ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DESIGN AND EVALUATION OF ENERGY MANAGEMENT SYSTEMS FOR CONNECTED HYBRID AND ELECTRIC VEHICLES

Ph.D. THESIS

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Mechatronics Engineering Programme

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BAĞLANTILI HİBRİT VE ELEKTRİKLİ ARAÇLAR İÇİN ENERJİ YÖNETİM SİSTEMLERİ GELİŞTİRİLMESİ VE DEĞERLENDİRİLMESİ

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To my family,

FOREWORD

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ABBREVIATIONS

CI	: Confidence Interval
CO_2	: Carbon dioxide
CO_{2eq}	: Carbon dioxide equivalent
DP	: Dynamic Programing
EMS	: Energy Management System
EU	: European Union
EV	: Electric vehicle
EVs	: Electric vehicles
GHG	: Greenhouse gas
HIL	: Hardware-in-Loop
HEVs	: Hybrid Electric Vehicles
I2V	: Infrastructure to Vehicle
ICE	: Internal Combustion Engine
ICEV	: Internal combustion engine vehicle
ICEVs	: Internal combustion engine vehicles
LCA	: Life cycle assessment
NVH	: Noise, Vibration and Harshness
OECD	: Organization for Economic Cooperation and Development
PMSM	: Permanent Magnet Synchronous Motor
REEV	: Range Extended Electric Vehicle
REEVS	: Range Extended Electric Vehicles
REx	: Range Extender
SFC	: Specific Fuel Consumption
SOC	: State of Charge
SOCend	: State of Charge at the end of Simulation
SOCin	: Initial SOC
SIL	: Software-in-Loop
TTW	: Tank-to-Wheels
V2I	: Vehicle to Infrastructure
V2X	: Vehicle to Everything

WTT **:** Well-to-Tank

WTW **:** Well-to-Wheels

SYMBOLS

$\boldsymbol{a_i}$	: Acceleration for Operating Points
$\bar{\boldsymbol{a}}$	: Average acceleration
CI	: Confidence Interval
$\mathbf{c}_{\boldsymbol{w}}$	: Aerodynamic Coefficient
$\mathbf{D_i}$	: Distance of the i^{th} Traffic Light
$\mathbf{F_0}$	: Static Friction Coefficient
$\mathbf{F_1}$	: Coulomb Friction Coefficient
$\mathbf{F_2}$	: Relative Wind Coefficient
$\mathbf{f_R}$	: Rolling Resistance
$\mathbf{F_T}$	: Tractive Force
$\mathbf{F_{St}}$	: Inclination Force
$\mathbf{F_L}$	: Aerodynamic Force
$\mathbf{F_x}$	: Wheel Force
$\mathbf{F_z}$	: Wheel Load
J	: Objectice Function
$\mathbf{L_{gi}}$	: Green Light Phase
n	: Number of Measurement Points
$\mathbf{m_w}$	: Vehicle Mass
$\boldsymbol{p_m}$	: Measured Power
$\boldsymbol{p_{mi}}$	: Measured Power at Operating Point
$\boldsymbol{p_s}$	: Simulated Power
$\boldsymbol{p_{si}}$	: Simulated Power at Operating Point
r	: Correlation Coefficient
SOC	: State of Charge
$\mathbf{SOC_{end}}$	: Final State of Charge
$\mathbf{SOC_{in}}$	: Initial State of Charge
t	: Time
$\mathbf{t_{REx}}$	: REx Operation Time During the Cycle
v	: Vehicle Speed

$\mathbf{v_i}$	**:** Platoon Speed for ith intersection
w	**:** Angular velocity
X	**:** Reaction Force
$\boldsymbol{\alpha}$	**:** Inclination Angle
ρ	**:** Air Density
$\boldsymbol{\eta_s}$	**:** System Efficiency
$\boldsymbol{\lambda}$	**:** Total Inertia Ratio
$\boldsymbol{\sigma}$	**:** Standart Deviation

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DESIGN AND EVALUATION OF ENERGY MANAGEMENT SYSTEMS FOR CONNECTED HYBRID AND ELECTRIC VEHICLES

SUMMARY

Transportation is one of the most significant sources of emissions across various industries. With the effect of Paris Climate Agreement and the Green Deal, environmental concerns and technological progress push the development and market penetration of electric vehicles and hybrid electric vehicles. The number of electric and hybrid vehicles which can be considered as a stepping stone for electric vehicles are increasing day by day.

On the other hand, transportation systems are becoming more efficient and safe by the improvement of the communication systems both on the vehicles and the infrastructure. There are significant improvements in connected and autonomous vehicles which has been started with the development of advanced driver assistance systems. The automotive industry, which plays a key role in the development of many accompanying technological ecosystems, is expected to be enhance more changes in the next 10 years than in the past 100 years. It is estimated that this transformation will dominance especially with the technologies progress in connected and autonomous vehicles.

The main purpose of the study is to develop smart energy management strategies for connected, hybrid and electric vehicles and evaluate the benefits of developed smart energy management strategies. At the same time, the effects of the transition to electric vehicles in terms of energy consumption and environment is evaluated. For the optimization studies the Well-to-Wheels emission values are calculated and used in order to ensure apple-to-apple comparison.

During the thesis study, three articles have been prepared and the preapared articles have been the substructure of the thesis. As of the date of submission of the thesis, one of the articles has been published and the requested revisions have been made for the other two articles and resubmitted. Prepared articles entitled as " Dynamic Programing Based Green Speed Advisory System Design for Mixed Platooning Vehicles”, " Driving Cycle Based Energy Management Strategy Development for Range Extended Electric Vehicles " and " Comparative Study on Well-to-Wheels Emissions between Fully Electric and Conventional Automobiles in Istanbul". The article about the comparative study on Well-to-Wheels emissions has been published in the eighty-seventh issue of the "Transportation Research Part D" journal.

Turkey’s energy mix is analyzed and the emission factor of electricity production of Turkey is estimated in order to make appropriate comparisons during optimization studies. The Well-to-Wheels equivalent carbon dioxide emissions of the electricity is calculated. By considering energy sources, the Well-to-Wheels emission of Turkey is calculated as 520 g carbon dioxide equivalent per kWh. By using the carbon intensity of electricity, it is possible to compare the same variable for electric energy and fossil fuels for hybrid and electric vehicles.

Vehicle models are created to use for model-based optimization studies. In order to develop an energy management system for serial hybrid vehicles, all critical subsystems are tested and a vehicle model which is validated by the test data is created. The model is developed by mathematical modelling of vehicle dynamics and testing the the electric motor, motor driver, battery cells and internal combustion engine. The developed models are validated by vehicle level testing on chassis dynamometer.

A driving cycle based energy management strategy is developed for range extended electric vehicles to increase system efficiency and equivalent vehicle range. The results showed that; the optimized strategy can save CO2 emission by 6.21%, 1.77% and 0.58% for heavy, moderate and light traffic respectively. The usage of range extender in an efficient way by taking the traffic data into account extends the vehicle range, especially in heavy traffic conditions.

For the hybrid vehicles which consumes both electric energy and fossil fuels, It will is important to compare the same value fort he objective function such as equivalent carbon dioxide emission. This study is a good example from this point of view. The developed energy management system will enable connected hybrid vehicles to be in more efficient way by using the route and traffic density information.

In addition, vehicle emission maps are developed as a vehicle feature. The vehicles are tested on the chassis dynamometer and emission maps which are based on speed and wheel force are created. It is offered that vehicle emission maps can be used for optimization studies, especially in traffic with different types of vehicles. Considering that there are many ongoing studies on reducing tranportation based emissions, the use of the standardized emission maps are important for system level efficient use of connected vehicles.

From this point of view, a multi-layer dynamic programing based optimizer is designed to minimize platooning Well-to-Wheels emissions of platooning vehicles where the platoon consists of an electric, a gasoline and a diesel vehicle. Vehicle emission maps and longitudinal dynamics are used for vehicle modelling. Tank-to-Wheels emission maps of internal combustion engine vehicles are produced by testing the vehicles on a chassis dynamometer.

The optimization process has exploration and exploitation layers. The cost function is total Well-to-Wheels emission, design variable is speed trace, constraints are speed limits, traffic light states and vehicle accelerations limits. The test results show that the developed optimizer helps to achieve a 19.8% reduction in total Well-to-Wheels emissions for the defined use case. Thus, there is a significant emission saving potential in using speed advisory system for platooning vehicles through signalized intersections.

On the other hand, driving cycles are used to examine the energy consumption and emission emissions of vehicles. In order to analyze the environmental effects of electric vehicles on a real driving cycle, a driving cycle has been developed for Istanbul by statistically analyzing the data collected on the determined routes.

By using the developed driving cycle, the vehicle test are conducted. Acoording to the results electric vehicles emit 73.9 g carbon dioxide equivalent per kilometer on the same route, while gasoline vehicles emit 183.4 g equivalent carbon dioxide emissions. Therefore, the transition to electric vehicles should be strengthened by more widespread use of renewable energy in order to effectively reduce emissions associated with electric vehicles in general. At the same time, the results of this study can be a guide for policy makers.

In summary, within the scope of the thesis electric carbon intensity of Turkey is calculated by considering Turkey’s energy mix and Well-to-Wheels greenhouse gas emissions are analyzed both for conventional and electric vehicles are measured. A dynamic programing based optimizer is developed to decrease total Well-to-Wheels emissions of the mixed conventional and electric platooning vehicles through signalized intersections. Vehicle emission maps are generated both for electric and conventional vehicles for model-based optimization. A driving cycle based energy management strategy is developed for range extended electric vehicles to increase system efficiency and equivalent vehicle range. The vehicle model is developed by critical subsystem testing. An up to date driving cycle for Istanbul is developed (so called Istanbul Driving Cycle) by using collected traffic data across various sections of the city. An internal combustion engine vehicle and an electric vehicle are tested on a chassis dynamometer under the same conditions to determine specific energy consumption and specific emissions.

BAĞLANTILI HİBRİT VE ELEKTRİKLİ ARAÇLAR İÇİN ENERJİ YÖNETİM SİSTEMLERİ GELİŞTİRİLMESİ VE DEĞERLENDİRİLMESİ

ÖZET

Günümüzde ulaşım kaynaklı emisyonlar en önemli emisyon kaynaklarından biri haline gelmiştir. Paris İklim Anlaşması ve Yeşil Mutabakat'ın da etkisi ile özellikle çevresel avantajları sebebiyle elektrikli araçlar ön plana çıkmaktadır. İlk olarak 1800 lerin sonunda ortaya çıkan elektrikli araçlar tekrar ön plana çıkmıştır ve her geçen gün trafikteki elektrikli araç sayısı artmaktadır. Hibrit araçlar ise elektrikli araçlara geçişte bir basamak olarak değerlendirilebilir ve artık mevcut araç stokunun önemli bir payını elde etmiştir.

Diğer yandan ileri sürücü destek sistemlerinin gelişimi ile başlayan sürecin, otonom ve bağlı araçlar teknolojisinde önemli gelişmelere öncülük etmesi beklenmektedir. Tam otonom araçlara geçişte araç haberleşme sistemlerinin araç üstü sensörler ile birlikte kullanılması kaçınılmazdır. Bu nedenle, beraberindeki birçok teknolojik ekosistemin gelişmesinde anahtar rol üstlenen otomotiv endüstrisinin, önümüzdeki 10 yıl içerisinde geçtiğimiz 100 yıldan daha fazla değişim geçirmesi beklenmektedir. Gelişen teknolojiler ile özellikle bağlantılı ve otonom araçlar ile bu dönüşümün gerçekleşmesi öngörülmektedir.

Bu çalışmanın temel amacı, bağlantılı, hibrit ve elektrikli araçlar için akıllı enerji yönetimi stratejileri geliştirmek, geliştirilen enerji yönetim sistemlerinin sağladığı faydayı değerlendirmektir. Ayrıca elektrikli araçlara geçişin enerji ve çevre açısından etkilerini değerlendirmektir. Gerçekleştirilen optimizasyon çalışmalarında özellikle aynı değişkenin karşılaştırılabilmesi için kaynaktan tekerlere emisyon değerleri de incelenmiştir.

