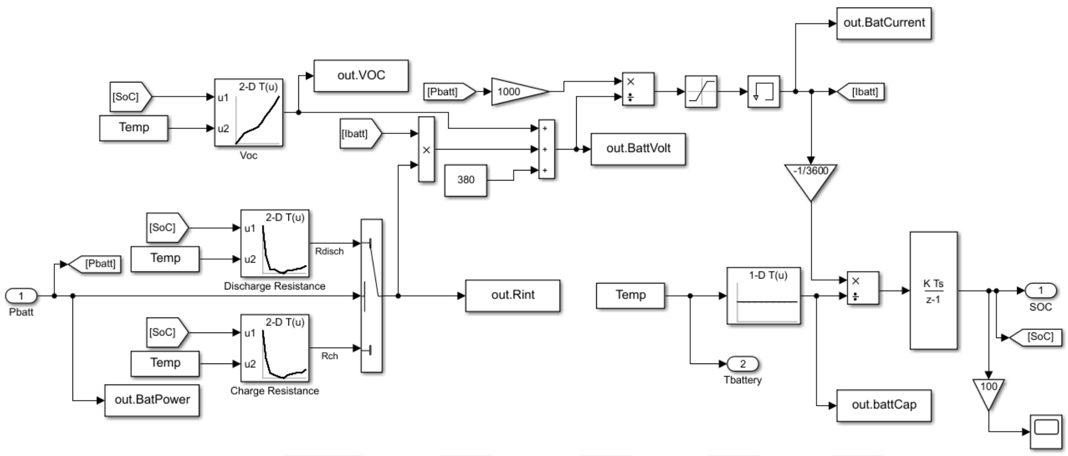


Figure 3.14 : High voltage battery model.

In the high voltage battery model, there are 3 main maps that defines the characteristic of battery: open circuit voltage, charging resistance of battery and discharge resistance of battery.

In the Figure 3.15, the open circuit voltage curve of high voltage battery is shown.

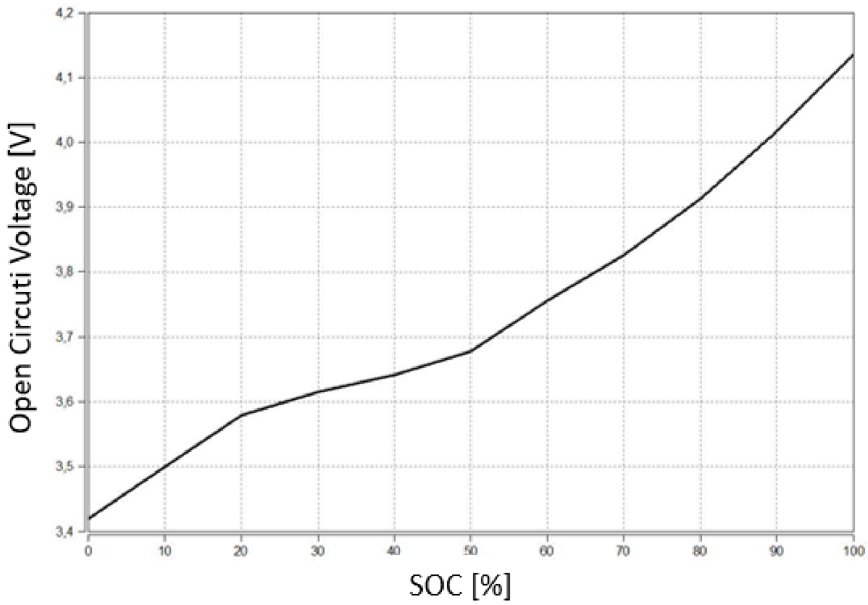


Figure 3.15 : Open circuit voltage (OCV).

Open circuit voltage is the difference in terms of voltage between positive and negative terminals of a battery without any load connected. In this case, there is no external current flows between the terminals. Open circuit voltage is also known as the electromotive force (emf) which represents the maximum potential difference when there is no load connection and circuit is not closed.

In the Figure 3.16, the charging resistance of HV battery is shown.

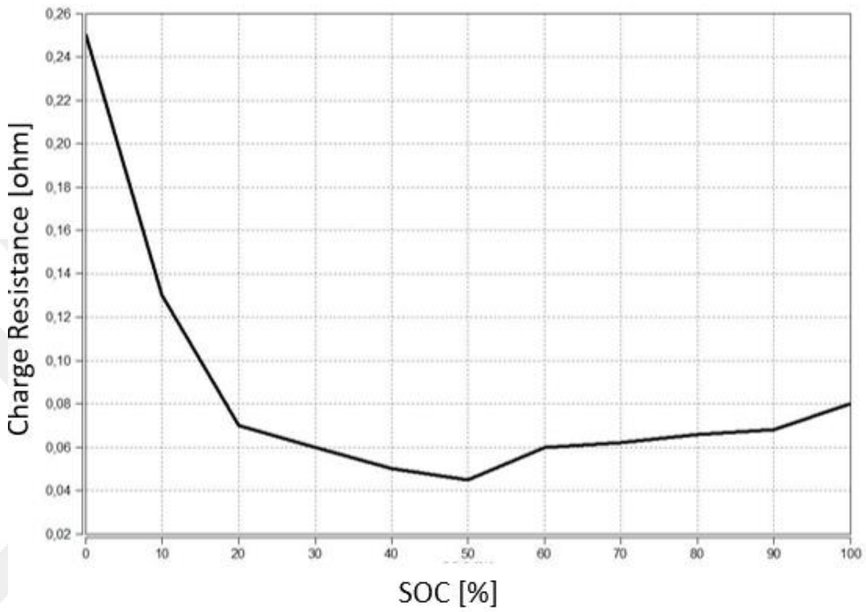


Figure 3.16 : Charging resistance of HV battery.

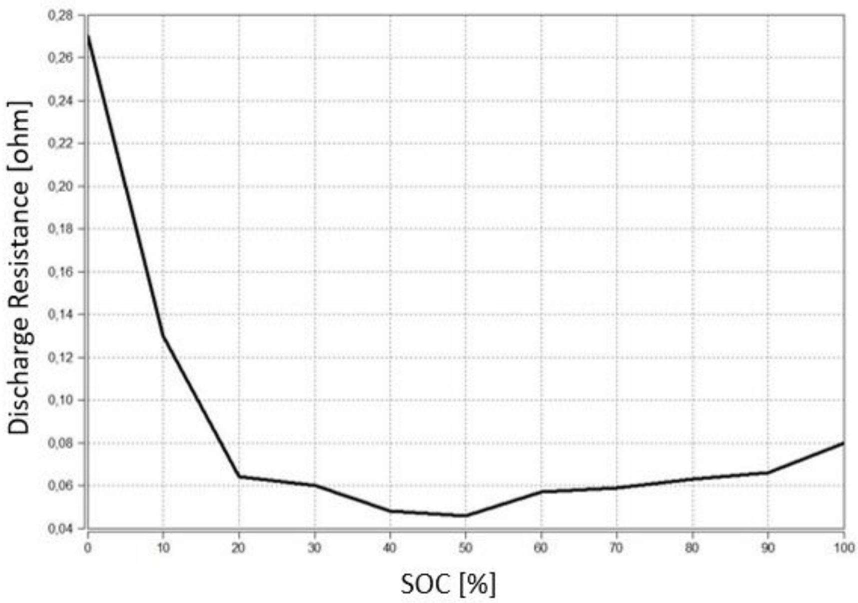


Figure 3.17 : Discharging resistance of HV battery.

For the nominal voltage of HV battery, 380V is given as an input. Depending on the whether battery is charging or discharging, charging or discharging resistances are selected to calculate internal resistance. This resistance value is multiplied by the current that flowing through the battery, then nominal voltage and open circuit voltage are added, and total battery operating voltage is calculated.

In this thesis, thermal effects on the battery neglected due to reduce the complexity of calculations. Normally, with the increasing battery current, temperatures on the battery also increases and cooling fan tries to reduce temperatures and this situation causes additional torque demand for the thermal management system. But in this study, battery temperature is considered constant and equals to 25℃.

4. DETAILS OF ECMS ALGORITHM

The Equivalent Consumption Minimization Strategy (ECMS) is a real-time optimization approach for reducing hybrid electric vehicle equivalent fuel consumption [36]. This approach is introduced for the first time by Paganelli 1999 as global minimization optimization method [37].

The main logic behind ECMS is to convert energy consumption of electric equipment into fuel consumption using an equivalent factor (EF), which is then added to the engine's real fuel consumption to produce the equivalent fuel consumption at any given time. The minimum energy distribution of HEVs is solved using the equivalent fuel consumption as the goal function.

Equivalent total fuel consumption is calculated like in the following formula 4.1:

$$\dot{m}_{eq}(t) = \dot{m}_{ICE}(t) + \dot{m}_{Bat\_eq}(t) \tag{4.1}$$

where $\dot{m}_{eq}$ is instantaneous equivalent total fuel consumption, $\dot{m}_{ICE}$ actual fuel consumption of internal combustion engine and $\dot{m}_{Bat\_eq}$ is the equivalent fuel consumption of the battery [38].

Actual fuel consumption of internal combustion engine can be calculated using the characteristic bsfc fuel consumption map of engine with the instantaneous engine speed and engine torque and it can be found like in formula 4.2:

$$\dot{m}_{ICE}(t) = \frac{P_{ICE}(t)}{\eta_{ICE}(t) * Q_{LHV}} \tag{4.2}$$

where P_{ICE} [kW] is the engine power, η_{ICE} [-] is the engine efficiency and Q_{LHV} [kJ/g] is the fuel lower heating value. In this thesis, as an engine type, gasoline engine is used, as a fuel type, gasoline is selected; so Q_{LHV} value is taken as 42,062 kJ/g depending on Europe WLTP fuel type criteria that defined in the technical specification documents of the authority.

Equivalent fuel consumption of the battery is calculated like in the following formula 4.3:

$$\dot{m}_{Bat_{eq}}(t) = \gamma * \frac{P_{batt}(t)}{\eta_{chg}(t) * Q_{LHV}} \;, P_{Batt}(t) < 0$$
$$\dot{m}_{Bat_{eq}}(t) = \gamma * \frac{P_{batt}(t)}{\eta_{disch}(t) * Q_{LHV}} \;, P_{Batt}(t) \geq 0 \qquad (4.3)$$

where, $\dot{m}_{Bat_{eq}}$ [g] is the equivalent fuel consumption rate of the battery, P_{batt} [kW] is battery power, Q_{LHV} is fuel lower heating value, η_{chg} is battery charging efficiency, η_{disch} is battery discharging efficiency, and γ is the equivalent factor, whose value is positive during the battery discharging events while being negative during charging events [38]. This approach leads to an exact prediction for the equivalent total fuel consumption but on the other hand requires solving a bi-dimensional minimization problem. For reducing the system complexity, bi-dimensional problem is reduced to one dimensional problem, and it is assumed that charging and discharging equivalent factors are the exactly same and unique [39].

So, the detailed equivalent total fuel consumption equation can be shown like in the following formula 4.4:

$$\dot{m}_{eq}(t) = \dot{m}_{ICE}(t) + \gamma * \frac{P_{batt}(t)}{Q_{LHV}} \qquad (4.4)$$

It's worth mentioning that the equivalent factor, which is impacted by driving conditions, battery SOC, driving style, road gradient, and other factors, is extremely sensitive to the results of ECMS. If the equivalent factor is set too high, the strategy will prefer to use gasoline, resulting in higher fuel usage and higher battery capacity. In contrast, the technique to decide the use of electricity, resulting in higher power consumption and lower battery capacity with lower actual fuel consumption.

ECMS searches continuously best power split between ICE and EM to achieve minimum equivalent total fuel consumption. In the code that is used in thesis study, ECMS algorithm scans the torque band of ICE for actual fuel consumption and after selecting the ICE torque, EM torque is calculated when ICE torque is extracted from total torque request on the transmission input level. After EM torque request is calculated, then battery power is calculated, and final target is to select best correlation for minimum equivalent total fuel consumption. This kind of correlation is obtained after lots of iteration trials. To reduce computational time, torque scanning step is selected as 5 Nm.

In the Figure 4.1, detail of working principle of ECMS algorithm is shown.