Bu tez çalışması sırasında üç adet makale hazırlanmış ve bu makalelerden tezin hazırlanmasında istifade edilmiştir. Tezin sunulduğu tarih itibariyle, bu makalelerden bir tanesi yayınlanmış diğer iki tanesi için de istenen revizyonlar yapılmış ve tekrar sunulmuştur. Hazırlanan makaleler " Farklı Güç Sistemlerine Sahip Araçlardan Oluşan Konvoy İçin Dinamik Programlama Tabanlı Çevreci Hız Öneri Sistemi Geliştirilmesi", "Menzili Artırılmış Elektrikli Araçlar için Sürüş Döngüsü Tabanlı Enerji Yönetimi Stratejisi Geliştirilmesi" ve "Tam Elektrikli ve Konvansiyonel Araçlar için Kaynaktan Tekere Emisyonlar Açısından Karşılaştırmalı Çalışma" başlıklarında sunulmuştur. Karşılaştırmalı çalışma içeren makale "Transportation Research Part D" dergisinin seksen yedinci sayısında yayınlanmıştır.

Optimizasyon sırasında kullanmak ve uygun karşılaştırmaları yapabilmek için elektrik enerjisinin kWs başına emisyon değerleri hesaplanmıştır. Bu çalışmada kaynaktan tekere metodolojisi kullanılmıştır. Elektrikli ve hibrit araçlarda kullanılan elektrik enerjisinin çevresel etkilerini hesaplamak ve optimizasyon çalışmalarında maliyet fonksiyonlarında kullanılmak üzere yapılan bu çalışma ile, ülkemizde elektrik üretiminin kaynaktan tekere eşdeğer karbondioksit salınımı ilk kez kapsamlı bir şekilde ortaya konmuştur. Enerji üretim kaynakları dikkate alınarak yapılan çalışmaya

göre ülkemizde kWs başına kaynaktan tanka emisyon değeri kWs başına 520 g karbondioksit eşdeğer olarak hesaplanmıştır. Bu değer kullanılarak hibrit ve elektrikli araçlar üzerine yapılan çalışmalarda elektrik enerjisi ve fosil yakıtlar için aynı değeri kıyaslayabilme imkanı sağlanmıştır.

Model bazlı optimizasyon çalışmalarında kullanılmak üzere araç modelleri oluşturulmuştur. Seri hibrit araçlarda enerji yönetim sistemi geliştirilmesi için tüm kritik alt sistemler test edilerek test verileri ile doğrulanmış bir araç modeli oluşturulmuştur. Elektrik motoru, motor sürücüsü, batarya hücreleri ve içten yanmalı motor test sonuçları kullanılarak bir araç modeli oluşturulmuş ve araç seviyesinde yapılan testler ile bu model doğrulanmıştır.

Oluşturulan alt sistem modellerini içeren araç modeli ve doğrusal dinamik araç modeli kullanılarak model bazlı optimize edici geliştirilmiştir. Aracın kullanılacağı güzergahın sürüş çevrimine bağlı olarak menzil uzatıcının daha verimli çalışacağı bir strateji geliştirilmiştir. Aynı seyahat süresi ve hız profilinde seyahat etmek koşulu ile menzil uzatıcının daha verimli çalışabileceği hız zaman aralıklarının belirlenmesi prensibi ile çalışan bir optimize edici geliştirilmiştir. Geliştirilen optimize edicinin kullanıldığı ve baz durumlar karşılaştırılmıştır. Sonuçlar yoğun trafikte %6.21, orta trafikte %1.77 ve hafif trafikte %0.58 karbondioksit emisyonlarının azaltılabileceğini ortaya çıkarmıştır. Hem fosil yakıt hem de elektrik enerjisi kullanan araçlarda yapılacak optimizasyon çalışmalarında eşdeğer karbondioksit salınımı maliyet fonksiyonu oluşturmak için aynı değeri karşılaştırmak açısından faydalı olacaktır. Bu çalışma da bu açıdan bir örnek teşkil etmiştir. Geliştirilen enerji yönetim sistemi bağlantılı hibrit araçların güzergah ve trafik yoğunluğu bilgisinin sağlanması ile daha verimli bir şekilde kullanılmasnı sağlayacaktır.

Ayrıca bir araç özelliği olarak araç emisyon haritaları ortaya konmuştur. Araçlar şasi dinamometresi üzerinde test edilerek hız ve teker kuvvetine bağlı olan emisyon haritaları oluşturulmuştur. Araç emisyon haritalarının özellikle farklı tipte ve farklı güç, aktarma sistemlerine sahip araçların bulunduğu trafikte optimizasyon çalışmaları için kullanılabileceği tezi savunulmuştur. Özellikle ualşım kaynaklı emisyonların azaltılması için yoğun çalışmaların yürütüldüğü ve yürütüleceği göz önüne alındığında, bağlantılı araçların daha verimli kullanılması için standartlaşmış emisyon haritalalarının kullanılması sistem seviyesinde optimizasyon yapılmasını kolaylaştıracaktır.

Bu noktadan hareketle benzinli, elektrikli ve dizel araçların içinde olduğu kooperatif hız kontrolünün yapıldığı bir konvoy için dinamik programlama bazlı bir optimize edici geliştirilmiştir. İstanbul Anadolu yakasaı sahil yolunun bir kısmını içeren örnek bir durum üzerinde geliştirilen model test edilmiştir. Belirlenen rotada araçlar trafik lambalarının olduğu bir güzehta belli bir mesafeyi kat etmişlerdir. Bu esnada salınan emisyonların en aza indirilmesi için katmanlı dinamik programlama tabanlı bir optimize edici geliştirilmiştir.

Bu çalışmada amaç fonksiyonu kaynaktan tekere emisyonları, sınır koşulları maksimum, minimum hız limitleri, trafik lambası durumlarını içermektedir. Sınır koşulları ve amaç fonksiyonuna göre hız profilleri optimize edilmektedir.

Trafik lambalarının durumlarına göre atanan noktalar, emisyon haritları ve araç modelleri kullanılarak emisyon salınımı açısından lokal minimum değerler tespit edilmiştir. Ardışık lokal minimum değerleri arasında yeni geçiş noktaları atanarak ikinci kademe dinamik optimizasyon gerçekleştirilmiştir. Son aşamada ise hız eğrilerinin kesişme noktaları için yavaşlama ve hızlanma profilleri farklı ivme değerleri göz önüne alınarak yine dinamik programlama yöntemi ile en uygun değerler seçilmiştir. Böylece trafik ışıklarının da olduğu bir ortamda farklı güç ve aktarma orgablarına sahip araçların bulunduğu bir konvoy için optimum hız profilini ortaya koyan dinamik programlama tabanlı çok katmanlı bir optimize edici geliştirilmiştir. Geliştirilen optimize edici tarafından bulunan optimum hız profilleri bağlantılı araçlarda hız öneri sisteminin bir girdisi olarak kullanılabileceği gibi otonom araçlarda araçların hız kontrlü için de kullanılabilecektir.

Geliştirilen optimize edicinin verimi kullanıldığı güzergaha göre farklılık gösterecektir. Belirlenen örnek güzergahta ilk duruma göre toplam konvoy emisyonunun aynı seyahat süresi için %19.8 oranında azaltıldığı ölçülmüştür. Bu çalışmada da ortaya koyulan dinamik kooperatif trafik kontrolünün dünyada 2030’lu yıllara doğru yaygınlaşmaya başlaması beklenmektedir.

Sürüş çevrimleri araçların özellikle enerji tüketimi ve emisyon salınımlarını incelemek için kullanılmaktadır. Elektrikli araçların çevresel etkilerinin gerçek bir sürüş çevrimi ile analiz edilebilmesi için sürüş çevrimi hazırlanarak testler gerçekleştirilmiştir. Belirlenen güzergahlarda toplanan veriler istatistiksel olarak analiz edilerek İstanbul için bir sürüş çevrimi geliştirilmiştir. Geliştirilen sürüş çevrimi kullanılarak, elektrikli araç kullanımı ile kaynaktan tekerlere emisyon değerlerinin gerçekte ne kadar değişeceği ortaya konmuştur. Yapılan şasi dinamometresi testlerinin sonuçlarına göre elektrikli araçlar aynı güzergahta kilometre başına 73.9 g eşdeğer karbondioksit salınımı gerçekleştirirken benzinli araçlar 183.4 g eşdeğer karbondioksit salınımı gerçekleştirmektedir. Bu nedenle, genel olarak elektrikli araçlara ilişkili emisyon azaltımını etkin bir şekilde gerçekleştirmek için elektriklere araçlara geçiş yenilenebilir enerjinin daha yaygın kullanımı ile güçlendirilmelidir. Aynı zamanda, bu çalışmanın sonuçları politika yapıcılar için de bir rehber olabilir.

Özetle, sunulan tez kapsamında ülkemiz için kaynaktan tanka, kaynaktan tekere emisyon salınımları incelenerek bu alanda ilk kez değerler hesaplanarak, ölçülerek literatüre kazandırılmış, ülkemizde elektrikli araçlara geçişin çevresel etkileri çalışması literatüre kazandırılmış, kritik araç komponentlerinin her birinin test edilmesi ile valide hibrit ve elektrikli araç modelleri kurulmuş, emisyon haritası kavramı ortaya atılarak farklı araçlar için emisyon haritaları oluşturulmuş, tek araç ve birden fazla aracın olduğu durumlar için hazırlanan modeller ve eşdeğer karbondioksit emisyonu değerleri dikkate alınarak dinamik programlama gibi yöntemler ile optimize ediciler geliştirilmiş, geliştirilen enerji yönetim sistemlerinin verimliliği dinamometre ortamında test edilmiştir.

1. INTRODUCTION

Transportation is one of the significant gas emission sources (IEA, 2018), especially in high population zones of metropolitan cities such as Istanbul. There are incentives for the transportation by alternative energy sources, especially for electric vehicles (EVs), which are accepted as more ecological in terms of Tank-to-Wheels (TTW) emissions comparing to internal combustion engines (ICEVs). There are incentives for hybrid, electric vehicles and alternative transportation solutions. In Turkey, the special consumption tax of passenger EVs are between 3% and 15% depending on electric power (GIB, 2019). And the tax rate of the vehicles with internal combustion engine has a range between 37% and 84% depending on engine volume and hybrid electric vehicles are not classified as EVs in the taxation system of Turkey (GIB, 2019). The EV market share in Turkey is still minor comparing to China and some of the European Union (EU) countries due to high cost of ownership, lack of charging infrastructure, long charging time and limited driving range. Estimations indicate that the market share of electric vehicles will increase rapidly. On the other hand connected and autonomous vehicl technologies are coming through as breakout technologies. Connectivity is being used on transportation systems especialy for safety and energy efficiency (Montanaro et al., 2019).

1.1 Brief History

The number of worldwide registered EVs in traffic has exceeded ten million, and estimations indicate that the market share of EVs in total will increase rapidly (IEA, 2021). Thus, a heterogeneous road traffic in terms of vehicle powertrains is emerging (He & Wu, 2018). Although electric vehicle technology seems like a new technology today, it is known that the first electric vehicles developed in 1800s. With the invention of rechargeable batteries, it gained the potential to capture a large market volume in the early 1900s. However, internal combustion engine vehicles dominated the market in the twentieth century due to low fuel prices and energy density. About 100 years after, electric and hybrid vehicles re-entered the market, this time with their technological improvements. The electric vehicle sales in the world was 1 million in 2017, and approached 2 million in 2018 as given in Figure 2.1 :. This represents a 68% annual growth in electric car sales between 2017 and 2018. The increase in this rate is due to the dominance of fully electric vehicles in the Chinese market and the increase in sales of fully electric vehicles in the US market, especially with the launch of the Tesla Model 3 (IEA, 2021). With more than 3 million electric cars sales, China is the world's largest electric car market. In 2021 total electric vehicle sales is more than 6 million all over the world and electric vehicle sales counts more than 8% of the total vehicle sales as represented in Figure 1.1.

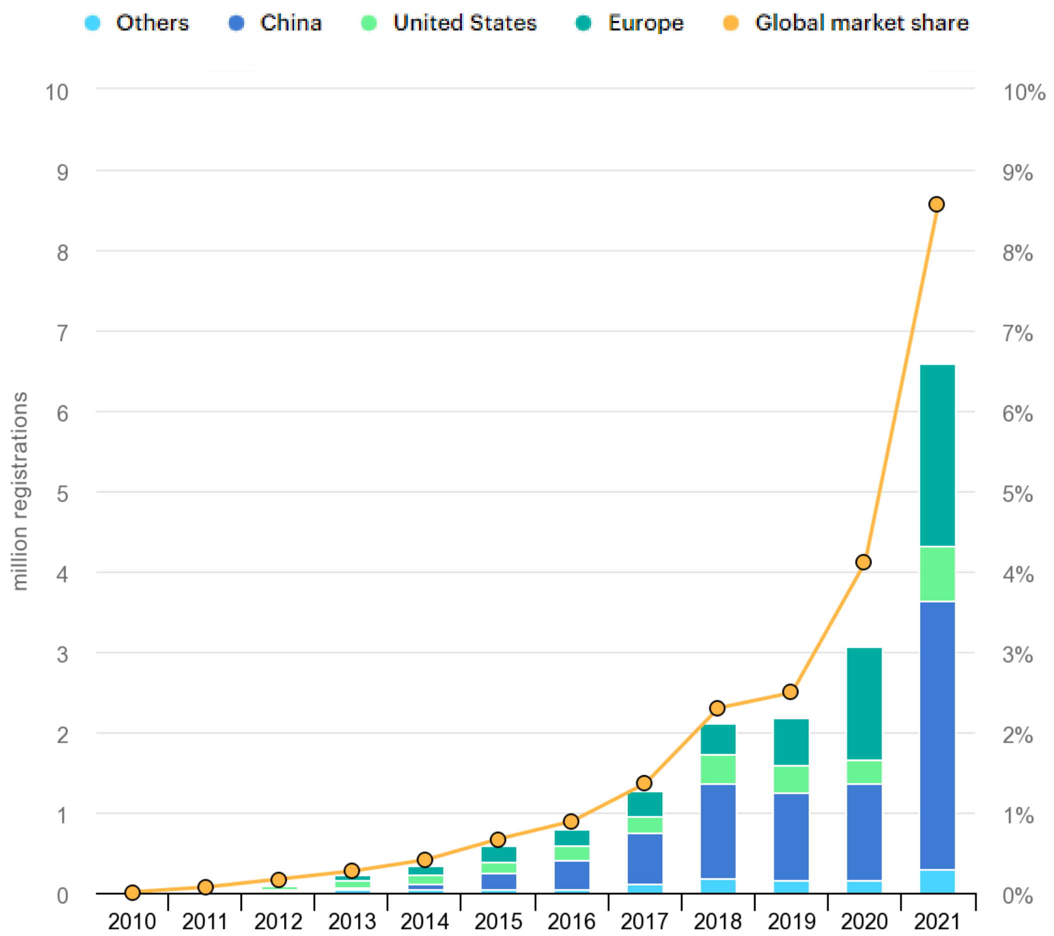

Figure 2.1 : Global electric vehicle sales (IEA, 2021).

For electric vehicle sales forecasts, two scenarios modeled by the International Energy Agency. The first scenario is the 'New Policies' scenario, in which the incentives that have already been announced continue in line with the current targets and regulations. According to the new policies scenario, approximately 23 million electric vehicle sales and 130-135 million electric vehicle stocks are expected in 2030. The second scenario assumes that; Electric Vehicles Initiative countries (Canada, France, Japan, Norway, Chile, Germany, Netherlands, Sweden, China, India, New Zealand) that participated in the EVI program, will announce more incentives to incerase electromobility. According to the EV30@30 scenario, the electric vehicle sales rate is estimated to be 30% in 2030, 43 million electric vehicle sales and 250 million electric vehicle stock in total are expected. Today, almost every class and type of vehicle can be developed with an electric powertrain. Electric vehicles are not only available for passenger cars, but also in heavier vehicles such as minibuses, buses and trucks.

On the other hand automation and connectivity enables energy efficient driving by connected vehicle control, cooperative vehicle control and road infrastructure control (Othman et al., 2021). Thanks to developments in the field of intelligent transportation systems, Vehicle-to-Everything (V2X) systems are being used for eco driving strategy development (HomChaudhuri et al., 2016; Ma et al., 2019, 2021; Montanaro et al., 2019; Xu, Hu, et al., 2020; H. Yang & Jin, 2014; Ye et al., 2019; Zhang et al., 2019). The transformation, which started with the development of advanced driver assistance systems, is expected to lead to significant developments in autonomous and connected vehicle technology. That's why, the automotive industry, which plays a key role in the development of many accompanying technological ecosystems, is expected to progress in the next 10 years more than in the past 100 years.

These transformations in vehicle technologies require the development and use of high technology in manufacturing and design. Simulations where virtual prototypes are created and tested in a computer environment, which save time and money, can be given as an example. In addition, the concepts of big data analytics and machine learning are more important for the automotive industry in terms of processing high volumes of data (Neilson et al., 2019).

Connected and smart mobility is important for safe and energy efficient transportation. For safety the aim is decreasing the road traffic accidents by using smart transportation systems. According to the road traffic accident statistics report of the Turkish Statistical Institute, 88.3% of the 243,125 fatal or injury traffic accidents in Turkey are caused by driver errors (TÜİK, 2020). The first step of autonomous vehicles can be accpeted as the vehicles which has advanced driver assistance systems such lane keeping assist, collision avoidance etc. Semi-autonomous driving systems use the same sensors (camera, radar, lidar, etc.) as advanced driver assistance systems, work on similar hardware structures, and are functionally developed with marginal steps above advanced driver assistance systems.

The main factor in rapid growth of the advanced driver assistance systems market is being mandatory in the USA, Japan and EU for new vehicles. Advanced Emergency Braking System and Lane Departure Warning System sub-systems have been mandatory in new medium-heavy duty vehicles since 2016 in the USA, Japan, and EU.

Another advantage of connected and electric vehicles is energy effiency. The energy effiency can be also defined as emission reduction where transportation related emissions account for more than a quarter of total emissions (EEA, 2021; EPA, 2020). Electric and hybrid vehicles have advantages in terms of Well-to-Wheels (WTW) greenhouse gas (GHG) emissions depending on the carbon intensity of the electricity mix (Moro & Lonza, 2018). Thus, the use of electric and hybrid vehicles is encouraged for environmental concerns. Thanks to the regulations and customer preferences the number of electric vehicles on the roads increases with each passing day. By connected electric and hybrid vehicles the transportation can be more sustainable and smart (EC, 2021). Strategies to promote the transition to sustainable and smart mobility under the European Green Deal (EC, 2019). According to EU Green Deal Transport accounts for a quarter of the EU's greenhouse gas emissions and is still growing. Therefore, transportation emissions will be reduced by 90% by 2050 (EC, 2019). The EU transport system and infrastructure will be developed to support new sustainable mobility services which can reduce congestion and pollution, particularly in urban areas. Mobility technologies will have an increasing importance along with the smart traffic management systems provided by digitalization. Intelligent systems will be developed for traffic management and Mobility as a Service solutions.

By the technological developments and regulations the transition to electric and connected vehicles are promoted to ensure sustainable and smart mobility.

1.2 Purpose of Thesis

The pupose of the thesis is to develop smart energy management strategies (EMS) for connected, hybrid electric vehicles. At the same time the purpose is to evaluate the benefit of developed strategies and electric vehicle usage in terms of WTW emissions. A dynamic programing based optimizer is developed to decrease total WTW emissions of the mixed conventional and electric platooning vehicles through signalized intersections. The design variable of the optimizer is the speed profile and the objective function is the total emission. Vehicle emission maps are generated both for electric and conventional vehicles for model-based optimization. As another use case, a driving cycle based EMS is developed for range extended electric vehicles to increase system efficiency and equivalent vehicle range. A validated vehicle model is developed by critical subsystem testing and a comparative study is conducted to assess the developed strategy. The usage of range extender in an efficient way by taking the traffic data into account extends the vehicle range, especially in heavy traffic conditions. WTW greenhouse gas emissions are analyzed both for conventional and EVs by using generated driving cycle. An up to date driving cycle for Istanbul is developed (so called Istanbul Driving Cycle) by using collected traffic data across various sections of the city. An internal combustion engine vehicle (ICEV) and an electric vehicle (EV) are tested on a chassis dynamometer under the same conditions to determine specific energy consumption and specific emissions. Turkey's electricity production infrastructure is analyzed and the emission factor of electricity production of Turkey is estimated. The WTW emissions are used for evaluations for apples-to-apples comparison.

2. CONNECTED HYBRID AND ELECTRIC VEHICLES

2.1 Connected Vehicles

Connected vehicles refer to systems that can send and receive data out of the vehicle with a connection (3G, 4G, 5G, or WLAN). Connected vehicle technology enables different vehicles to communicate with each other, with people or with city infrastructure, using technologies that can communicate one-way or two-way. As given in Figure 2.1 vehicles can communicate with infrastructure, network, grid, vehicle, device or pedestrian (Martin & Ivanov, 2018).

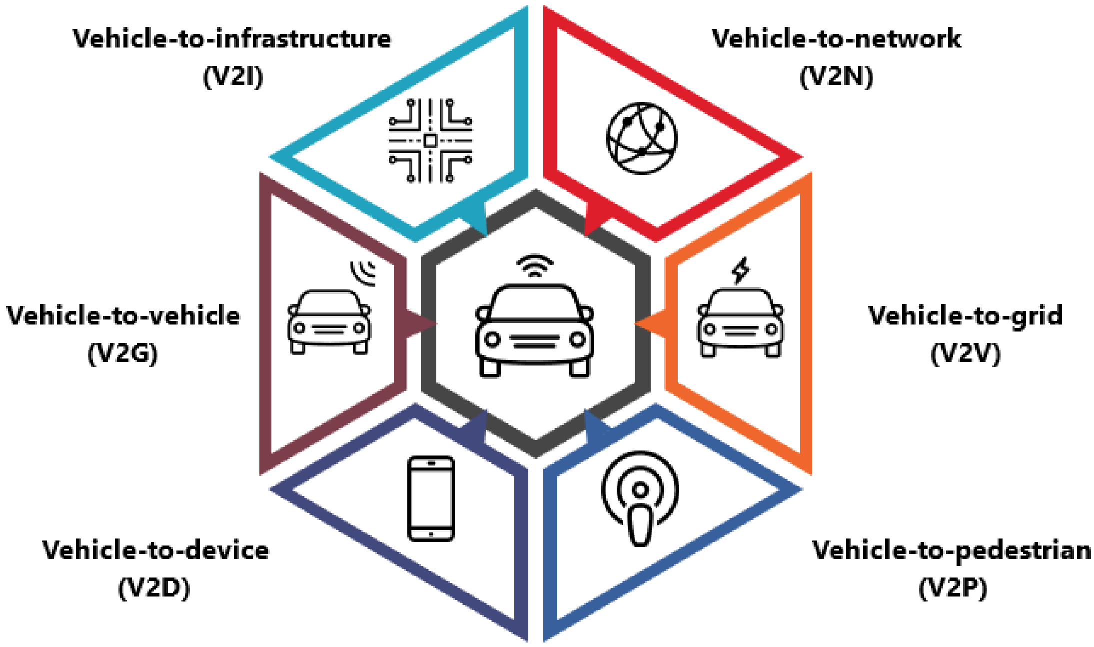

Figure 2.1 : Vehicle to everything (V2X) technology (Martin & Ivanov, 2018).