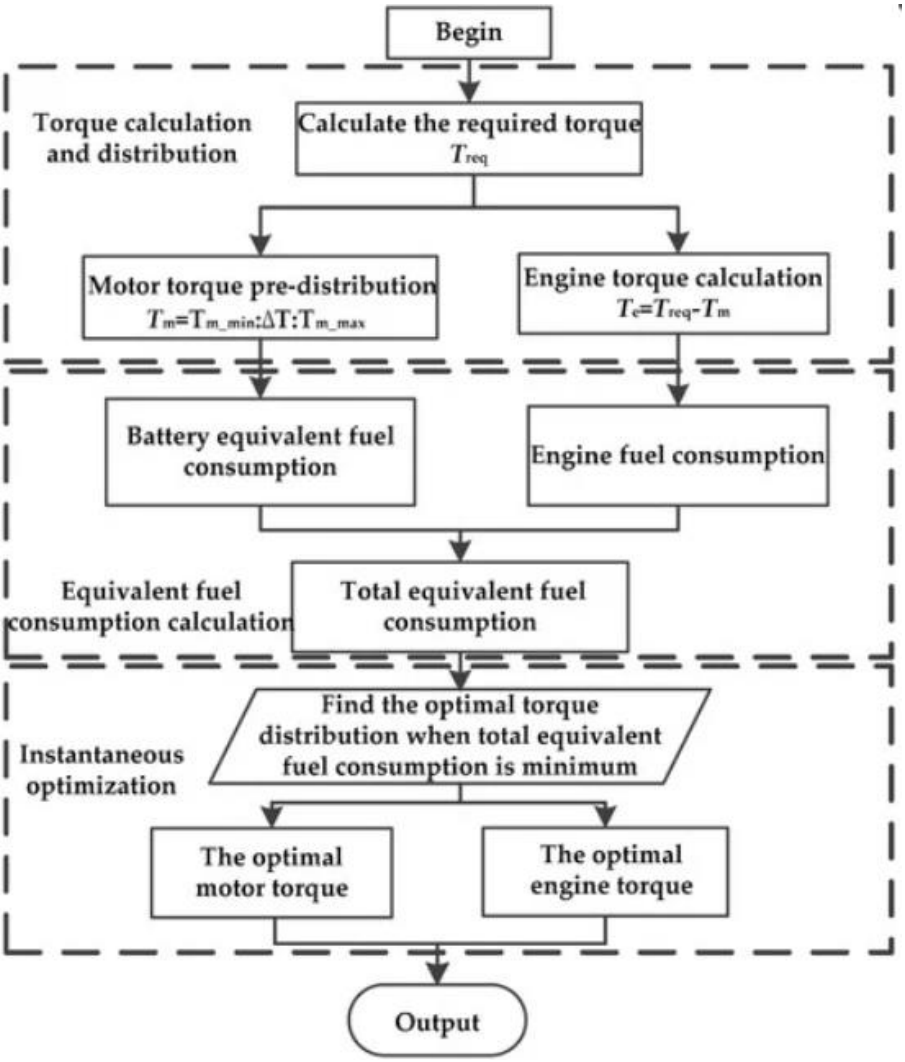


Figure 4.1 : The working principle of ECMS algorithm [40].

In addition to equivalent total fuel consumption, also deviation from SOC setpoint is so critical for battery health. If the battery is consumed completely until it goes down to 0% SOC level and then it charged until SOC goes up to 100% SOC level, the SOC charging and discharging amplitude will be too high and it will decrease the battery health. Due to battery health is considered, for charge sustaining test, it is so important to keep the SOC over a certain threshold as 11% SOC. So, a penalty function regarding the deviation from SOC setpoint is added to formula 4.4 and formula 4.5 is obtained like in the following.

$$\dot{m}_{eq}(t) = \dot{m}_{ICE}(t) + \gamma * \frac{P_{batt}(t)}{Q_{LHV}} * p_{SOC} \tag{4.5}$$

This penalty function is a correction function which gives a penalize rate regarding deviation from the target SOC while keeping it in the allowed limits. Details are shown in formula 4.6.

$$p_{SOC} = 1 - \left(\frac{SOC(t) - SOC_{target}}{(SOC_{max} - SOC_{\min})/2} \right)^{a} \tag{4.6}$$

where p_{SOC} is the penalty factor, SOC_{target} is the target state of charge, SOC_{min} and SOC_{max} are the minimum and maximum limits of state of charge and e is the exponential value of function.

In the Figure 4.1, the penalty functions of SOC deviation are shown.

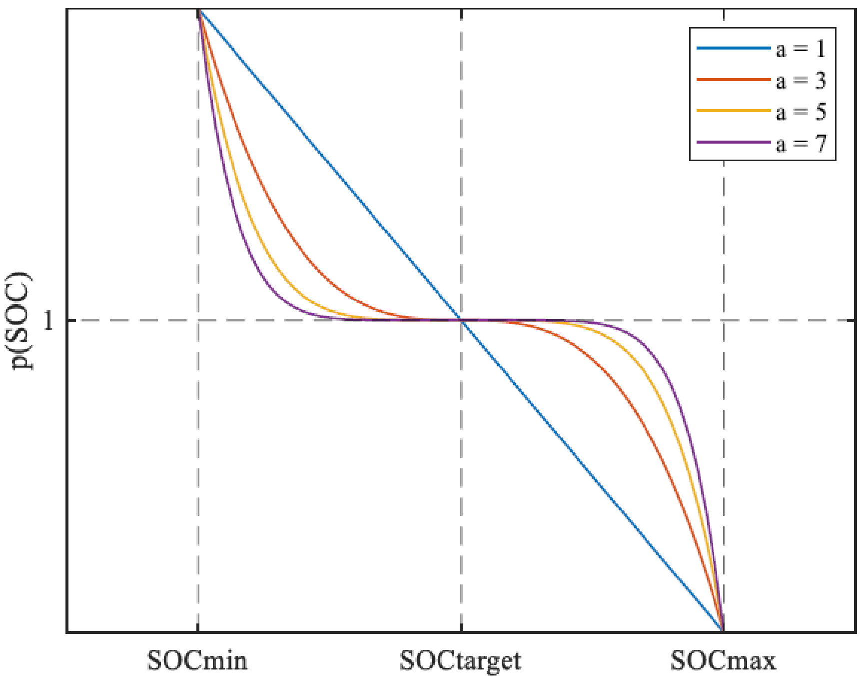


Figure 4.2 : Penalty function rate for SOC deviation [41].

As it can be seen in the figure above, if the instantaneous SOC is between the SOC target and SOC max value, penalty factor will be smaller than 1 which means energy management system will behave in more discharging way. In contrary, the penalty factor will be higher than 1 and equivalent fuel consumption will start to increase due to higher penalty factor. In this case, the system will diminish making discharging and more ICE activation will start.

The exponential value of the function is used to change the slope of the penalty function regarding the deviation from SOC target. If the exponent is 1, characteristic of the penalty function will be linear, in this case in any deviation from target, penalty factor will be applied. If the exponent increases, the region around SOC target is increased, it means deviations until certain threshold will not be penalized. In this thesis, exponent is selected as 3 based on lots of literature searches.

As a result, all the system constraints for the ECMS algorithm can be summarized like in the following formula 4.7:

$$\begin{gathered} w_{EMmin} \leq w_{EM}(t) \leq w_{EMmax} \\ w_{ICEmin} \leq w_{ICE}(t) \leq w_{ICEmax} \\ T_{EMmin(w_{EM(t)})} \leq T_{EM}(t) \leq T_{EMmax(w_{EM(t)})} \\ T_{ICEmin(w_{ICE(t)})} \leq T_{ICE}(t) \leq T_{ICEmax(w_{ICE(t)})} \\ SOC_{min} \leq SOC(t) \leq SOC_{max} \end{gathered} \tag{4.7}$$

5. SIMULATON RESULTS ON VEHICLE MODEL

In the simulation section, Worldwide Harmonised Light Duty Vehicles Test Cycle (WLTP) is performed with different vehicle model setups. As a first step, the vehicle model is configured like a conventional vehicle without electric motor, battery package and all hybrid electric vehicle related components. Test mass is considered exactly same with the hybrid electric vehicle model and base fuel consumption is calculated. Then in the second step, hybrid electric vehicle model including the battery package, electric motor, inverter and other hybrid vehicle components is performed in MATLAB Simulink and fuel consumption is calculated with the ECMS strategy. In the third step, ECMS equivalent factor is optimized to find minimum equivalent total fuel consumption value.

5.1 Selection of Test Type and Vehicle Parameters

In the regulation for the approval tests for hybrid and electric vehicle, all OVC-HEVs, NOVC-HEVs, and PEVs are have to be regulated with Class 3 WLTP test. Emissions and a number of other parameters are examined in both charge depleting and charge sustaining modes during the Class 3 (Class 3a or Class 3b) cycle. Details of the test matrix is shown in the Figure 5.1:

		WLTP		WLTP city
		Charge-depleting	Charge-sustaining	Charge-depleting
		Criteria Emissions, FC, CO_2, AER, EAER, R_{CDC}, R_{CDA}, E_{AC}	*Criteria Emissions, FC, CO_2*	*AERcity, E_{AC}city*
OVC-HEV	Class 3a	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	Low 3 + Medium 3-1
	Class 3b	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	Low 3 + Medium 3-2 + High 3-2 + ExtraHigh 3	Low 3 + Medium 3-2
NOVC-HEV	Class 3a	--	Low 3 + Medium 3-1 + High 3-1 + ExtraHigh 3	--
	Class 3b	--	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	--
PEV	Class 3a	Low 3 + Medium 3-1 + High 3-1 + Extra High 3	--	Low 3 + Medium 3-1
	Class 3b	Low 3 + Medium 3-2 + High 3-2 + Extra High 3	--	Low 3 + Medium 3-2

Figure 5.1 : WLTP test matrix for hybrid and electric vehicles [42].

The class of the WLTP is splitted regarding the power mass ratio (PMR) [W/kg] as Class 1, Class 2 and Class 3. Class 1 defines low power vehicles for PMR ≤ 22, Class 2 defines the power mass ratio for the 22 < PMR ≤ 34 and Class 3 for PMR > 34 [43].

Table 5.1 : Details of WLTP classes [42].

Class	PMR, W/kg	v_max, km/h	Speed Phase Sequence
Class 3b	PMR > 34	v_max ≥ 120	Low 3 + Medium 3-2 + High 3-2 + Extra High 3
Class 3a		v_max < 120	Low 3 + Medium 3-1 + High 3-1 + Extra High 3
Class 2	34 ≥ PMR > 22	-	Low 2 + Medium 2 + High 2 + Extra High 2
Class 1	PMR ≤ 22	-	Low 1 + Medium 1 + Low 1

As it can be seen in the above table, main classes are categorized depending on the power mass ratio, but Class 3 is also splitted into two categories inside according to max allowable speed value. Vehicles with maximum speed is higher than 120 km/h has to be certified with Class 3b cycle while the vehicles which maximum speed is lower than 120 vehicles have to be with Class 3a for the approval tests.

In this thesis study, the vehicle parameters in terms of power mass ratio satisfy the WLTP Class 3b, so as a confirmation cycle for energy management, WLTP Class 3b is used.

In the Figure 5.2, details of WLTP Class 3b is shown. WLTP Class 3b includes 4 main phases like low, medium, high and extra high in terms of speed range. Maximum allowable vehicle speed is greater equal to 120 km/h in Class 3b. Total duration is 1800 seconds and total distance is 23.266 meters. Speed trace is shown in Figure 5.3.

Phase	Duration	Stop Duration	Distance	p_stop	v_max	v_ave w/o stops	v_ave w/ stops	a_min	a_max
	s	s	m		km/h	km/h	km/h	m/s²	m/s²
Class 3b (v_max ≥ 120 km/h)									
Low 3	589	156	3095	26.5%	56.5	25.7	18.9	-1.47	1.47
Medium 3-2	433	48	4756	11.1%	76.6	44.5	39.5	-1.49	1.57
High 3-2	455	31	7162	6.8%	97.4	60.8	56.7	-1.49	1.58
Extra-High 3	323	7	8254	2.2%	131.3	94.0	92.0	-1.21	1.03
Total	**1800**	**242**	**23266**						

Figure 5.2 : Details of WLTP class 3b cycle [42].