In connected vehicles, the communication between two vehicles is referred to as "V2V" (vehicle to vehicle), the vehicle's form of communication with its surroundings is referred to as "V2X" (vehicle to X), and the vehicle's connection to the transportation infrastructure is referred to as "V2I" (vehicle to infrastructure). V2I covers any infrastructure where vehicles can be communicated, such as the road, traffic signs and lights, bridges, other components of the road infrastructure. Vehicles equipped with V2V and V2I communication technology can send or receive data (brake status, location, direction, speed and other vehicle data) while driving which can be used for eco-driving. Autonomous vehicles, can be classified according to the role of the driver. SAE International has divided the autonomous driving capabilities into five levels where level 0 is defined as conventional driving as represented in Figure 2.2.

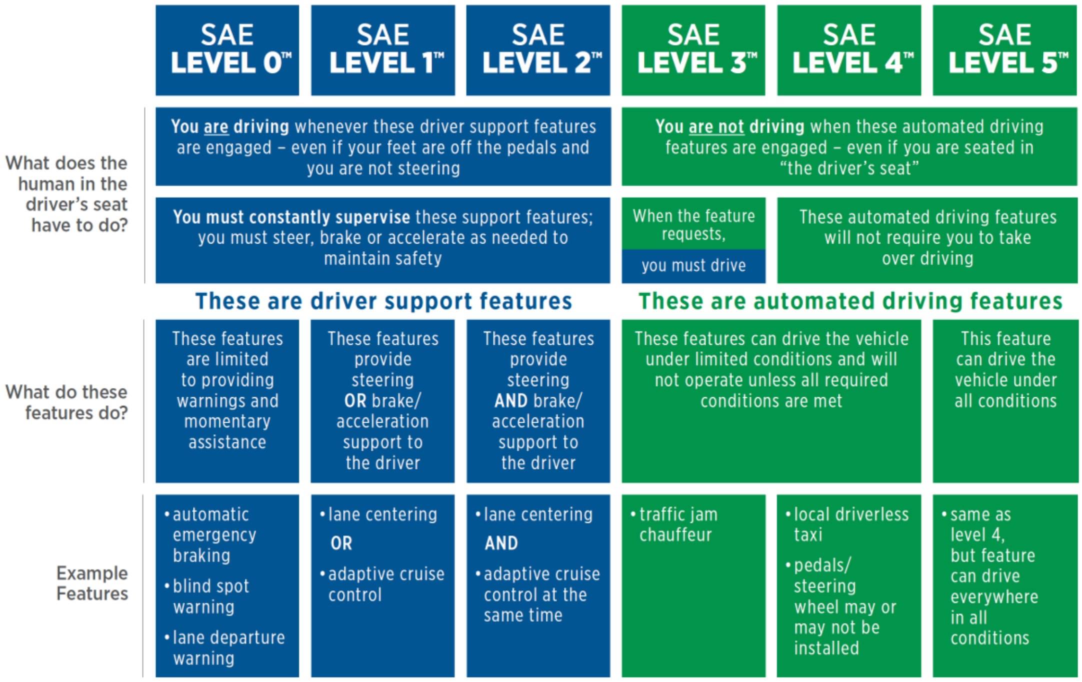

Figure 2.2 : SAE levels of driving automation (SAE, 2021).

As represented in Table 2.1 according to the definitions, the 5th level autonomous vehicles, which is the highest level, refers to completely driverless use. Today, level 1 and level 2 autonomous vehicle technologies are entering our daily use.

Table 2.1 : Levels of automated driving and definitions.

Level	Automation	Definition
Level 0	No automation	Manual control by human
Level 1	Driver assistance	Single automation systems such as cruise control
Level 2	Partial automation	Advanced driver assistance systems
Level 3	Conditional automation	Vehicle can perform automation but driver is still required
Level 4	High automation	Vehicle can perform automation in most of the scenerios
Level 5	Full automation	Vehicle performs automated driving in all conditions

The first two level of automation classifications can be described as driver assistance systems with the features such as speed advisory system, eme lane tracking, park assist etc.

Although the use of advanced driver assistance systems in vehicles has becoming widespread, there can be performance degregation for sensors in some conditions such as fog, snow, rain, night driving etc. Vehicle communication systems (V2X) are less affected by these environmental conditions and when used together with on-board sensors, an increase in driving safety can be ensured. V2X communications can be used for energy consumption, crash avoidance, smart line management and emergency comunication studies. By using V2X systems the CAN signals(such as brake pedal signal, vehicle velocity etc.) from front vehicle can be sent to following vehicle or platooning vehicles. The data transfer can be done in different ways. The data can be sent to a cloud or a server by using IoT(Internet of Things) applications, can be transferred by a router or can be directly send from device-to-device. In the first case the data is can be transferred by using communication systems like GSM, 3G, 4G, 5G etc. For the second case the data can be transferred by a router which works as a connection hub to connect the vehicles or systems around it. The Figure 2.3 shows an example of road-side unit which has 4.5G communication capacity which is working as a router between vehicles in the range.

Figure 2.3 : Vehicle communication system road-side unit.

There are defined regulations for vehicle communication systems in theUnited States and Europe. The standart IEEE Syd 802.11p-2010 under IEEE Std 802.11 defines the protocols for vehicle communicaton systems. The frequency in Europe is between 5.855 GHz and 5.925 GHz.

When we look at the V2X use cases two use cases safety and energy efficiency come to the forefront. As given in Figure 2.4 the efficiency use case of V2X systems has been started with local hazard, traffic information and autonomous emergy braking. The next phase of safety systems including V2X system is estimated to be hazard information and map information collecting and sharing for autonomous vehicles (5GAA, 2020). The next phase of V2X based safety systems can be named as collective awareness based on 5G, LTE communication systems. Another short term usage of V2X systems are expected to be automated parking systems by using the shared data.

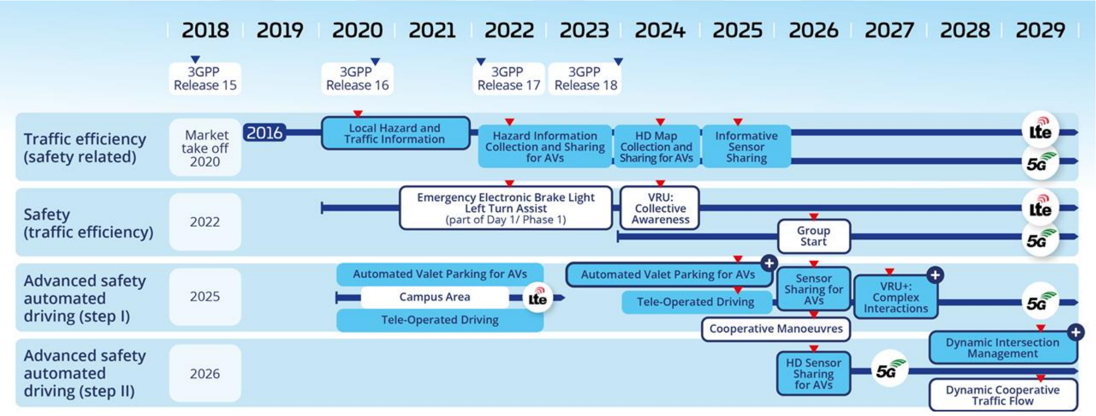

Figure 2.4 : Expected timeliness for V2X use case applications (5GAA, 2020).

In the medium term dynamic cooperative traffic flow is expected to be emerged which can increase efficiency and safety.

2.2 Hybrid and Electric Vehicles

The concept of e-mobility covers all vehicles that use an energy storage system and electrical drive or energy system as a primary energy source or to increase the efficiency of a conventional vehicle. The investments in electric vehicle technologies are increasing day by day and it can be considered that electric vehicle technologies are the new game changer in the automotive industry.

In the most general sense, hybrid and electric vehicles can be inspected in three categories:

- Hybrid electric vehicles (HEV)
- Plug-in hybrid electric vehicles (PHEV)
- Electric vehicles (EV).

In addition to the EVs and HEVs there are also vehicles with micro-hybrid technology which have function such as stop/start system or regenerative braking system (Ozdemir & Mugan, 2013). The micro-hybrid vehicles can also offer energy efficiency, although not as much as EVs or HEVs.

EVs or full electric vehicles has sub components such as traction motor, inverter, converter, battery including thermal and management systems, charger and transmission as represented in Figure 2.5.

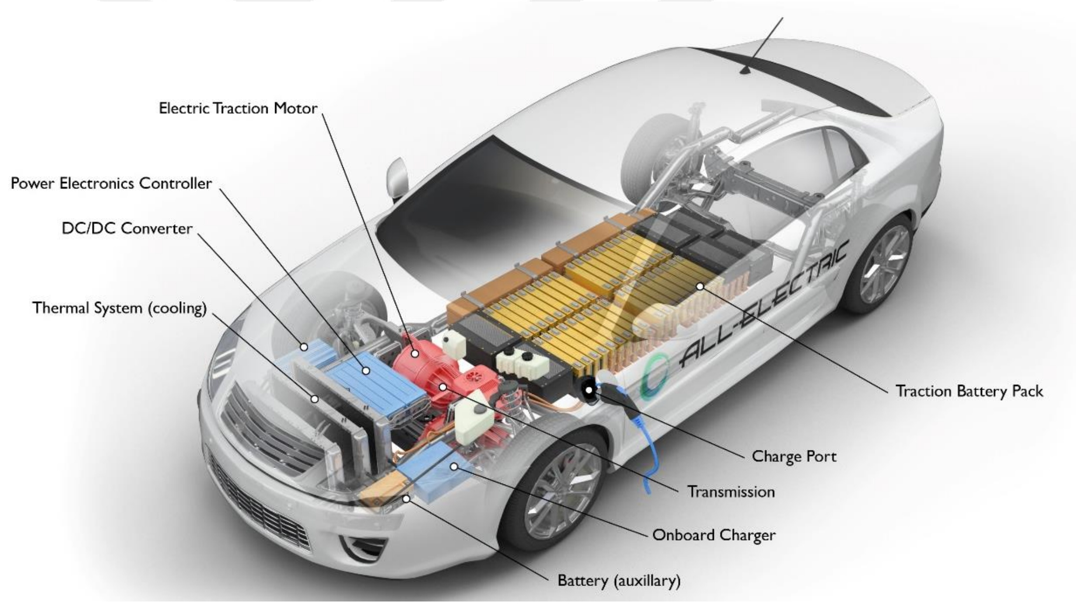

Figure 2.5 : All-electric vehicle subsystems (U.S. Department of Energy, 2022).

The battery package is the energy storage system of an electric vehicle. The battery package includes battery modules which is consisted of battery cells. The energy storage system includes battery cooling system and battery management systems. Commonly Lithium-Ion batteries are used in electric vehicles.

Traction motor drives the vehicle by using the energy stored in the batteries. The traction motor converts the chemical energy in batteries in to the rotation. At the sime time generally the electric motor works as a generator during braking in order to regenerate the braking energy.

The drivetrain also includes a transmission which is generally a one step gearbox for electric vehicles. The transmission ratio depends on the electric motor spesifications and the vehicle requirements such as inclination capability, maximum speed. The transmission transfers the mechanical power to the wheels by increasing the torque and decreasing the rotational speed.

The DC-DC converter, converts the power of battery back to lower levels to be able use for auxaliry systems and charging auxiliary battey.

The hybrid electric vehicles can be classified as series hybrid electric vehicles and parallel hybrid electric vehicles. The series hybrid electric vehicles can also be called as PHEV.

In addition to the internal combustion engine, parallel hybrid vehicles have an electric motor and battery. The battery is charged by regenerative braking and internal combustion engine. The vehicle cannot be charged externally. Series hybrid electric vehicles so called PHEV also contain an internal combustion engine and an electric motor as represented in Figure 2.6. The difference from HEVs is that they can be charged externally. EVs do not have an internal combustion engine. It can be charged externally by connecting to an electrical power source or by regenerative braking.

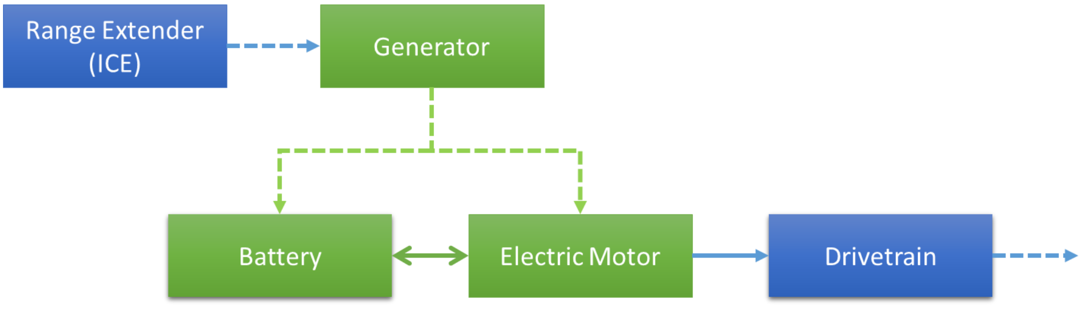

Figure 2.6 : Series hybrid electric vehicle topology.

The series hybrid electric vehicles have an internal combustion engine which is also clled the range extender. The range extender can be used to increase the vehicle range. The range extenders have operation modes such as charge sustaining, charging and charge depleting.

Both series and parallel hybrid systems have some advantages and disadvantages. In serial hybrid system, power is transmitted to the wheels only via electric motors.

Therefore, the power capacities of electric motors are sized to meet the need at full load. The internal combustion engine is coupled to the generator, and the generator can charge the batteries and can supply energy needed by the electric motor. In the series hybrid system, there is no mechanical power transmission between the internal combustion engine and the wheels.

The advantages and disadvantages of the serial hybrid drive system can be briefly listed as follows.

- Since the internal combustion engine is connected to the generator, the internal combustion engine can be operated in the region where it is most efficient, regardless of the driving conditions.
- A series hybrid system can be more easily converted to an all-electric system.
- Regenerative braking energy can be used more comparing to parallel hybrid systems.
- Due to the torque-speed characteristic of the electric motor, a simple single-stage gearbox is usually sufficient for the smooth transmission of the driving power from the electric motor to the wheels. However, more than one step reduction may be required depending on the torque and speed range and performance requirements of the electric motors.
- Although the vehicle often runs below maximum power, system components are designed to meet the maximum power required.

In parallel hybrid system operation, the power can be transmitted to the wheels by the electric motor and the combustion engine or both as represented in Figure 2.7.

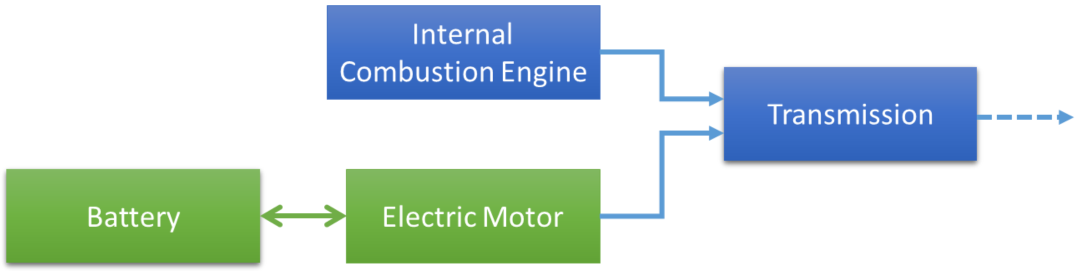

Figure 2.7 : Parallel hybrid electric vehicle topology.

The electric motor receives its energy only from the energy storage system. With parallel hybrid drive system;

- Electric motor, internal combustion engine and transmission integration is more complex comparing to series systems and it must be calibrated for specific sub systems.
- Even if the electric motor fails, the vehicle can be driven by the internal combustion engine at a certain power level.
- The power capacity of the electric motor and energy storage system can be selected lower than the serial hybrid architecture.
- More complex transmission and control structures are needed to properly transmit the power from the internal combustion engine and electric motor to the drive wheels.
- According to the paralleling ratio (combustion engine power capacity / electric motor power capacity), system components are selected and regenerative braking energy depends on the electric traction system.

3. VEHICLE ENERGY CONSUMPTION AND EMISSIONS

3.1 Driving Cycle

Driving cycles are used to assess vehicle performance especially for energy consumption and emissions by simulating on Hardware-in-Loop (HIL), Software-in-Loop (SIL) or testing on chassis dynamometers. There are common driving cycles such as the New European Driving Cycle (NEDC), United States Environmental Protection Agency (EPA) Federal Test Cycle (FTP) and Japanese JC08 cycle (EPA, 2017; UNECE, 2018). For the vehicle homologation procedure, Worldwide Harmonized Light Vehicles Test Cycle (WLTC) has taken the place of NEDC which is more realistic and transient than NEDC (Tutuianu et al., 2013).

There are specific driving cycle studies, for specific cities, which were developed by using different methodologies such as micro trip based cycle construction, segment based cycle construction, pattern classification and modal cycle construction (Abas et al., 2018; Arun et al., 2017; Berzi et al., 2016; Ergeneman et al., 2010; Fotouhi & Montazeri-Gh, 2013; Hung et al., 2007; Wang et al., 2015). Even though there are several studies on the driving conditions of Istanbul (Ergeneman et al., 2010), the rapid increase in number of vehicles and new constructed infrastructures remarkably change the transportation habit in Istanbul in recent years. The number of all road vehicles in Istanbul reached to 4.2 million by 2019 by increasing 25% in last five years (TUIK, 2014, 2019). New transportation infrastructures taken into operation cause significant changes in Istanbul traffic flow. For example, between Asia and Europe, a new bridge to the north of two existing suspension bridges and a road tunnel that crossing underneath the Bosporus have been constructed. The Northern Marmara Motorway, which is intended to bypass Istanbul to the north, has been partly opened for use. In addition, new commissioned subway lines lead to change in Istanbul traffic flow.

In this section, the driving cycle development methodology is clarified and an up to date Istanbul Driving Cycle is developed, which includes heavy traffic, inner road, main road and highway sections.

The Figure 3.1 represents the driving cycle development methodology, that includes data collection, data analyze and cycle generation studies. The vehicle data, which includes speed, acceleration and coordination etc. is collected on predefined routes. The routes are defined according to traffic density and use cases such as commuting, jaunting, night drive and rush hour driving. The traffic density data is collected by Istanbul Metropolitan Municipality, Traffic Control Center since 2014 (IBB, 2020). The routes and test timings are defined by considering the traffic density and popular center of attraction points such as airports, shopping mall, workplaces etc.

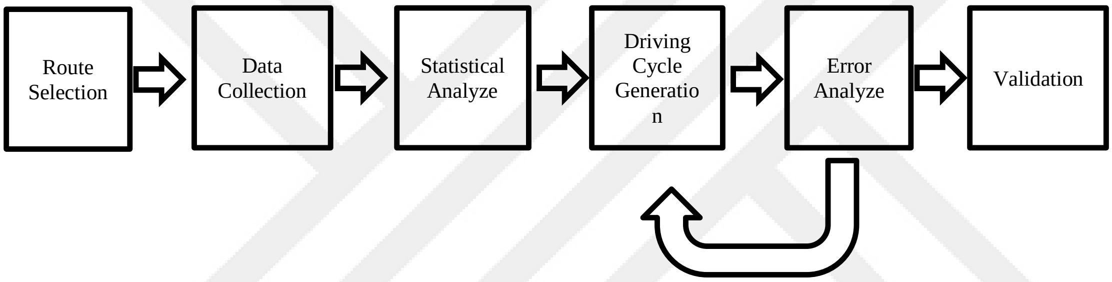

Figure 3.1 : The Driving Cycle Development Methodology.

The sample standard deviation is calculated as given in equation (3.1) for confidence interval (CI) calculation of acceleration values to eliminate measurement errors and extraordinary measurement points where n is number of measurement points, a_i is acceleration for operating points, $\overline{a}$ is the average acceleration value of whole measurement and σ is the standard deviation.

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(a_i - \overline{a})^2}{n-1}} \tag{3.1}$$

The measurement points outside of the CI have been excluded by using CI and standard deviation as given in equation (3.2). The excluded measurement points are exceptional operating points and measurement errors. Exceptional operating points are very high deceleration and acceleration cases such as emergency braking and sudden acceleration. The exclusion does not have major effect on results because number of excluded measurement points are less than 0.1% of the number of operating points and there is not major change in standard deviation, mean acceleration and mean velocity values of the reference data set.

$$CI = \frac{|a_i - \overline{a}|}{\sigma} \tag{3.2}$$

The frequency distribution matrix is consisted of occurrence frequencies in defined speed and acceleration intervals. The driving cycle is built by minimizing the error between the frequency distribution matrix of the driving cycle and measurements.

The driving data is collected on previously defined trips with equipped vehicles. The routes are defined by considering traffic situations and use cases. The routes are including highways (E-80, O-6), main roads (D-100, E-5), inner roads and linking roads on both European and Asian side. To collect the data Vector CAN/LIN interface VN1630A is being used. Vector has 4 CAN/LIN. In addition to CAN data the GPS data is collected and analyzed. For post processing Vector post processing tool and Matlab are used.

By statistically analyze of the acceleration values; the measurement points in the CI are taken into consideration. The Figure 3.2 represents the frequency distribution of the data where the average speed is 10.56 m/s (38.03 km/h) and the idle duration is 14.2%.

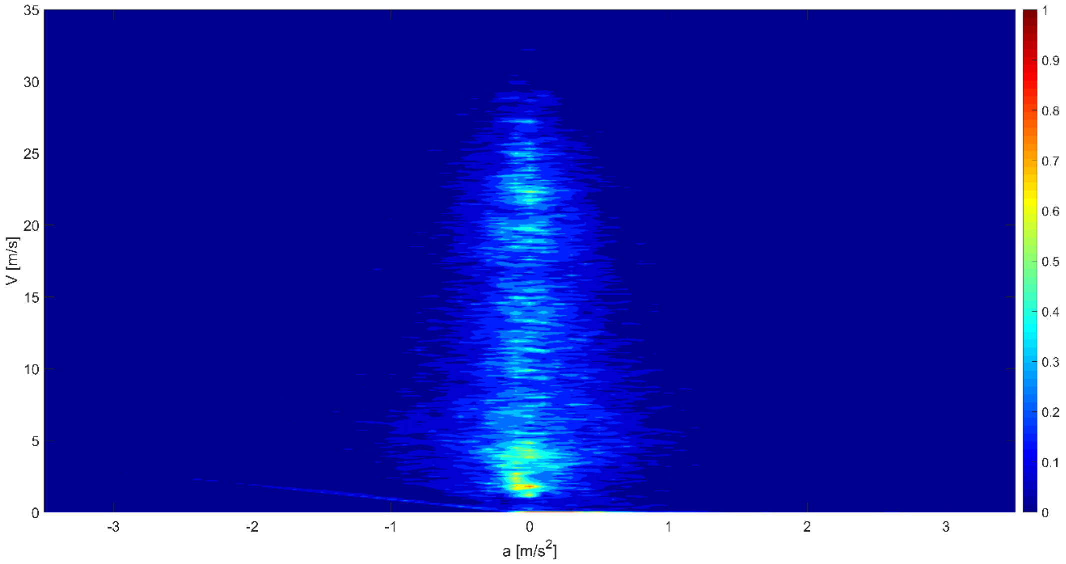

Figure 3.2 : Normalized presentation of the frequency distribution of the measurements.

The collected data is transformed in to two dimensional frequency distribution matrix according to acceleration and speed. According to intensiveness in frequency distribution, the micro trips from road data are selected and combined. The micro trips are the traces between two consecutive stops (Abas et al., 2018). The micro trip selection is processed until the error between the frequency distribution matrix of the driving cycle and the frequency distribution matrix of the measurements are minimized. Table 3.1 represents the technical specifications of the proposed Istanbul Drive Cycle.

Table 3.1 : The technical specifications of the developed drive cycle.