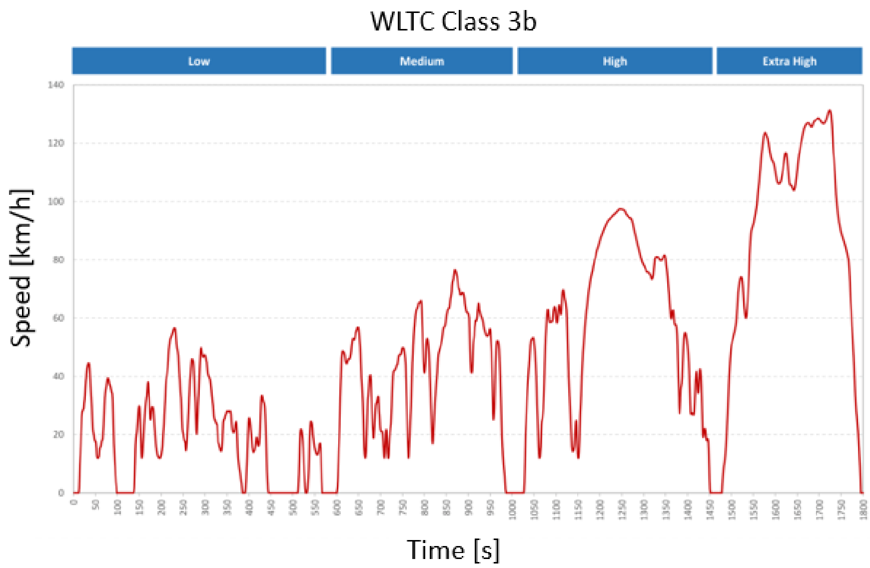


Figure 5.3 : Speed trace of WLTP class 3b [43].

In the below Table 5.2, vehicle parameters that are used in the MATLAB simulation are given.

Table 5.2 : Vehicle parameters used in the simulation.

Parameter	Unit	Value	Description
VehicleMass	kg	2792	Vehicle Mass
RrollCoeff	-	0.02	Rolling Coefficient
AirDensity	kg/m^3	1.225	Air Density
RaeroCoeff	-	0.25	Drag coefficient
Front Area	m^2	2.68	Front area of vehicle
WheelRadius	m	0.3553	Radius of wheel
GR	4.714, 3.143, 2.106, 1.667, 1.285, 1.000, 0.839, 0.667, 0.500, FDR: 4.077	7	Gear ratios for 9 speed automatic gearbox
MaxBatCap	Ah	73.50	Maximum Battery Capacity
ICEInertia/EM Inertia	kgm^2	1.20/0.22	ICE and EM inertia loss coeff.
BattInitSoC	%	Changes	Initial Battery SOC

5.2 Conventional Internal Combustion Engine Model

In conventional combustion engine model, all the plug-in hybrid electric vehicle components are removed from the component section. Also, to be fair for fuel consumption comparison, all the hybrid component weights are decreased from the test mass of the vehicle. For this kind of mass estimation, market investigation is done.

In the Figure 5.4, highly integrated electric powertrain EMR3 in power class 2 (100 to 150 kW) belongs to Continental brand is shown. With the power class, it satisfies the power requirement that is used in this thesis study. So, for sensible mass estimation, this powertrain specifications can be used as reference.

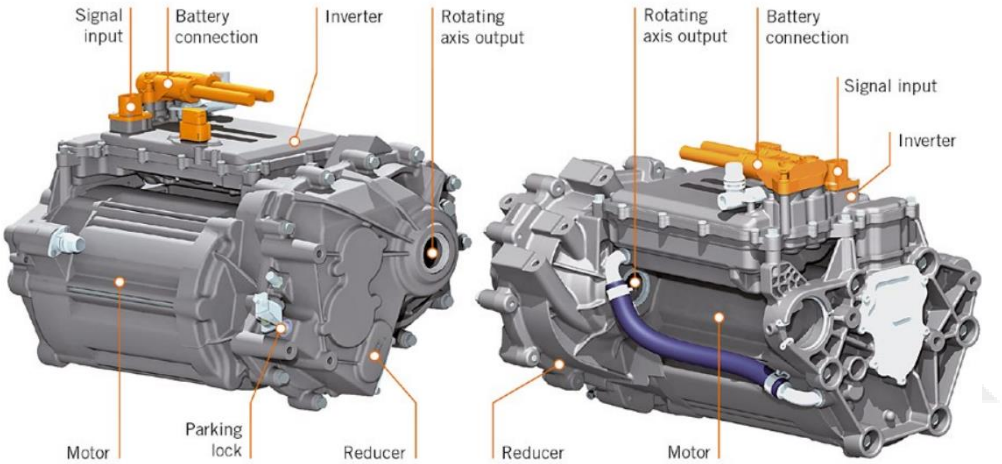


Figure 5.4 : Electric powertrain EMR3 in power class 2 (100 to 150 kW) (© Continental) [44].

Depending on the technical data sheet, this electrified powertrain weighs around 75 kg including the aluminium case, inverter and all other stuff [44].

According the researches regarding the HV battery package weight, a HV battery package which shows similarities in terms of nominal voltage and energy as kWh weighs around 267 kg with 372V nominal voltage, 37 kWh installed and 33 kWh usable battery energy and 100 Ah battery capacity [45]. In the Figure 5.5, dimensional data of HV battery is shown. Due to this battery capacity is higher than the battery package, which is used in thesis study, a linear proportion approximation is done with the mass and battery capacity as Ah, for a battery package with 73.5 Ah, mass is calculated around 196 kg.

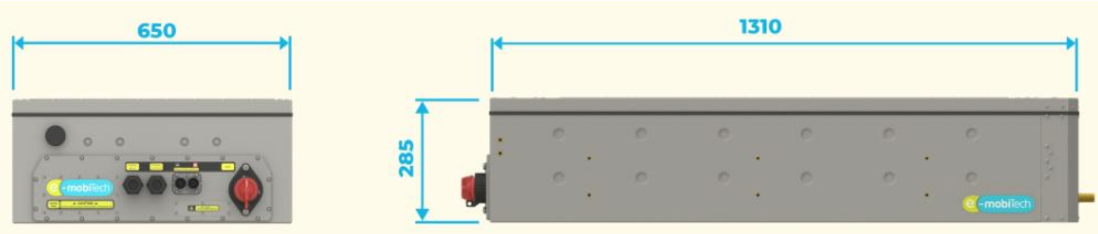


Figure 5.5 : NMC 372V 37 kWh battery package [45].

As a results, 75 kg is calculated for electrified powertrain, 196 kg is calculated for HV battery package and approximately 14 kg is estimated for the HV battery connection cables and connectors. In sum, 285 kg is to be extracted from hybrid electric vehicle mass to eliminate all the hybridization components. In this case, for a hybrid model, vehicle mass is taken as 2792 kg but for conventional ICE model, 2507 kg has to be taken for vehicle mass for the simulation.

In the Figure 5.6, the analysis of conventional ICE model can be seen.

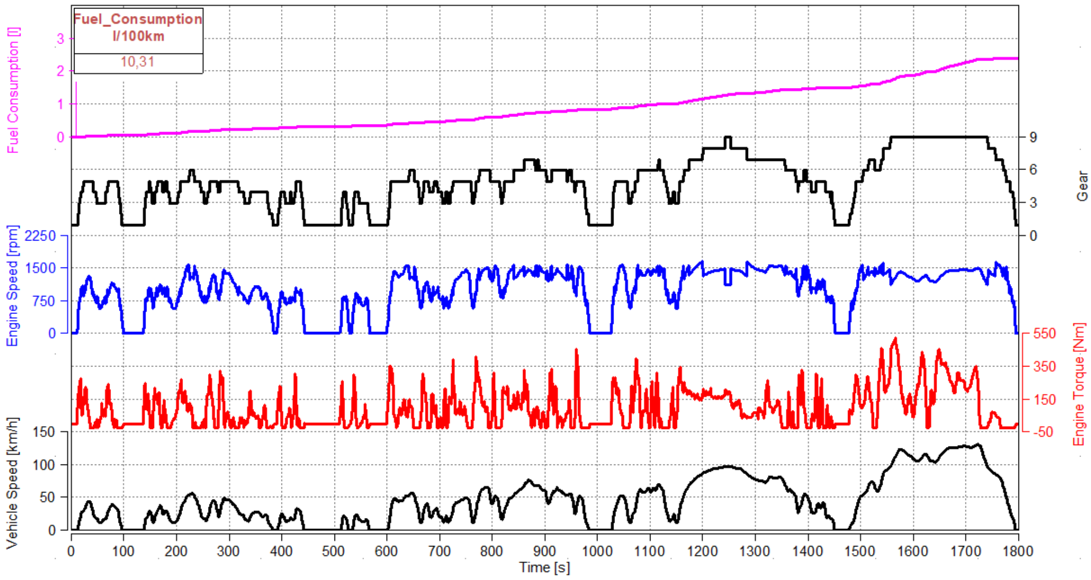


Figure 5.6 : Conventional ICE fuel consumption analysis.

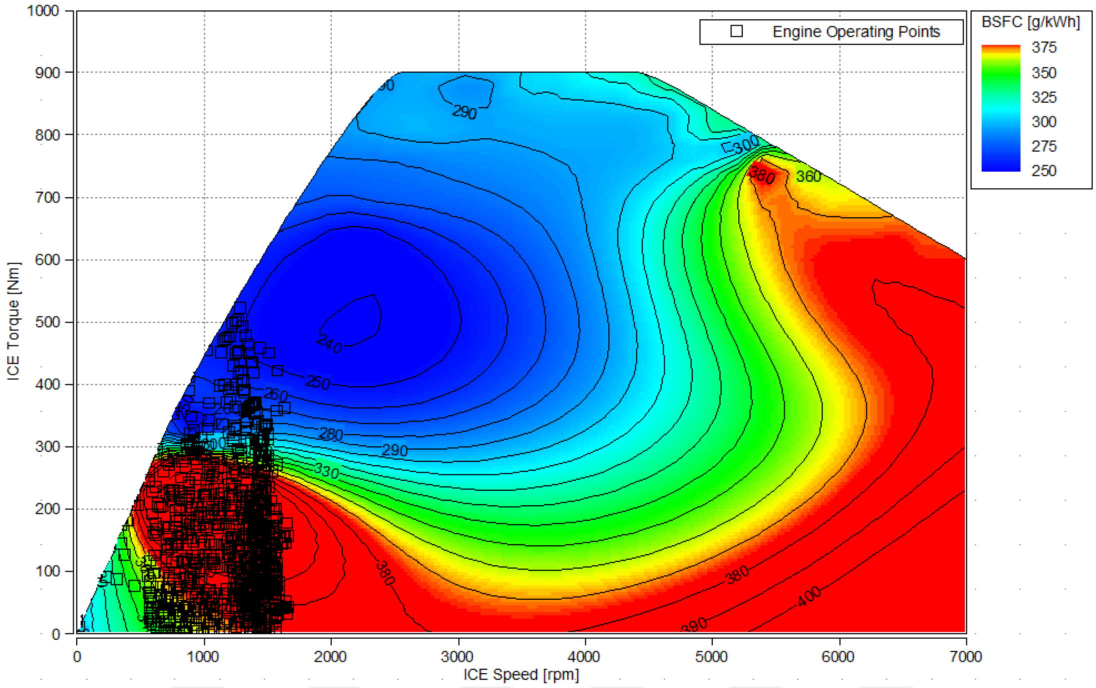


Figure 5.7 : ICE operation points on BSFC map.

Fuel consumption simulation results in conventional combustion engine mode for WLTP Class 3b test with different units are shown in Table 5.3.

Table 5.3 : Fuel consumption results for conventional ICE model

Model	Parameter	Unit	Value
Conventional ICE	Fuel Consumption	l/100 km	10.31
Conventional ICE	Fuel Consumption	l	2.40

5.3 Plug-in Hybrid Engine Model

In plug-in hybrid engine model, all the plug-in hybrid electric vehicle components are used in the component section. Also, to be fair in terms of fuel consumption comparison, all the hybrid component weights are considered inside the test mass.

In this section, mainly 2 tests are performed. First one is charge sustaining and the other one is charge depleting tests.

5.3.1 Charge sustaining test

In the sustaining WLTP test, as explained in previous section (Section 4), the behaviour of SOC and fuel consumption is directly linked with the dynamic change of equivalent factor.

If the factor is chosen too high, the algorithm will prefer to use more ICE instead of electric motor and high voltage battery due to its high cost. In this case, fuel consumption will be too high. Figure 5.8, 5.9, 5.10, 5.11 and 5.12 shows the details of operational points when equivalent factor is chosen as 5.