Parameter	Value
Total Distance	7.85 km
Total Time	756 seconds
The Percentage of Idle Time	14.2 %
Average Speed	38.04 km/h
Maximum Speed	124 km/h
Speed Standard Deviation	39.02 km/h
Maximum Acceleration	1.74 m/s^2
Minimum Acceleration	-2.6 m/s^2
Mean Acceleration	~ 0 m/s^2
Acceleration Standard Deviation	0.57 m/s^2
Total Distance	7.85 km

The Figure 3.3 represents the combined drive cycle, which is harmonized for chassis dynamometer compatibility. The developed drive cycle includes heavy traffic, inner road, main road and highway sections. At the same time Istanbul Metropolitan Municipality, Traffic Control Center shares instantaneous traffic density data, which is obtained by traffic measurement systems (IBB, 2020).

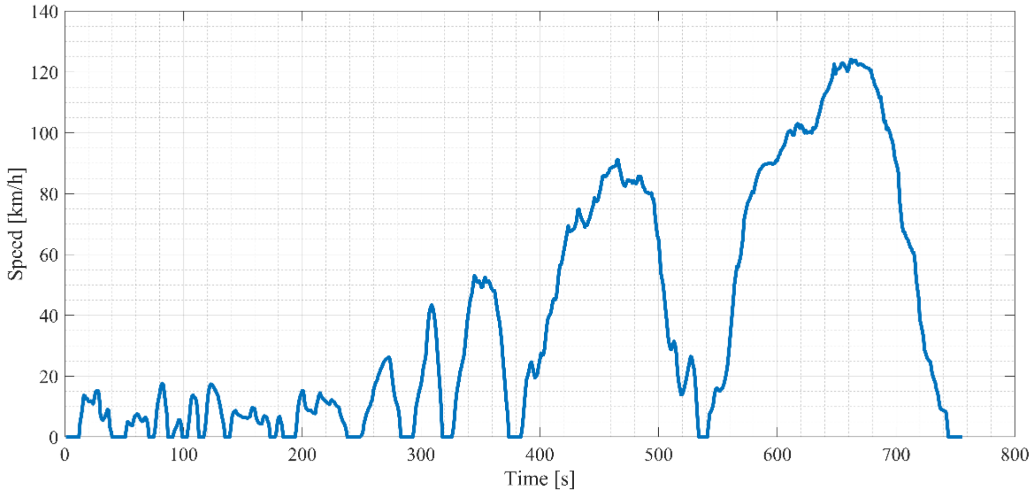

Figure 3.3 : The Istanbul Drive Cycle.

At the same time Istanbul Metropolitan Municipality, Traffic Control Center shares instantaneous traffic density data, which is obtained by traffic measurement systems (IBB, 2020). The vehicle speed distributions on defined routes provided by the Traffic Control Center, the measurements on the predefined routes and the developed driving cycle are also in accordance with each other.

3.2 Cycle Spesific Energy Consumption

Cycle specific energy consumption and emission tests are performed by using developed drive cycle. In this section the testing procedure and the results are represented.

A gasoline vehicle and an EV are tested on chassis dynamometer under the same conditions by using generated drive cycle for the comparative study. The vehicle tests are performed on the twin axle chassis dynamometer at TUBITAK RUTE. The road load data is obtained for ICEV by coast down method. Coast down is a test for determining the resistive forces acting on the vehicle at certain speeds. The coast down tests are performed by speeding up the vehicle to 135 km/h with the engine ungeared and recording the vehicle behavior until it stops. The coast down test is repeated few times to get the accurate road loads. Same road load parameters are used for both vehicles to present a comparative study depending on energy sources. The case of different powertrains on the same vehicle can be tested by using the same road loads and vehicle parameters for both vehicles.

The vehicle mass is accepted as 1500 kg and the road loads are given in Table 3.2 where F_0 is the constant term for static friction (N), F_1 is the first order term(N/km/h) coefficient, F_2 is the second order term(N/(km/h)^2) coefficient.

Table 3.2 : The Coast down test parameters

Parameter	Value
Vehicle mass	1500 kg
F_0	17.27 N
F_1	0.6175 N/(km/h)
F_2	0.0232 N/(km/h)^2

The equation (3.3) represents the correlation between static friction (F_0), Coulomb friction (F_1), relative wind (F_2) coefficients, vehicle speed (v) and the road load (F). The same coast down test parameters are used for ICEV and EV to obtain comparative results depending on energy source.

$$F = F_0 + F_1.v + F_2.v^2 \tag{3.3}$$

As test vehicles, a gasoline automatic transmission vehicle and a full EV are used. The Figure 3.4 illustrates the test chamber and EV testing.

Figure 3.4 : Vehicle testing at chassis at TUBITAK dynamometer with BMW i3.

The test cell used for vehicle testing has humidity and temperature control system. There are power and speed measurement systems on each drums. The test driver follows demanded speed by using driver aid computer. The exhaust emissions are measured by using particle number counter, constant volume sampler, dilution tunnel and emission bags (Kaya et al., 2018). For conventional vehicle, the emission values are obtained by bag results. For electricity consumption measurement of the EV, a power analyzer is used.

The test vehicles are tested under conditioned ambient air temperature and humidity thanks to climatic test chamber. The tests are performed at 22 ºC ambient air temperature and 45% relative humidity. The emission values of ICEV, are illustrated in Table 3.3 which are measured by using constant volume sampler and bag. For CO_{2eq} calculation the 100-year global warming potential estimations are used.

Table 3.3 : Specific test results of ICEV.

Parameter	Result	Unit
Fuel Consumption	6.5	[l/100 km]
CO_2	148.4	[g/km]
CO	627.4	[mg/km]
NO_X	21.2	[mg/km]
THC	42.2	[mg/km]
CH_4	6.5	[mg/km]
N_2O	15.6	[mg/km]
NMHC	35.8	[mg/km]

The constants for global warming potential estimations are 1 for CO_2, 28 for CH_4 and 265 for N_2O (Myhre et al., 2013). By considering the 100-year global warming potential estimations, the TTW emissions of ICEV is 152.7 g CO_{2eq}/km.

As represented in Figure 3.4 : the EV is also tested under same conditions with ICEV on chassis dynamometer. The same ambient air conditions (22 ºC ambient air temperature and 45% relative humidity) and coast down parameters are used for EV testing. The energy consumption of EV is measured as 0.142 kWh per kilometer, which includes the charging losses. Fast charging may increase the specific energy consumption due to losses.

3.3 Emission Analyze of Electricity Production

In this section Turkey’s power sources and the environmental impacts of electricity production are given. The WTT CO_{2eq} emissions of electricity are calculated thanks to studies in the literature.

There are several methods for evaluation of the real world energy consumption and emissions of the vehicles (Yuan et al., 2017). A WTW analysis takes into consideration of both energy production and usage (Robert et al., 2014). The WTW method is accepted as a simplified life cycle assessment (LCA) and can be used for transportation policy determination (Moro & Lonza, 2018). The LCA takes into account the GHG emissions relating construction, destruction and maintenance processes of the power plants, vehicles and transportation infrastructures (Moro & Lonza, 2018; Qiao et al., 2019).

3.3.1 Energy resources of Turkey

By the end of September 2019 the installed power capacity of Turkey is 90720 MW and the installed power capacity distribution according to the power sources are given at (MENR, 2020).

Table 3.4 : The distribution of installed power capacity of Turkey.

Installed Power Resource	Capacity Distribution
Hydraulic	31.4 %
Natural Gas	28.6 %
Coal	22.4 %
Wind	8.1 %
Solar	6.2 %
Geothermal	1.6 %
Other	1.7 %

Turkey's primary energy source is consisted of domestic coal and imported coal (TKI, 2017). The large majority of domestic coal is lignite, which has low calorific value and high sulphur and ash content (Atilgan & Azapagic, 2015). Natural gas and hydraulic power are the major energy sources of Turkey (MENR, 2020). In 2019, the distribution of electricity production according to power resources are given in Table 3.4 (TEIAS, 2020). Annual electricity generation of Turkey follows the gross demand. The electricity imports and exports have small parts in total energy gross demand.

3.3.2 The emission factor of electricity production of Turkey

There are several studies on estimation of the emissions generated by electricity production in Turkey. According to IEA (2018) Report, Turkey's total emissions from fuel combustion is 338.8 million tons of CO_2 for 2016. The prime mover is coal with 151 tons of CO_2 (IEA, 2018). Turkey's total emissions of oil and natural gas combustion in 2016 are 99 and 87 tons of CO_2 respectively (IEA, 2018). The carbon emission factors from electricity generation in Organization for Economic Cooperation and Development (OECD) member countries are given as 1020 g CO_2/kWh for lignite, 400 g CO_2/kWh for Natural gas, 700 g CO_2/kWh for gas/diesel oil and 845 g CO_2/kWh for coking coal (IEA, 2018).

Ozcan (2016) estimated the GHG emissions of Turkey based on assumptions of WNA (2011) and Melikoglu (2013). The GHG emissions of Turkey is calculated as approximately 533 g CO_{2eq}/kWh for 2013 (Ozcan, 2016). Ari and Koksal (2011) calculated CO_2 emissions due to electricity generation and fuel specific CO_2 emissions for Turkey. Ari and Koksal (2011) calculated the CO_2 emissions associated to generated electricity 106.6 million tons, which corresponds to 538.83 g CO_2/kWh (Ari & Koksal, 2011).

WNA Report (2011) provides the GHG emissions of power plants with different energy sources such as nuclear, coal, natural gas, oil, solar, biomass, hydroelectric and wind by reviewing 21 different studies. The GHG emissions are given as 1054 tons CO_{2eq}/GWh for lignite, 888 tons CO_{2eq}/GWh for coal, 733 tons CO_{2eq}/GWh for natural gas, 85 tons CO_{2eq}/GWh for solar power, 45 tons CO_{2eq}/GWh for biomass, 29 tons CO_{2eq}/GWh for nuclear, 26 tons CO_{2eq}/GWh for hydroelectric and wind (WNA, 2011).

Atilgan and Azapagic (2015) calculated the emissions of coal and gas power plants in Turkey by taking into consideration the mining, processing, transportation, plant construction and decommissioning phases. The major contributors to emissions are operation of the facilities and transportation of fuels, for electricity generation by using fossil fuels (Atilgan & Azapagic, 2015). The emissions due to lignite transportation is negligible as lignite is not imported and the lignite power plants are close to lignite coal pits (Atilgan & Azapagic, 2015). Table 3.5 represents the calculated air emissions, which involve the effect of transportation for imported fuels (Atilgan & Azapagic, 2015).

Table 3.5 : GHG emissions of electricity generation from fossil fuels in Turkey (Atilgan & Azapagic, 2015).

	Lignite (g/kWh)	Hard coal (g/kWh)	Natural gas (g/kWh)
CO_2	1020	923	364
N_2O	0.03	0.04	0.016
CH_4	0.02	0.02	0.02

By considering WNA Report (2011), Atilgan and Azapagic (2015) and the distribution of electricity production according to power resources (TEIAS, 2020), Turkey's WTT emissions of electricity production is estimated as 520.3 g CO_{2eq}/kWh.

3.4 Well-to-Wheels Emissions Analyze

The WTW methodology includes Well-to-Tank (WTT) and TTW pathways. For ICEV the processes between oil field to oil station is called WTT which includes extraction, transport, refining and distribution processes. For EV the WTT pathway includes energy source generation, transportation and electricity generation, transformation, distribution. The TTW defines the emissions and the use of fuel in the tank or the energy in the energy storage system while driving.

In the EU and the United States, the regularity actions are taken by the assessments based on WTW approaches (Moro & Lonza, 2018). This paper is based on WTW approach, as WTW methodology is the essential method to assess the environmental effects of transportation.

The studies show that the usage of EVs instead of ICEVs can contribute the decrease of transportation based emissions(Choi & Song, 2018; Karabasoglu & Michalek, 2013; Moro & Lonza, 2018). In the EU the average values show that there is a potential of 50% - 60% GHG savings by using EVs instead of ICEVs (Moro & Lonza, 2018). Choi and Song (2018) analyzed the WTW emissions of the EVs and ICEVs for South Korea, which is an energy dependent country like Turkey. Driving EVs instead of ICEVs have 90-110 g CO_{2eq}/km advantage in South Korea (Choi & Song, 2018). Karabasoglu and Michalek (2013) compared the GHG emissions and the lifetime cost of conventional, hybrid and EVs under simulated various driving conditions. Karabasoglu and Michalek (2013) indicates that the electric and hybrid EVs can reduce the GHG emissions up to 60% under the urban New York City driving cycle according to simulation results.