In the below figure 5.8, blue bars show the load point shifting maneuvers where the ICE and EM is activated together, and EM is charged by ICE with increasing its operating points to keep the SOC on a certain level. The green bars show the recuperation brake maneuvers where the battery is charged. The purple one shows the hybrid discharge moments where the ICE and EM is activated together for traction. The pink one represents where the just EM is used only power source. The red one shows where the E-Drive mode is activated, and it is generally observed when start SOC is 100% and this mode is activated by driver manually on the vehicle.

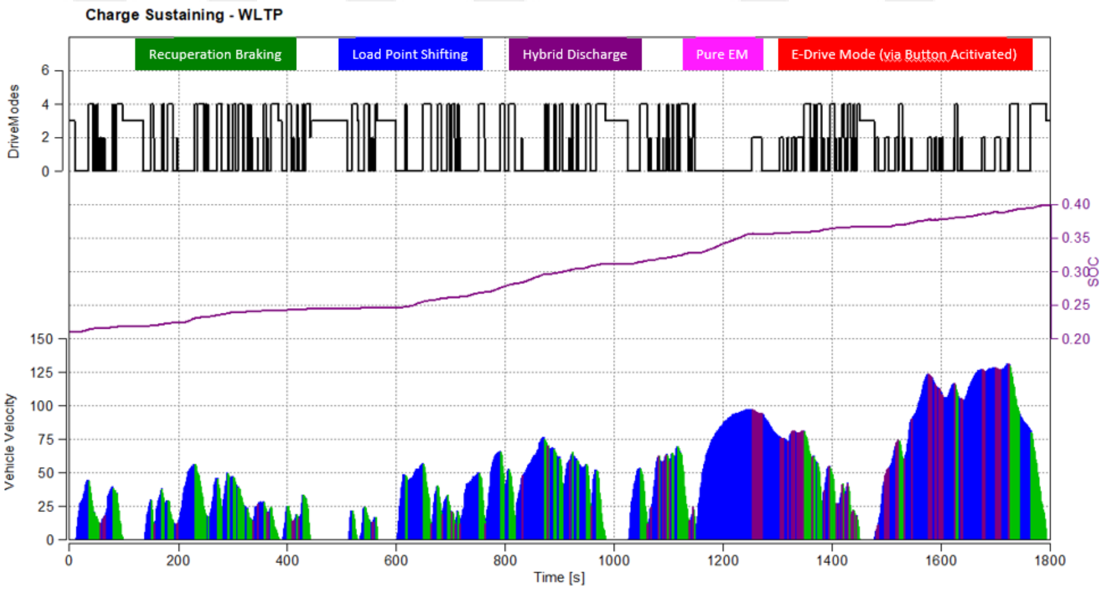


Figure 5.8 : Drive modes for equivalent factor 5 in CS test.

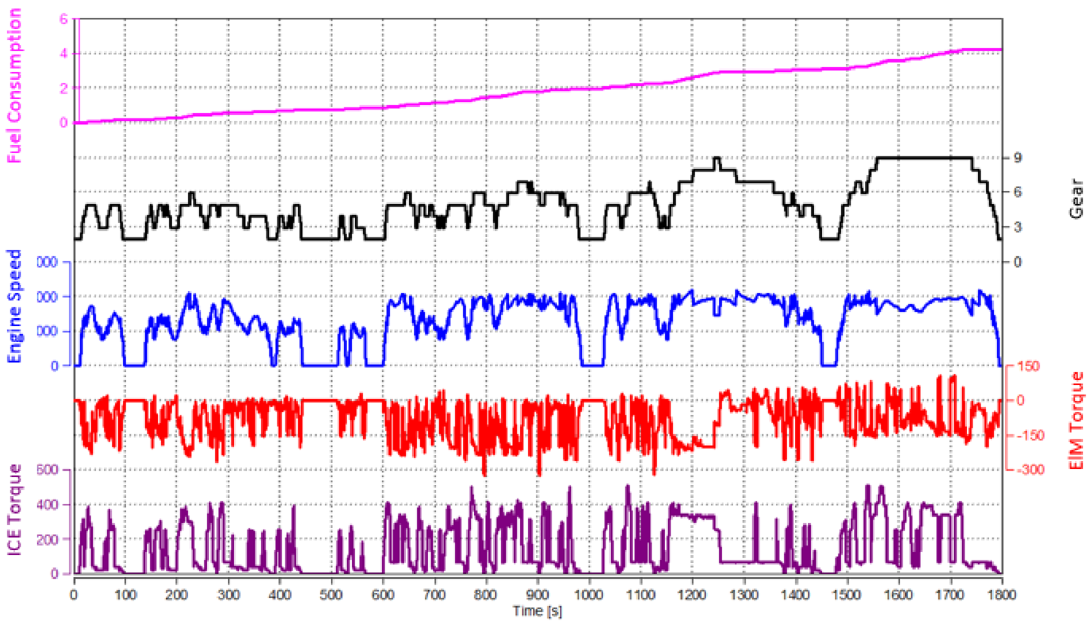


Figure 5.9 : General overview for equivalent factor 5 for CS test.

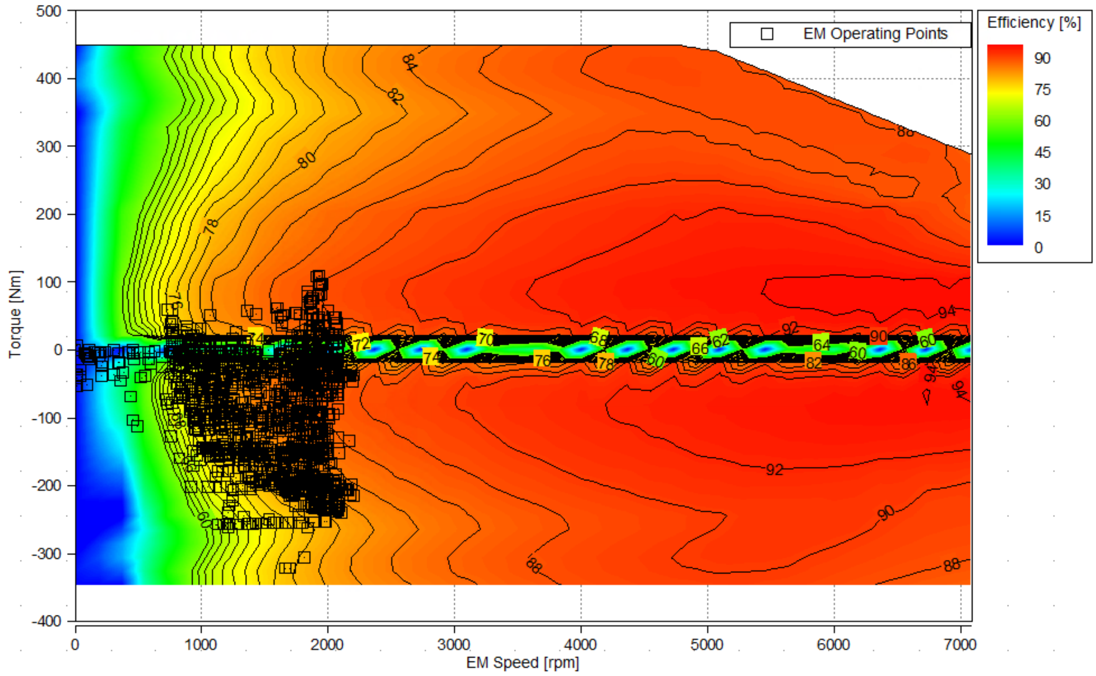


Figure 5.10 : EM operating points for equivalent factor 5 for CS test.

The black square boxes in the Figure 5.10 and 5.11 shows the scattering of operating points of EM and ICE over their efficiency and break specific fuel consumption maps respectively.

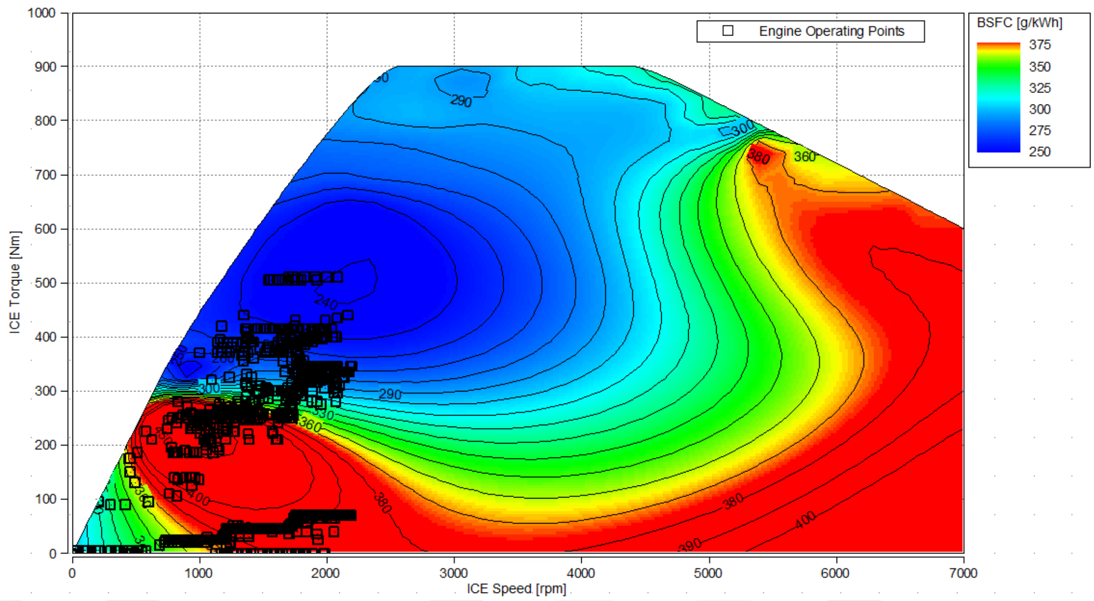


Figure 5.11 : ICE operating points for equivalent factor 5 for CS test.

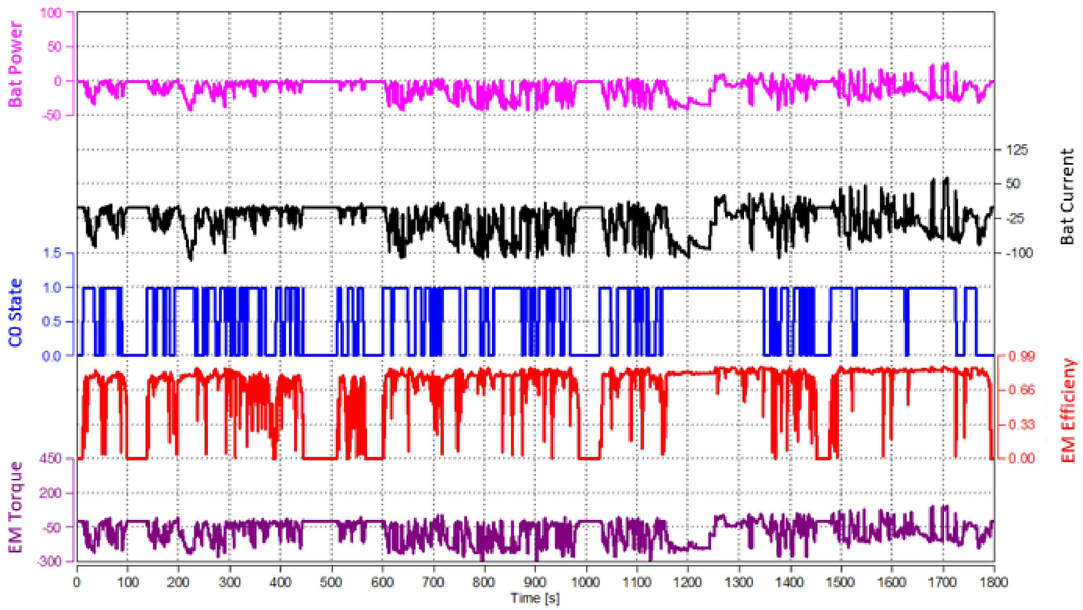


Figure 5.12 : Battery calculations for equivalent factor 5 for CS test.

If the factor is chosen too low, the algorithm will prefer to use more electric motor and battery instead of ICE due to its too low cost. In this case, fuel consumption will be too low but due to excessive use of battery, SOC will drop down. In the Figure 5.13, 5.14, 5.15, 5.16 and 5.17 details of operational points when equivalent factor is chosen as 1 are shown.