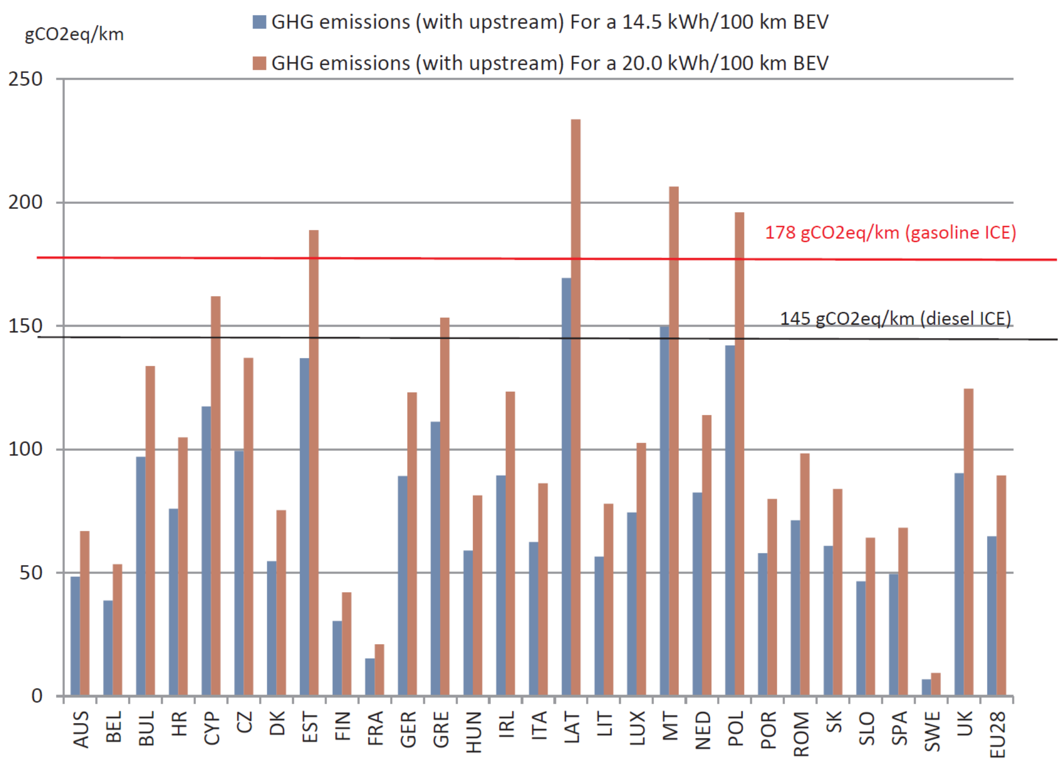

Figure 3.5 : Comperative GHG emissions of electric vehicle usage (Moro & Lonza, 2018).

The GHG savings by using electricity in transportation depends on power sources. Moro and Lonza (2018) compare the GHG emissions of EVs and ICEVs for the EU member states by calculation of member states carbon intensities of electricity. The carbon intensity of electricity used in the EU is 447 g CO_{2eq}/kWh in 2013 (Moro & Lonza, 2018). As represented in Figure 3.5 according to UN ECE 101 regulation WTW emissions of ICEVs are lower than EVs in countries with high carbon intensities of electricity such as Latvia, Malta, Poland and Estonia (Moro & Lonza, 2018).

For countries with nuclear or renewable main power sources, the usage of EVs has a positive effect on greenhouse gases (Moro & Lonza, 2018). The usage of EV can produce 7 g CO_{2eq}/km in Sweden and 169 g CO_{2eq}/km in Latvia where the EU average is 65 g CO_{2eq}/km according to UN ECE 101 cycle (Moro & Lonza, 2018).

The WTW pathway consist of WTT and TTW parts. For the EV the WTT emissions are depending on energy sources. WTT emission of the EV is 520.3 g CO_{2eq}/kWh by considering Turkey's energy mix (Atilgan & Azapagic, 2015; TEIAS, 2020; WNA, 2011). The test results show that TTW energy consumption of EV is 0.142 kWh/km. The WTW emissions of EVs can be obtained by using specific energy consumption and the WTT emissions. WTW emission of the electric passenger car is estimated as 73.9 g CO_{2eq}/km under the Istanbul Driving Cycle, considering the Turkey's energy mix.

Table 3.6 : Comparison of WTW emissions of ICEV and EV.

Vehicle Type	WTW Emissions (g CO_{2eq}/km)
CO_2	1020
N_2O	0.03
CH_4	0.02

WTT is the extraction, transport, refining and distribution processes of the fuel for ICEV. According to JEC Report by the European Commission, Joint Research Centre the average WTT emission of gasoline is 13.8 g CO_{2eq}/MJ in the EU (JEC, 2014). As energy density of gasoline is 34.2 MJ per liter, the WTT emission factor of gasoline is 471.9 g CO_{2eq} per liter (JEC, 2014). As the fuel consumption is measured as 0,065 liters per kilometer under the test conditions, WTT emission is calculated as 30,7 g CO_{2eq}/km for ICEV. According to developed drive cycle the TTW emission of ICEV is measured as 152.7 g CO_{2eq}/km.

As given in Table 3.6 the WTW emissions of ICEV and EV are estimated as 183.4 g CO_{2eq}/km and 73.9 g CO_{2eq}/km respectively.

There are estimations for significant increase in the market share of EVs over the next decade. The environmental effect of transition to EVs depends on the power generation mix. As Turkey predominantly relies on fossil fuels for energy generation, the EV usage in the country also has certain environmental costs. By considering global warming potential estimations, WTT emissions of electricity production is estimated as 520. 3 g CO_{2eq}/kWh without considering the construction and decommissioning of power plants. The energy consumption and emission values are measured by using generated driving cycle for Istanbul. The chassis dynamometer test results show that the energy consumption of EV is 0.142 kWh/km and the TTW emissions of gasoline vehicle is 152.7 g CO_{2eq}/km according to proposed drive cycle. The results show that WTW emissions of ICEV is 183.4 g CO_{2eq}/km and for EV it is 73.9 g CO_{2eq}/km.

Thus, introduction EVs to Istanbul on a large scale can reduce the WTW emissions by 60 %, excluding the emissions associated with the vehicle production and power plant construction. Even though this reduction is quite beneficial, it is under the European average due to the current reliance of fossil fuels on the energy generation mix (Moro & Lonza, 2018). Hence, the switch the EVs should be reinforced with more widespread usage of renewable energy in the country to realize the full impact of emission reduction generally associated with EVs. At the same time, the results in this paper can also be a guide for policy makers.

4. VEHICLE MODELLING

4.1 Vehicle Equation of Motion

The force equation for the horizontal axis of the wheel is provided in equation (4.1); where m_w is the mass of the wheel, $\ddot{x}$ is the acceleration, F_x is the wheel force and X is the reaction force.

$$m_w\ddot{x} = F_x - X \tag{4.1}$$

The generated emission maps are based on tire force and vehicle speed. The search space consists of speed traces. For the given speed traces, vehicle tractive forces are simulated. The vehicle's equation of motion for tire force calculation is introduced in equation (4.2); where F_T is the tractive force, F_B is the vehicle acceleration force, F_{St} is the inclination force, F_L is the aerodynamic force and F_R is the rolling resistance.

$$F_T = F_B + F_{St} + F_L + F_R \tag{4.2}$$

Vehicle acceleration force is described in equation (4.3) where λ is the total inertia ratio and m is the total mass.

$$F_B = \lambda m\ddot{x} \tag{4.3}$$

Inclination force is proportional to inclination angle(α) as described in equation (4.4).

$$F_{ST} = mg \sin \alpha \tag{4.4}$$

The aerodynamic force is provided in equation (4.5); where c_w is the aero coefficient, ρ is the air density, A is the frontal area and v is the vehicle velocity. As provided in the equation, the aerodynamic force is proportional to the square of the vehicle velocity.

$$F_L = \frac{1}{2}\rho c_w A v^2 \tag{4.5}$$

The rolling resistance is defined in the equation (4.6) as the rolling resistance coefficient multiplied by thewheel load.

$$F_R = f_R F_z \tag{4.6}$$

With the help of the above equations, the tractive force can be written as follows.

$$F_T = m\ddot{x} + (f_R + p)mg + \frac{1}{2}\rho c_W A v^2 \tag{4.7}$$

4.2 Vehicle Subsystem Modelling

4.2.1 Electric motor

The critical subsystem models are developed according to test results. As represented in Figure 4.1electric motor is tested at the testrig.

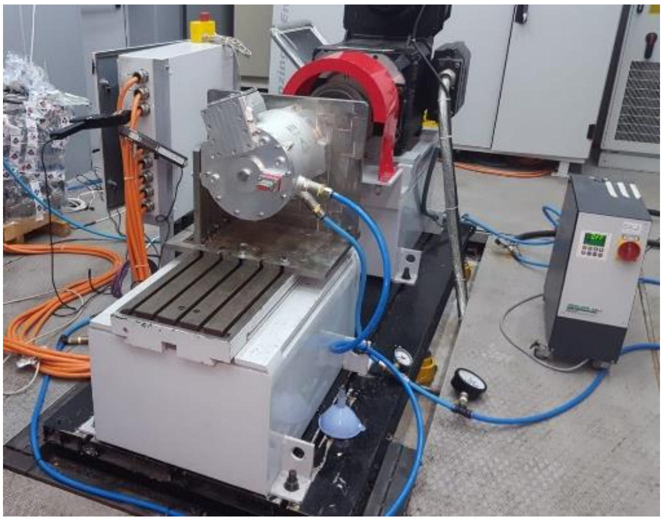

Figure 4.1 : Electric motor testing at testrig.

Figure 4.2 :Figure 4.2 represents the electric motor and inverter total efficiency, tested on the dynamometer. A PMSM engine, which is preferred generally for EVs due to

their higher efficiency and power density is used(Bilgin et al., 2019). The engine map containing engine torque, power and efficiency is obtained by using test data. The maximum efficiency is obtained to be 95% while, the maximum torque is 270 Nm and the peak power is 170kW.

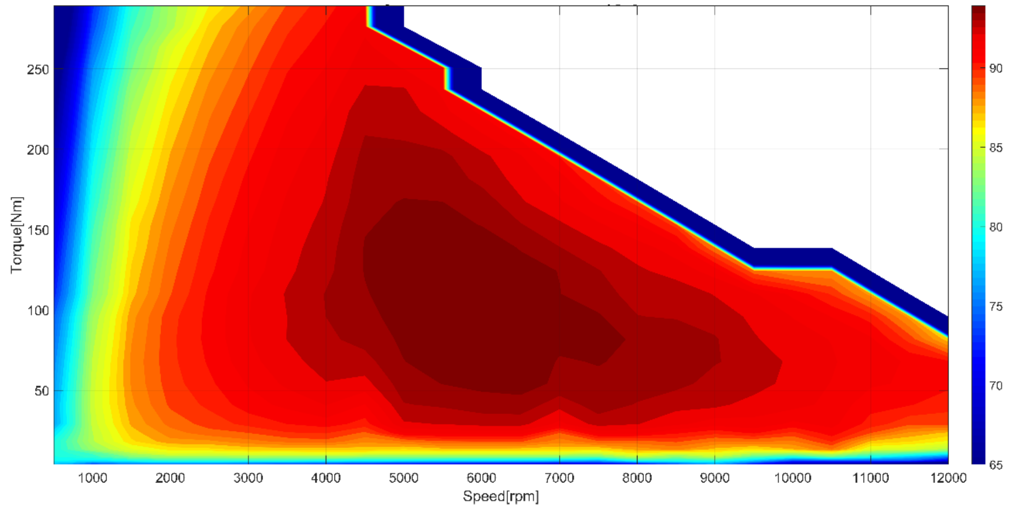

Figure 4.2 : Electric motor and inverter total efficiency map.