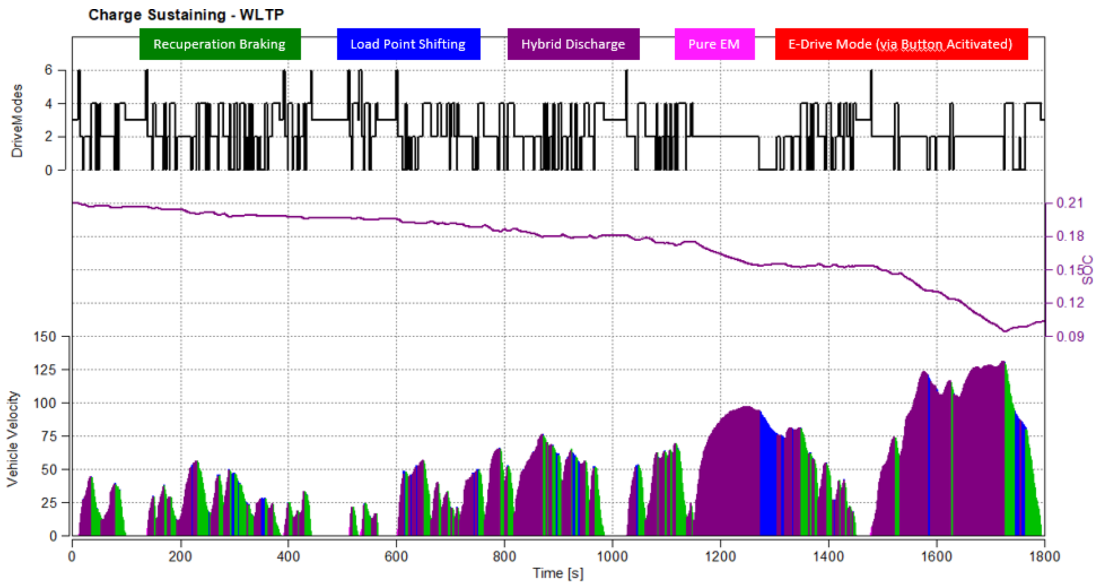


Figure 5.13 : Drive modes for equivalent factor 1 for CS test.

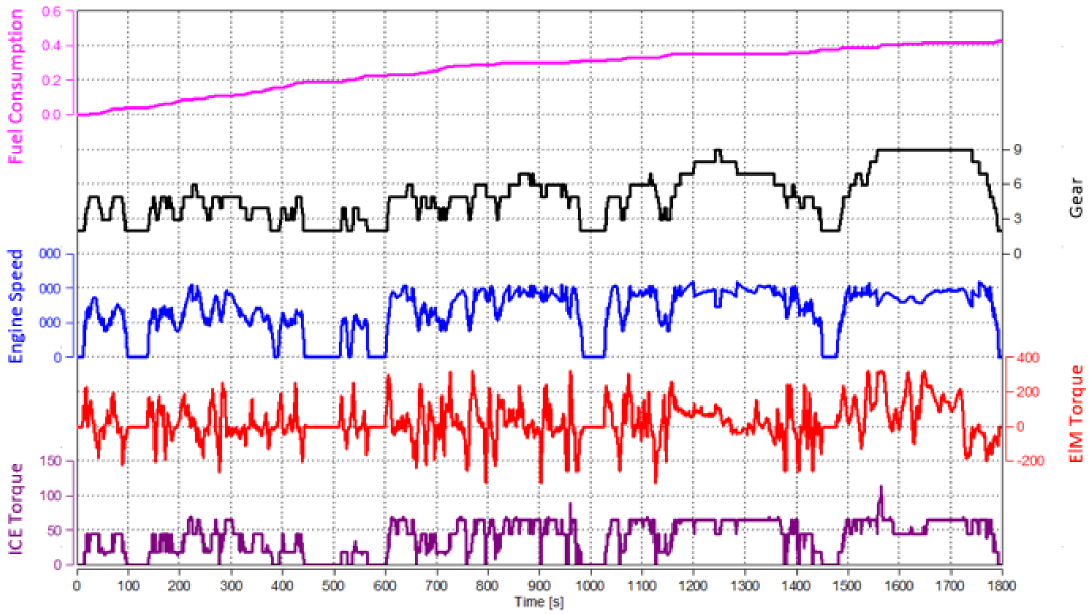


Figure 5.14 : General overview for equivalent factor 1 for CS test.

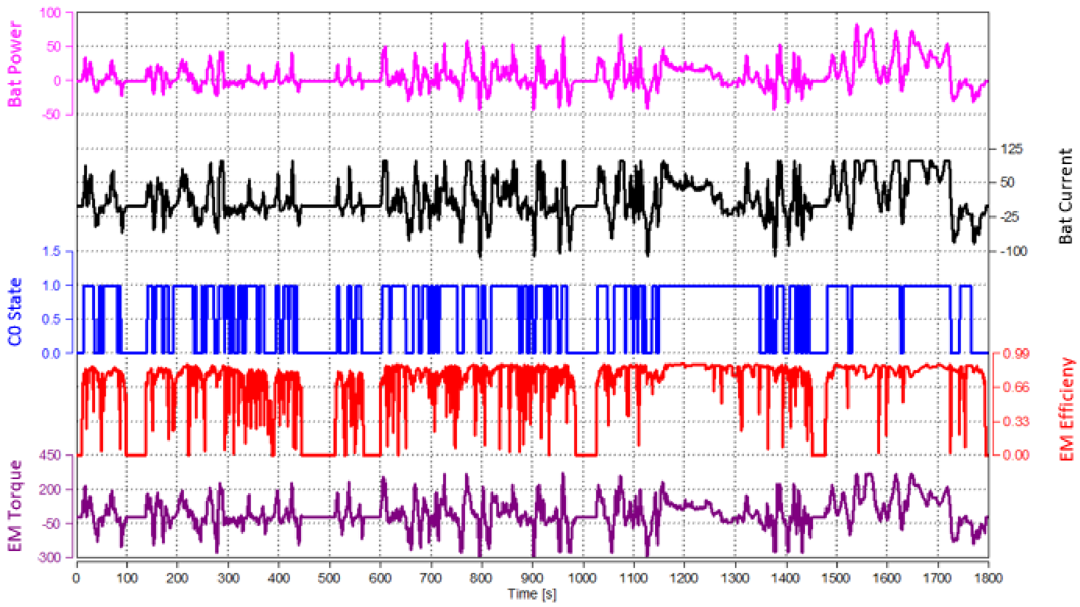


Figure 5.15 : Battery calculations for equivalent factor 1 for CS test.

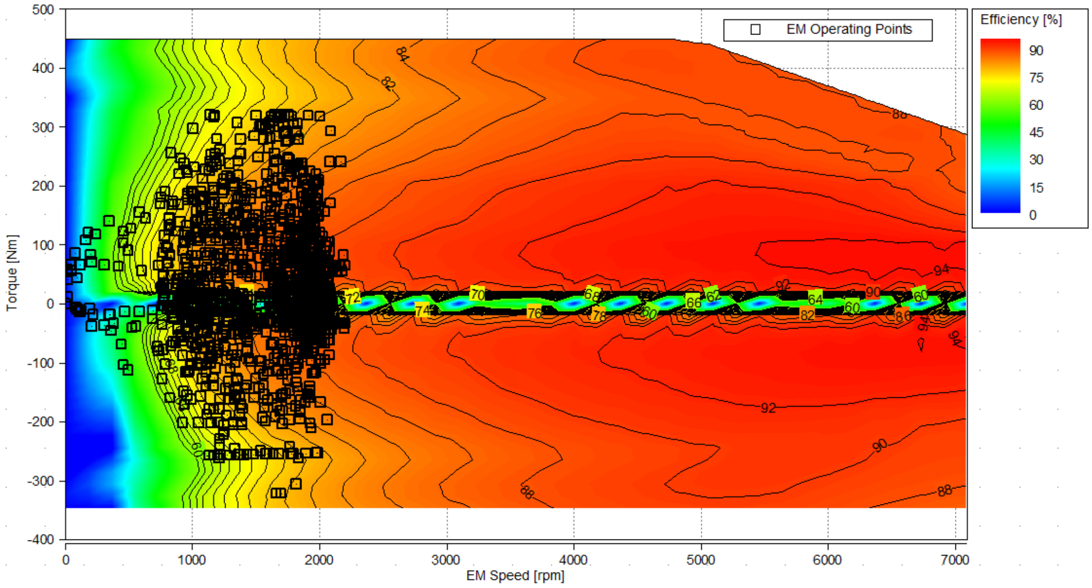


Figure 5.16 : EM operating points for equivalent factor 1 for CS test.

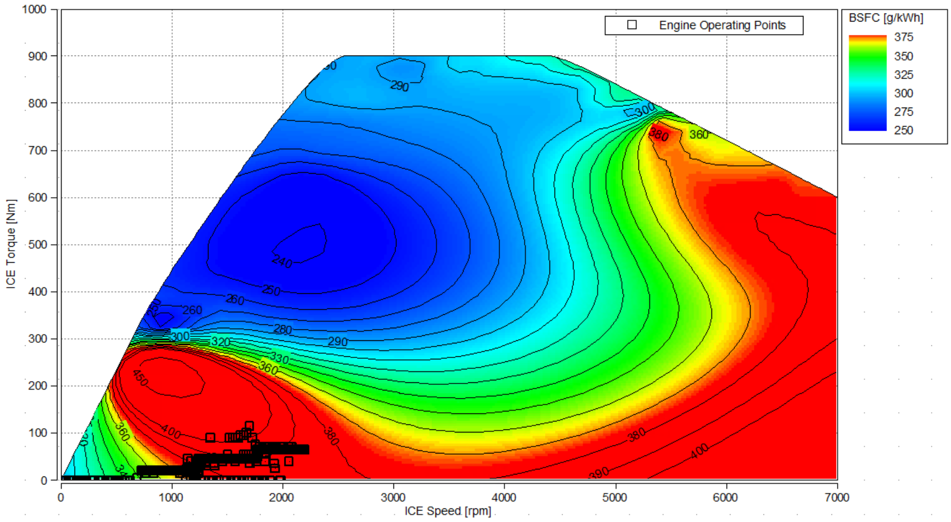


Figure 5.17 : ICE operating points for equivalent factor 1 for CS test.

As it can be seen in the above figures, with the different equivalent factor selection, system characteristic and dynamic responses are changing too much. Due to this reason, the EF which gives the optimum equivalent fuel consumption with the optimum SOC deviation has to be found.

To find the optimum EF value, lots of iterations are performed for CS tests to find the minimum equivalent fuel consumption and SOC deviation and as a result, optimum EF value for WLTP Class 3b is found as 3.654.

In the Figure 5.18, 5.19, 5.20, 5.21 and 5.22, the simulation results for the optimum equivalent factor (3.654) are shown respectively.

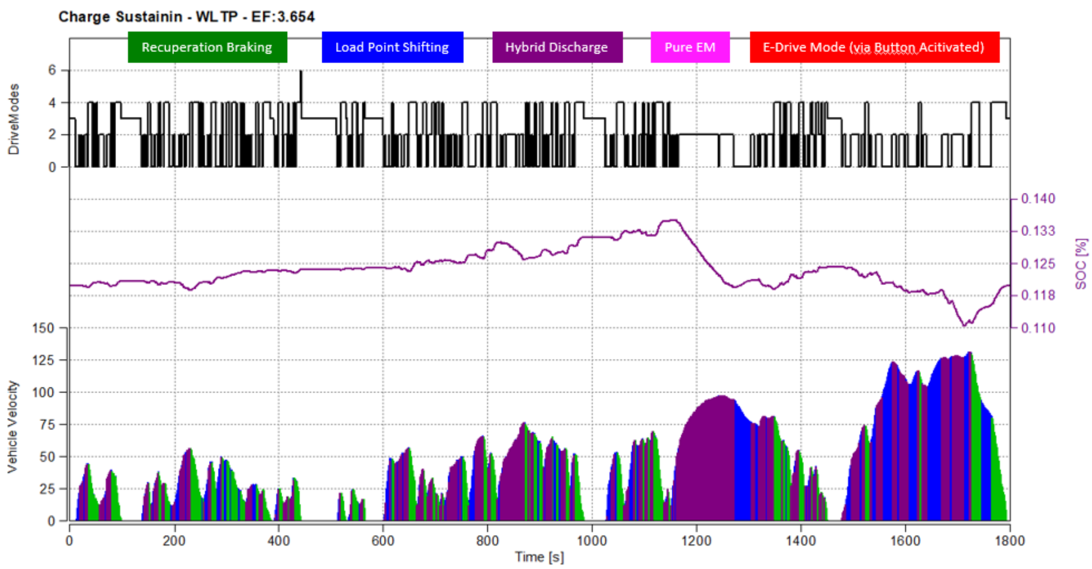


Figure 5.18 : Drive modes with optimum EF value for CS test.

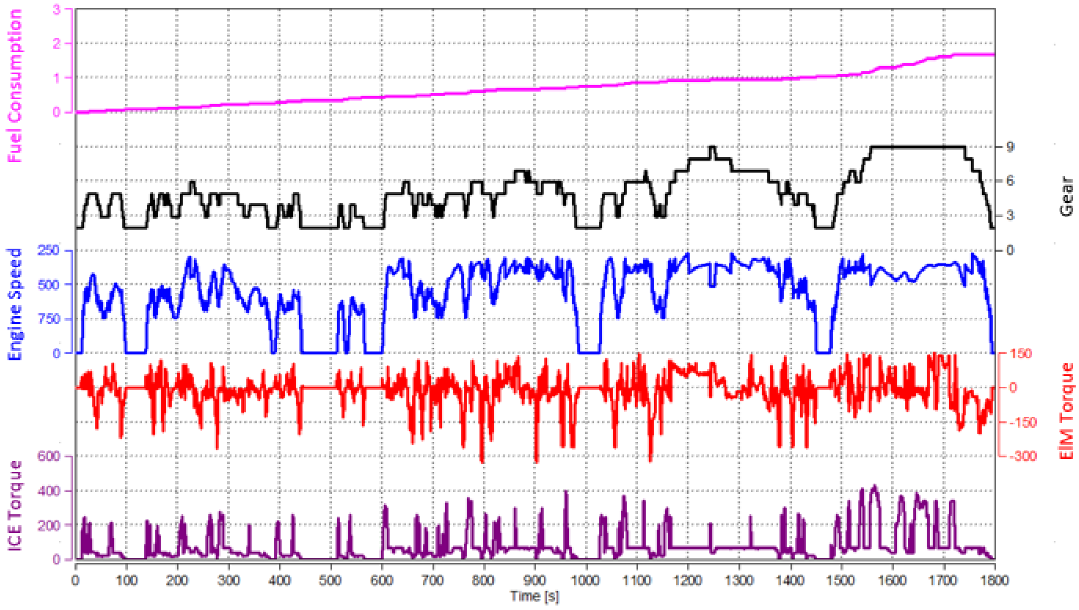


Figure 5.19 : General overview with optimum EF value for CS test.

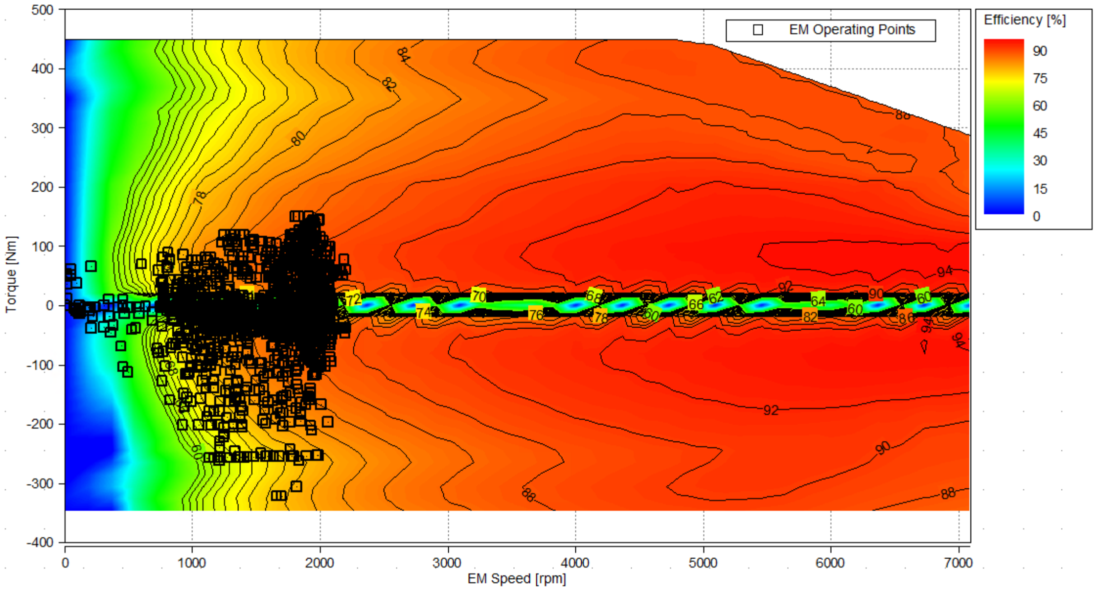


Figure 5.20 : EM operating points with optimum EF for CS test.

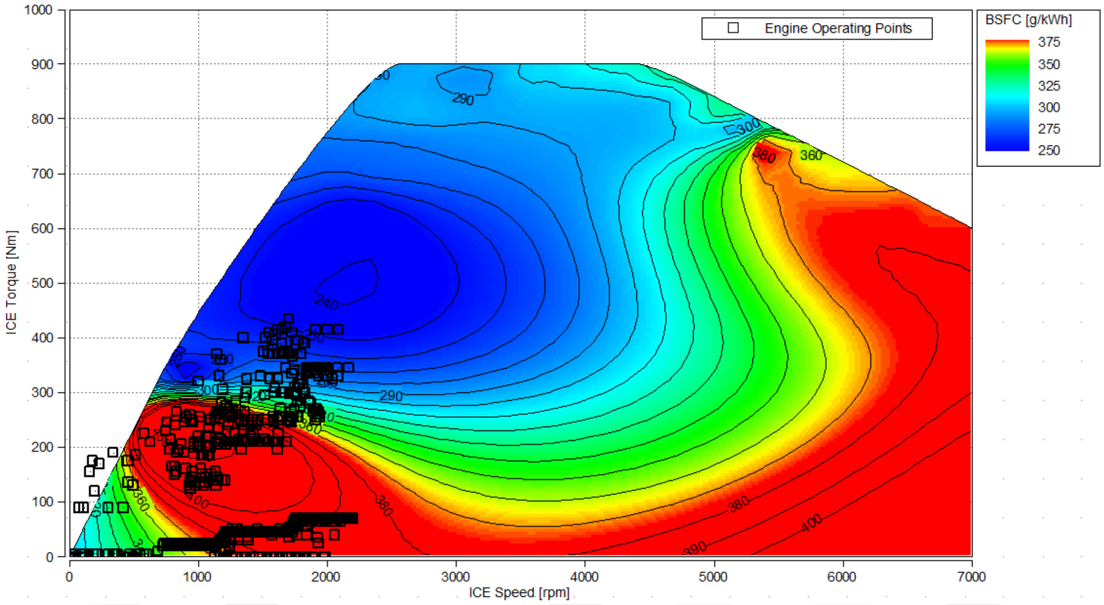


Figure 5.21 : ICE operating points with optimum EF for CS test.

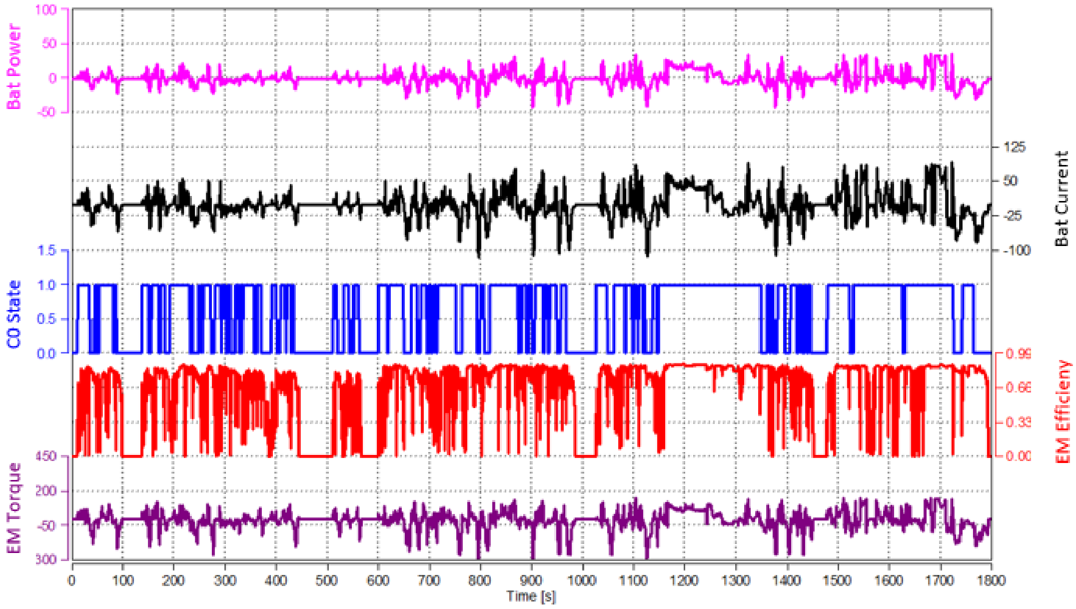


Figure 5.22 : Battery stats with optimum EF for CS test.

In the Table 5.4, all the comparison results with the plug-in hybrid vehicle model which has different EF values for ECMS algorithm are shown.

Table 5.4 : SOC and fuel consumption comparison for different EF values

Test Type [-]	Model [-]	EF [-]	Start SOC [%]	End SOC [%]	Fuel Consumption [l]	Fuel Consumption [l/100km]
WLTP 3b – CS	Plug-in Hybrid	5	12.00	37.99	5.23	22.48
CS WLTP 3b – CS	Plug-in Hybrid	1	12.00	1.50	0.43	1.84
CS WLTP 3b - CS	Plug-in Hybrid	3.654	12.00	12.00	1.70	7.31

As it can be seen in the above table, with the optimum equivalent factor, the same start and end SOC is obtained with the optimal fuel consumption. Normally, due to SOC target and end SOC difference, the excessive use of battery energy is converted to "actual" fuel consumption but in this case, it is not necessary. Because, when EF is selected as 3.654, start SOC and end SOC is completely same, so it can be thought that there is no additional energy from battery is consumed.

5.3.2 Charge depleting test

In charge depleting test, the battery is fully charged with AC or DC charger from grid before the test and test is started with 100% SOC. Until certain SOC point (13.9%), all the traction is provided just by electric motor, this mode is called as e-drive mode. After e-drive mode is finished, ICE is activated to keep the charge above a certain SOC threshold (11%) for battery health. After that point, ECMS decides the torque distribution between electric motor and ICE.

In below Figure 5.23, 5.24, 5.25, 5.26, 5.27 and 5.28, details of charge depleting are shown respectively.

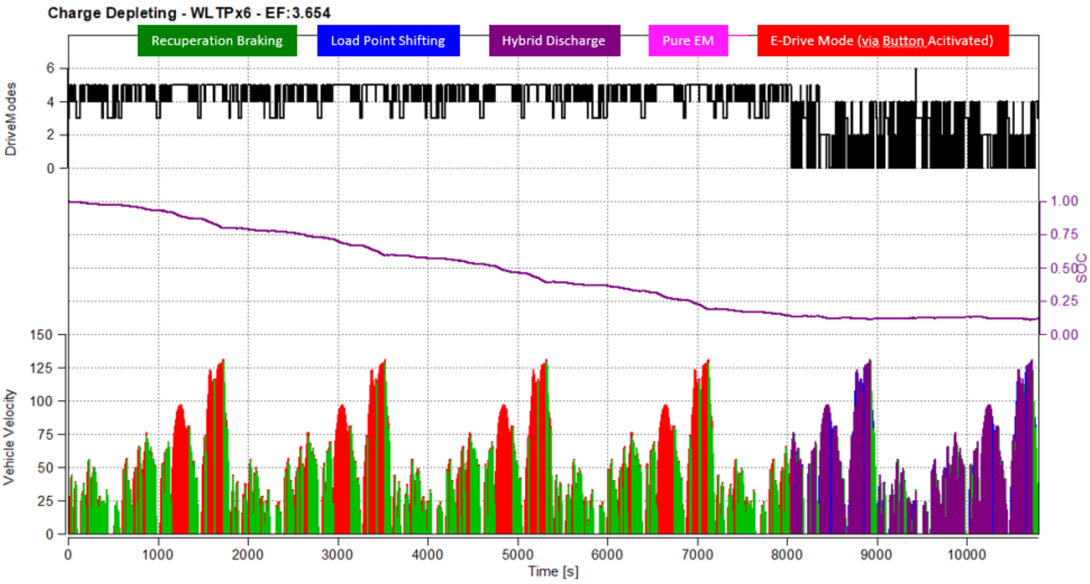


Figure 5.23 : Drive modes overview for CD test with optimum EF.

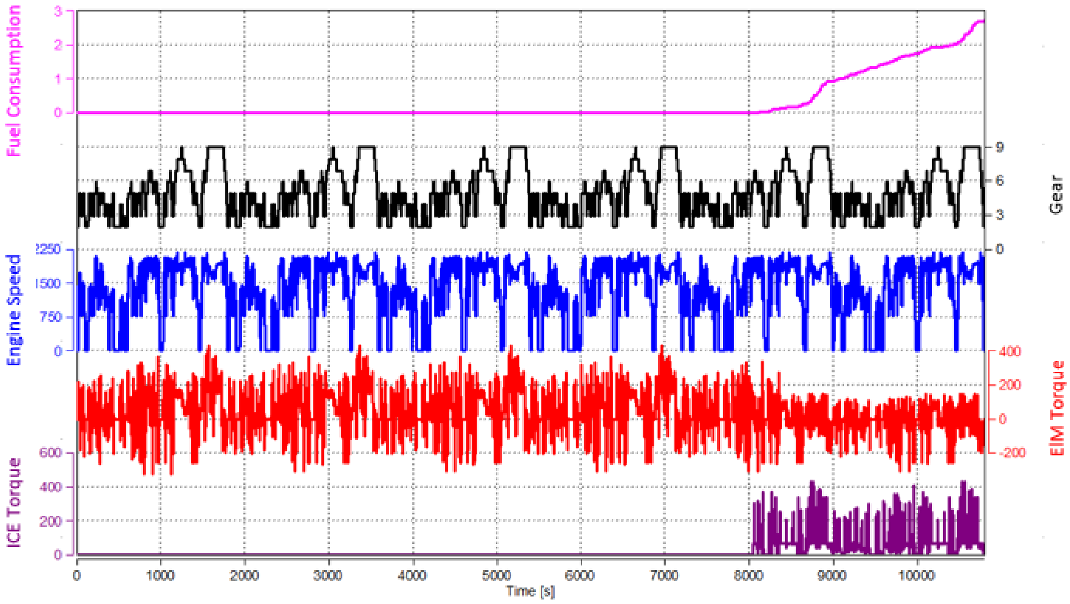


Figure 5.24 : General overview of CD test with optimum EF.

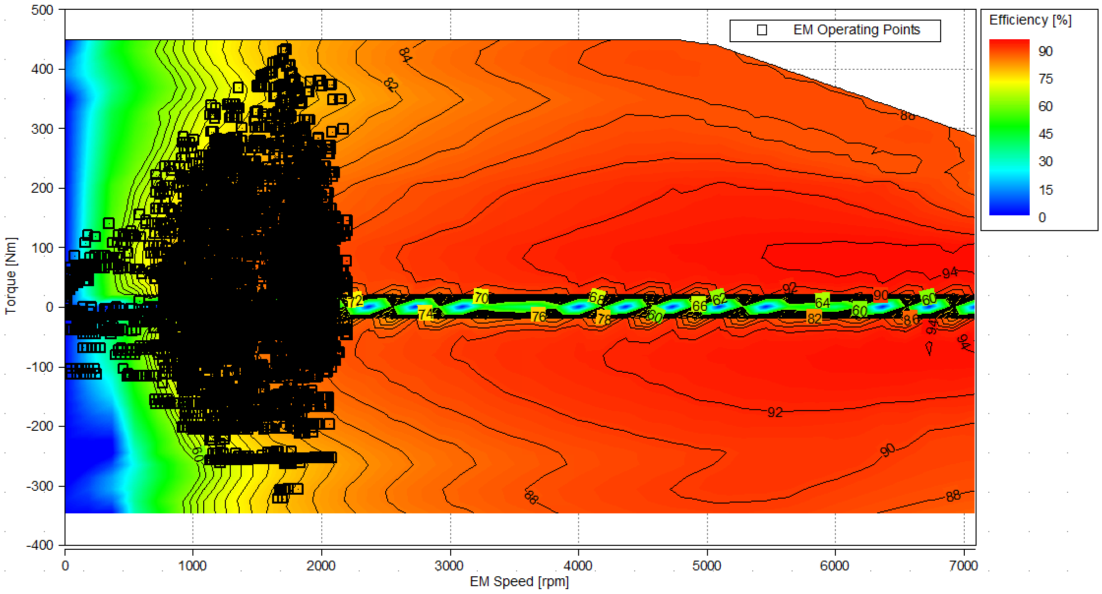


Figure 5.25 : EM operating points for CD test with optimum EF.

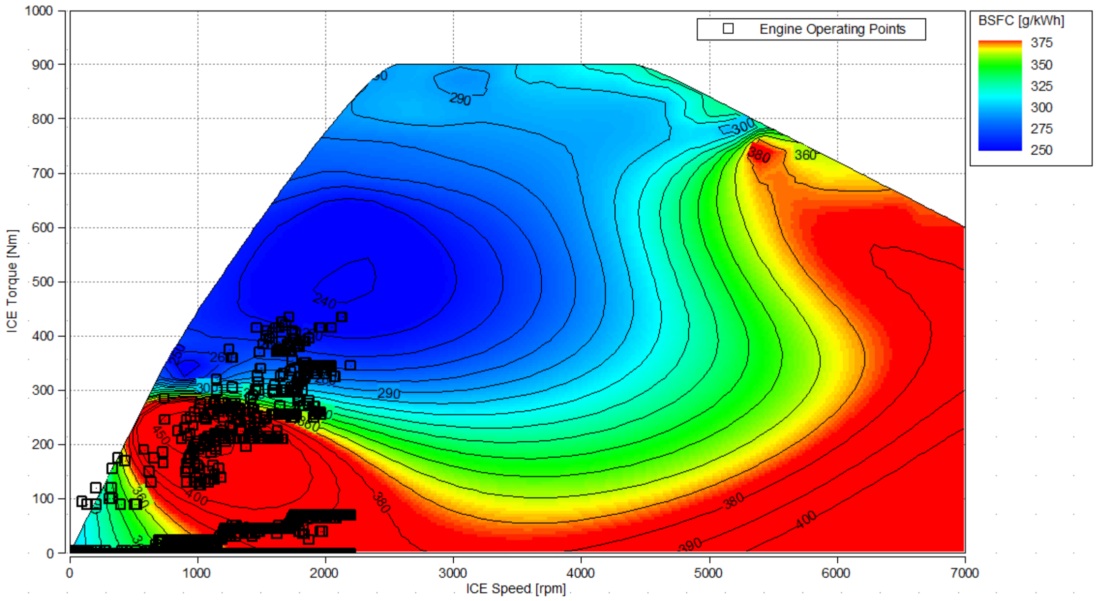


Figure 5.26 : ICE operating points with optimum EF for CD test.

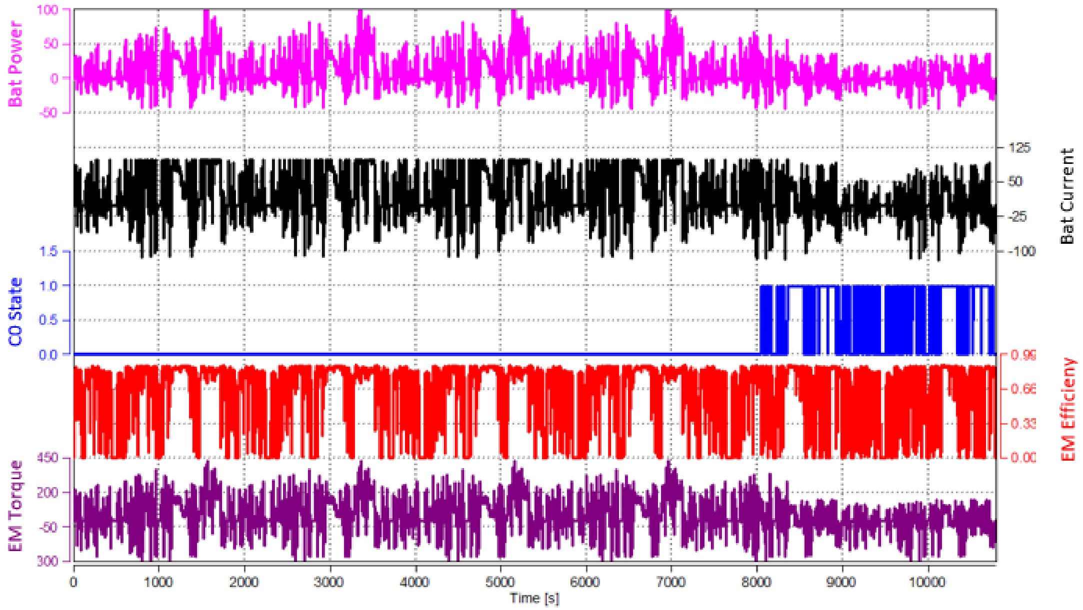


Figure 5.27 : Battery and EM stats with optimum EF for CD test**.**

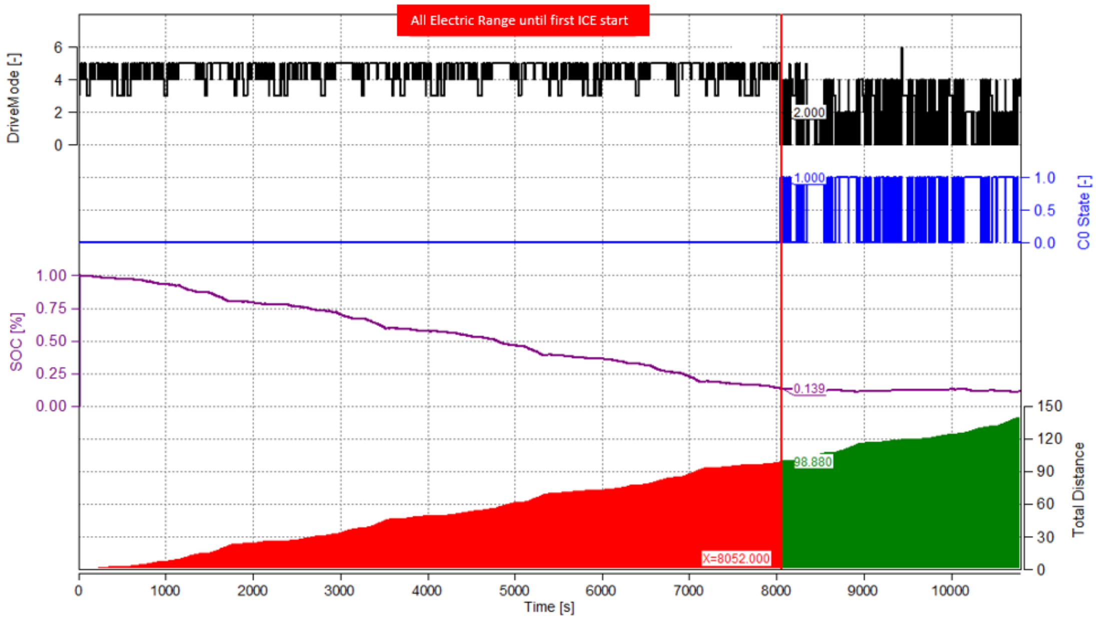


Figure 5.28 : All electric range calculation with optimum EF for CD test.

In the above figure, red area shows the total electric range that is travelled just with electric motor during the charge depleting test. In charge depleting tests, the high voltage battery is charged fully before the test and until SOC drops down 13.9%, just EM is used as a traction source. This is called as E-Drive, and it should be activated by manually in the vehicle.

As a result, the fuel consumption rate found with the optimum EF (3.654) as 1.70 l and 7.31 l/100 km without any SOC deviation. If there would be any SOC deviation from the target, the deviation had to be converted to real fuel consumption due to excessive use of battery but in this case, due to start SOC and end SOC values are completely same, the fuel consumption rate can be used directly for the comparison.

Table 5.5 : Fuel comparison for conventional ICE and ECMS hybrid model

Test Mass [kg]	Model [-]	EF [-]	Start SOC [%]	End SOC [%]	Fuel Consumption [l]	Fuel Consumption [l/100km]
2507	Conventional	-	-	-	2.40	10.31
2792	Plug-in Hybrid	3.654	12.00	12.00	1.70	7.31

6. CONCLUSION AND RECOMMENDATIONS

In this thesis, a P2 plug-in hybrid electric vehicle model was created in MATLAB Simulink including both ICE and EM with high voltage battery system to calculate total fuel consumption.

According to the regulation for plug-in hybrid electric vehicle, charge depleting and charge sustaining tests were performed on the vehicle model. For the energy management side, ECMS algorithm was implemented to plug-in hybrid electric vehicle model as a controller for the torque distribution between ICE and EM.

For a comparison, the plug-in hybrid electric vehicle model was converted the conventional ICE model considering the weight decrease due to electrified powertrain and battery group to be fair in terms of fuel consumption and the fuel consumption rate was calculated. Then the plug-in hybrid model with the ECMS energy management system was performed and the results showed that, with the optimum static equivalent factor selection, fuel consumption was decreased about 29.10%. And also, in charge depleting test, in 6 times back-to-back WLTP tests, 98.88 km electric range was obtained where just EM was used as traction source. Also, after the charge depleting test, during the confirmation cycle where the e-drive was switched off and ICE is activated, charge state of HV battery was kept as expected over a certain threshold.

Temperature effects on fuel usage and battery/electric motor efficiency were not considered in this thesis study. Implementing the effect of temperature and making a relationship between the equivalent factor and temperature can be suggested as future ideas.

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REFERENCES

[1] **Url-1** <https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>, date retrieved 20.05.2022.

[2] **Url-2** <https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-4a.html>, date retrieved 20.05.2022.

[3] **Url-3** <https://www.eea.europa.eu/data-and-maps/daviz/share-of-transport-ghg-emissions-1/#tab-dashboard-01>, date retrieved 20.05.2022.

[4] **Url-4** <https://www.eea.europa.eu/ims/co2-performance-of-new-passenger#:~:text=The%20average%20fleet%20target%20for%202019%20is%20130%20gCO2%2Fkm.>, date retrieved 20.05.2022.

[5] **Url-5** <https://europe.autonews.com/environmentemissions/european-auto-industry-braces-tougher-co2-emissions-targets-2030>, date retrieved 20.05.2022.

[6] **Url-6** <https://www.goldmansachs.com/insights/pages/briefly/from_briefings_21-Jan-2020/new-era-in-co2-regulation.pdf>, date retrieved 20.05.2022.

[7] **Url-7** <https://www.researchgate.net/publication/342575397_Energy_Management_Strategies_for_Hybrid_Electric_Vehicles_Review_Classification_Comparison_and_Outlookhttps://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks>, date retrieved 20.05.2022.

[8] **Url-8** <https://ieeexplore.ieee.org/abstract/document/7737440>, date retrieved 20.05.2022.

[9] **Url-9** <https://www.sciencedirect.com/science/article/pii/S1474667015342567>, date retrieved 20.05.2022.

[10] **Url-10** <https://en.wikipedia.org/wiki/Fuzzy_logic>, date retrieved 20.05.2022.

[11] **Automotive.** (2015). FUZZY LOGIC BASED ENERGY MANAGMENT SYSTEM FOR HYBRID ELECTRIC VEHICLE (2nd ed.). Malaysia: Tareq Z, Sulaiman N., Hannan M.A., Mohamed A., Majlan E.H., Daud W.RW.

[12] **Url-12** <https://www.eea.europa.eu/data-and-maps/daviz/share-of-transportghg-emissions-1/#tab-dashboard-01>, date retrieved 20.05.2022.

[13] **Url-13** <https://www.researchgate.net/publication/270810472_Global_Optimal_Energy_Management_Strategy_Research_for_a_PlugIn_Series_Parallel_Hybrid_Electric_Bus_by_Using_Dynamic_Programming>, date retrieved 20.05.2022.

[14] **Url-14** < https://www.mathworks.com/help/gads/what-is-the-genetic-algorithm.html>, date retrieved 20.05.2022.

[15] **Url-15** <https://easychair.org/publications/open/6CD4>, date retrieved 20.05.2022.

[16] **Url-16** <https://folk.ntnu.no/skoge/prost/proceedings/cdc-ecc05/pdffiles /papers/3034>, date retrieved 20.05.2022.

[16] **Url-16** <*https://folk.ntnu.no/skoge/prost/proceedings/cdc-ecc05/pdffiles/ papers/3034*>, date retrieved 20.05.2022.

[17] **Url-17** <*https://www.mathworks.com/videos/series/understanding-model-predictive- control.html*>, date retrieved 20.05.2022.

[18] **Url-18** <*Model Predictive Control Based Energy Management Strategy for a Plug-In Hybrid Electric Vehicle*>, date retrieved 20.05.2022.

[19] **Url-19** <*https://www.raillynews.com/2022/01/what-is-a-hybrid-car-how-do-hybrid-cars-work-how-to-charge-hybrid-cars/*>, date retrieved 20.05.2022.

[20] **Url-20** <*https://otomobilarsiv.com/hibrit-otomobil-nedir/*>, date retrieved 20.05.2022.

[21] **Url-21** <*https://www.greencarcongress.com/2021/04/20210425-aceaq1.html*>, date retrieved 20.05.2022.

[22] **Url-22** <*https://www.acea.auto/fuel-pc/fuel-types-of-new-cars-battery-electric-9-1-hybrid-19-6-and-petrol-40-0-market-share-full-year-2021/*>, date retrieved 20.05.2022.

[23] **Url-23** <*https://afdc.energy.gov/vehicles/how-do-hybrid-electric-cars-work*>, date retrieved 20.05.2022.

[24] **Url-24** <*https://x-engineer.org/micro-mild-full-hybrid-electric-vehicle/*>, date retrieved 20.05.2022.

[25] **Url-25** <*https://group-media.mercedes-benz.com/marsMediaSite/en/instance/ko/ Sales-release-for-the-S-Class-as-a-plug-in-hybrid.xhtml?oid=50807749*>, date retrieved 20.05.2022.

[26] **Url-26** <*https://en.wikipedia.org/wiki/State_of_charge*>, date retrieved 20.05.2022.

[27] **Url-27** <*https://www.nrel.gov/docs/fy09osti/42240.pdf*>, date retrieved 20.05.2022.

[28] **Url-28** <*https://www.renaultgroup.com/en/news-on-air/news/the-range-of-hybrid-cars/*>, date retrieved 20.05.2022.

[29] **Url-29** <*https://muhaz.org/wltp-2013-019-consolidated-draft-gtr-12-04-2013-running-histor.html?page=16*>, date retrieved 20.05.2022.

[30] **Url-30** <*https://wallbox.com/en_catalog/faqs-difference-ac-dc*>, date retrieved 20.05.2022.

[31] **Url-31** <*https://blog.evbox.com/difference-between-ac-and-dc*>, date retrieved 20.05.2022.

[32] **Url-32** <*https://www.mdpi.com/1996-1073/13/13/3352*>, date retrieved 20.05.2022.

[33] **Url-33** <*https://www.ucsusa.org/resources/all-about-drivetrains*>, date retrieved 20.05.2022.

[34] **Url-34** <*https://x-engineer.org/mild-hybrid-electric-vehicles-mhev-types/*>, date retrieved 20.05.2022.

[35] **Url-35** <*https://www.wevolver.com/article/the-electrified-car-s-powertrain-explained*>, date retrieved 20.05.2022.

[36] **Zhou, B., Burl, J. B., & Rezaei, A.** (2020). Equivalent Consumption Minimization Strategy With Consideration of Battery Aging for Parallel Hybrid Electric Vehicles. IEEE Access, 8, 204770-204781.

[37] **Paganelli, G.** (1999). Conception et commande d'une chaîne de traction pour véhicule hybride parallèle thermique et électrique (Doctoral dissertation, Valenciennes)..

[38] **Url-38** <*https://www.researchgate.net/publication/333151020_Towards_ a_ Smarter_Energy_Management_System_for_Hybrid_Vehicles_A_Comprehensive_Review_of_Control_Strategies*>, date retrieved 20.05.2022.

[39] **Musardo, C., Rizzoni, G., Guezennec, Y., & Staccia, B.** (2005). A-ECMS: An adaptive algorithm for hybrid electric vehicle energy management. European Journal of Control, 11(4-5), 509-524.

[40] **Url-40** < *https://www.mdpi.com/1996-1073/13/20/5407/htm*>, date retrieved 20.05.2022.

[41] **Kalaycı B.** (2021). Adaptive Equivalent Comsumption Minimization Strategy With Driving Pattern Recognition for Hybrid Electric Vehicles (Master Thesis). Istanbul Technical University, Institute of Science, ISTANBUL.

[42] **Url-42** <*https://dieselnet.com/standards/cycles/wltp.php*>, date retrieved 20.05.2022.

[43] **Url-43** <*https://en.wikipedia.org/wiki/Worldwide_Harmonised_Light_ Vehicles_Test_Procedure*>, date retrieved 20.05.2022.

[44] **Url-44** <*https://www.continental-automotive.com/getattachment/92ebca6e-95f2-48a6-8c87-036fd6922350/ATZ_EMR3_Highly-integrated-electric-powertrain.pdf*>, date retrieved 20.05.2022.

[45] **Url-45** <*https://e-mobitech.com/en/nmc-370-battery-37kwh-372v/*>, date retrieved 20.05.2022.

APPENDICES

APPENDIX A: ECMS MATLAB code

APPENDIX A

```
function [Tice,Tem,DrvMode,C0St] =
fcn(EF,Treq,nmot,SOC,ICEMaxTrqTbl,ICEFuelTrqBkp,ICEMaxTrqTblBkp,ICEFue
lMap,EMEffTrqBkp,EMEffSpdBkp,EMEffMap,ICEFuelSpdBkp,VehSpd,BattInitSo
C)
%     0: Load Point Shifting
%     2: Hybrid Discharging
%     3: Start&Stop Activation
%     4: Recuperation Braking
%     5: E-Drive Mode with Button
%     6: Pure EM

Tice=0;
Tem=0;
C0St=0;
DrvMode=0;

Lhv = 42.062; % kJ/g
SOCmin = 0.11;
SOCmax = 1.00;
SOCtarget = 0.12;
TemCnd = 0;
TiceCnd = 0;

if  BattInitSoC > 0.50 && VehSpd >0 && SOC > 0.139
   if  Treq <= 0
      Tice = 0;
      Tem = Treq;
      C0St = 0;
      DrvMode = 4;
   else
      Tice = 0;
      Tem = Treq;
      C0St = 0;
      DrvMode = 5;
   end

elseif  VehSpd == 0
       C0St = 0;
       DrvMode = 3;

else
   Cost = 100000;
   Tmax = interp1(ICEMaxTrqTblBkp,ICEMaxTrqTbl,nmot);
   for i=0:5:Tmax
      if i == 0
         fuelCnsmp = 0;
      else
```

```
            fuelCnsmp_base=
interp2(ICEFuelTrqBkp,ICEFuelSpdBkp,ICEFuelMap,i,nmot);
            fuelCnsmp = fuelCnsmp_base*i*nmot/9550/3600
        end

            TemTmp = Treq-i;
        EmEff = interp2(EMEffTrqBkp,EMEffSpdBkp,EMEffMap,TemTmp,nmot);

        if TemTmp >= 0
            Pbatt = TemTmp*nmot/9550/(EmEff/100);
        else
            Pbatt = TemTmp*nmot/9550*(EmEff/100);
        end

        pSOC = 1 - ((SOC - SOCtarget)/((SOCmax-SOCmin)/2))^3;
        Cost2 = fuelCnsmp + (EF/Lhv)*Pbatt*pSOC;

        if Cost2 < Cost
            TemCnd = TemTmp;
            TiceCnd = i;
            Cost = Cost2;
        end
    end

    Tem = TemCnd;
    Tice = TiceCnd;

    if  Tem >0 && Tice > 0
        DrvMode = 2;
        C0St = 1;

    elseif Tem <0 && Treq >0
        DrvMode = 0;
        C0St = 1;

    elseif Treq < 0
        Tem = Treq
        DrvMode = 4;
        C0St = 0;

    elseif Treq > 0 && Tem == Treq
        DrvMode = 6;
        C0St = 0;
     end
end
```

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