4.2.2 Battery

The battery is modelled by using battery data. The battery test is performed at cell level and the battery package model is developed. Figure 4.3 represents the battery cell testing at the testrig.

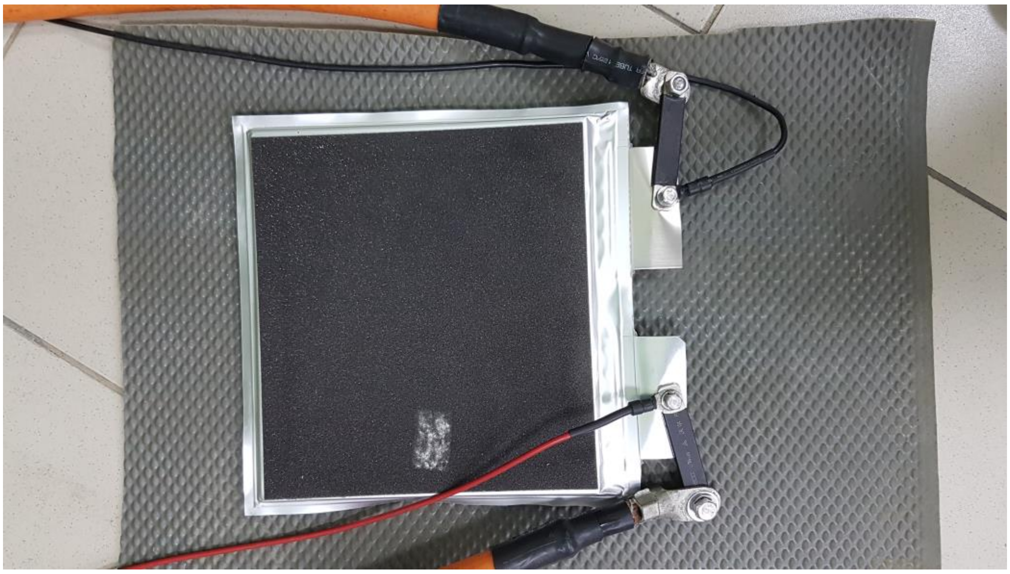

Figure 4.3 : Battery cell testing.

The battery cell was tested by using digatron battery cell testing system. The battery cell was charged and discharged at various C rates such as 0.3 C(20 Ampers), 1 C (60 Ampers), 2 C (120 Ampers) and 3 C (180 Ampers) as given in Figure 4.4 The battery C rate is calculated by dividing the charge current by battery capacity.

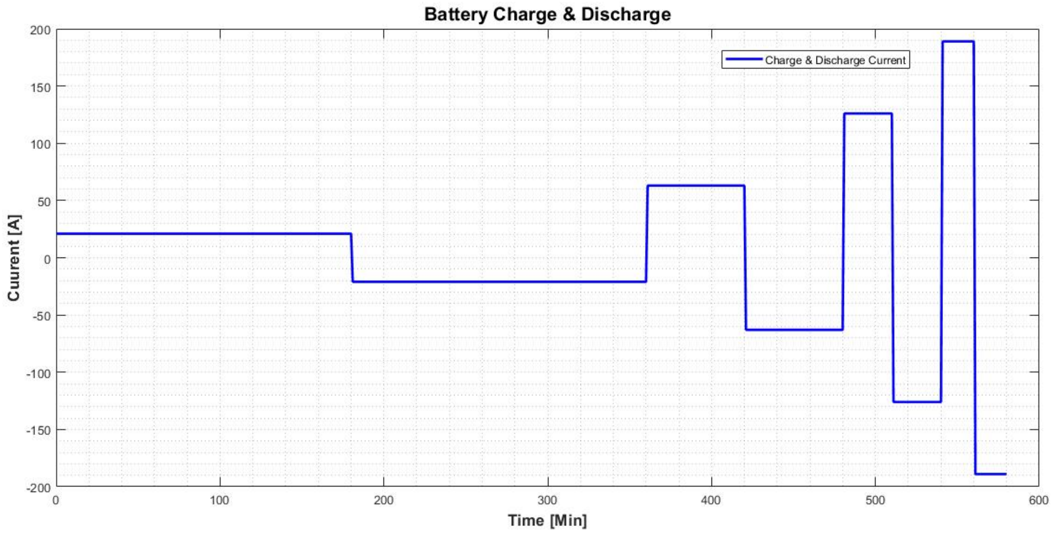

Figure 4.4 : Battery charge and discharge testing.

The battery cell efficiency is calculated by using discharge characteristics. The battery efficiency is decreased by increasing battery current. battery cell is tested to obtain battery efficiency at different charging and discharging currents. Chemical efficiency decreases by the increasing rate of charge and discharge as represented in Figure 4.5.

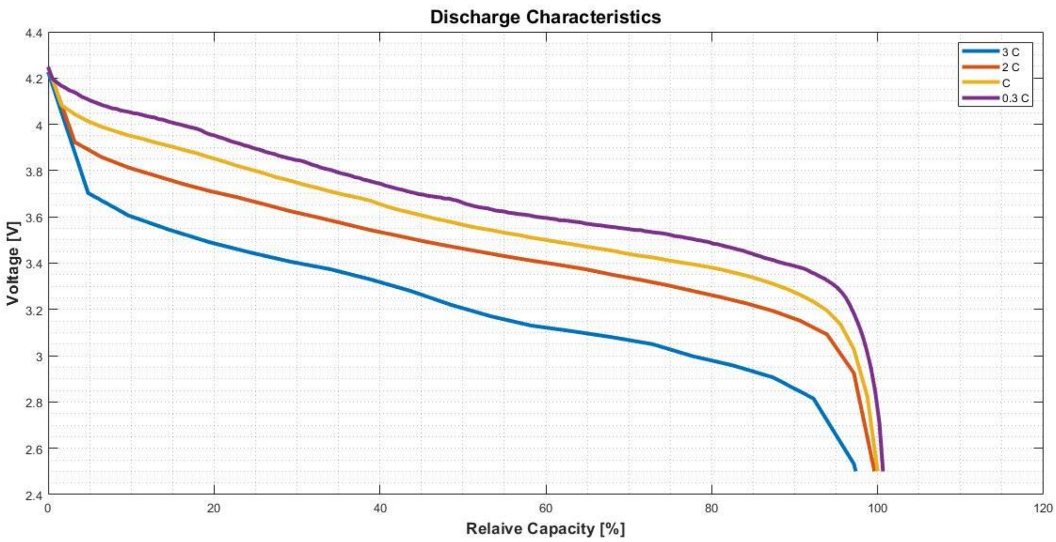

Figure 4.5 : Battery cell dischare characteristics.

When the battery cell state of charge is 100% and discharged with 60 Amperes, usable energy is measured as 240 Wh. On the other hand, if the discharge current is 180 Amperes, while the C rate is 3C, the usable energy is measured as 232 Wh. The efficiency is calculated as 97 % at 3C discharge rate. The battery cell discharge characteristic under different discharge rates is illustrated in Figure 4.5.

Chemical efficiency efficiency decreases by inreasing rate of charge and discharge as represented in Table 4.1.

Table 4.1 : Battery cell efficiency for various discharge rates.

C Rate	Efficiency
0.3 C	100 %
1 C	100 %
2 C	99 %
3 C	97 %

Depending on the operating conditions, battery capacity decreases as it is used. To calculate the battery capacity and related functions such as the vehicle range, the aging of the battery is included in the model. The battery cell capacity reduction as a function of cycle is provided in Figure 4.6.

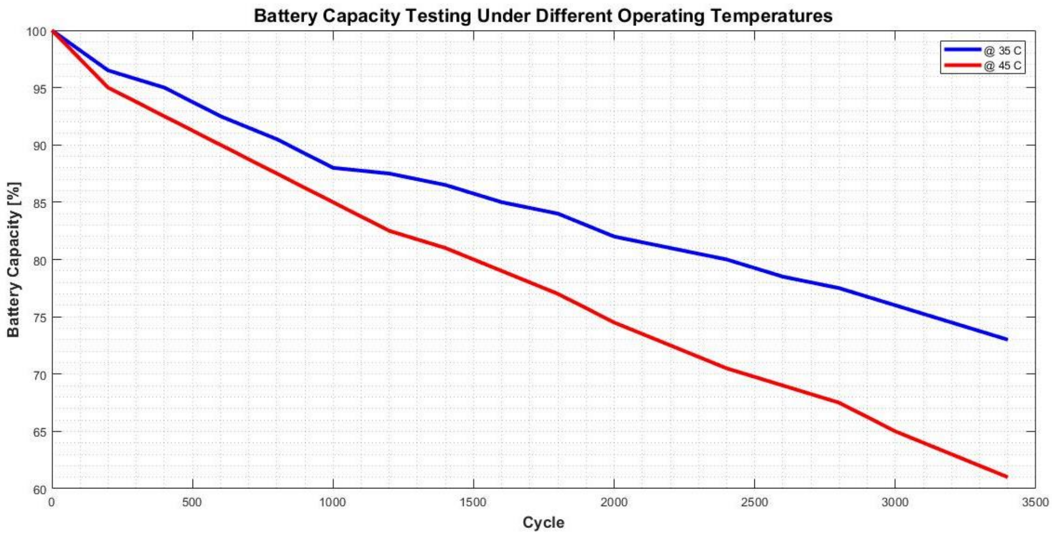

Figure 4.6 : Battery capacity decrease under various opearing conditions.

The decrease in battery capacity depends on the cycle and operating temperature. Besides, the coolant temperature affects the battery life-time. The measurements show that when the battery cell is cooled around 35°C, after 3400 charge & discharge cycle, the battery cell capacity is around 75% compared to the initial cell capacity. By setting the operating temperature to 45°C by keeping the other variables the same, the battery cell capacity is around 62 % compared to the initial cell capacity. Series connected aged cells with different voltages also affect the power and energy capability of the whole battery package (Bruen & Marco, 2016). The battery cell model is developed by using battery efficiency and aging measurements as shown in Figure 4.7.

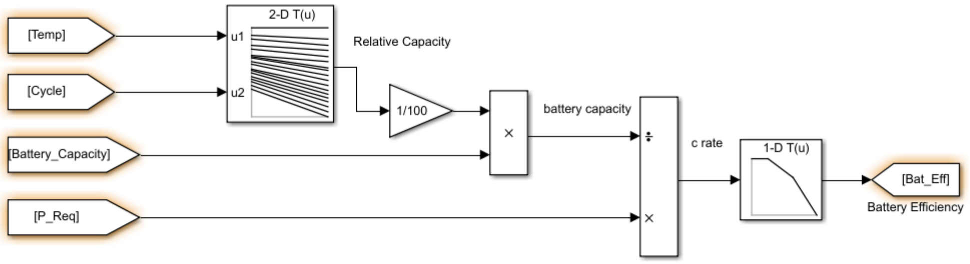

Figure 4.7 : Battery model block diagram.

4.2.3 Range extender

The range extender model is built by using the test data and the technical spesifications. The internal combustion engine data can be obtained by testing the engine on an engine dynamometer as shown in Figure 4.8.

Figure 4.8 : Internal combustion engine testing at engine dynamometer.

In the use case which includes an EMS development for a series hybrid electric vehicle, the series hybrid vehicle has a 0.9 liter 2 cylinder engine. The engine works as a range extender with acoupled generater. The proporties of the range extender unit is given in Table 4.2.

Table 4.2 : Range extender unit spesifications.

Technical spesifications	
Engine displacement	0.9 liters
Bore	83.0 mm
Stroke	83.0 mm
Compression ratio	10:1
Number of cylinders	2 cylinders
Stroke	4 stroke
Fuel injection	Port fuel injection
Generator	38 kW
Maxiumum power	30 kW at 4000 rpm
Peak torque	72 Nm between 2000-4000 rpm
Engine weight	50 kg (dry)
Generator weight	20 kg

The engine map of the internal combustion engine is illustrated in Figure 4.9.

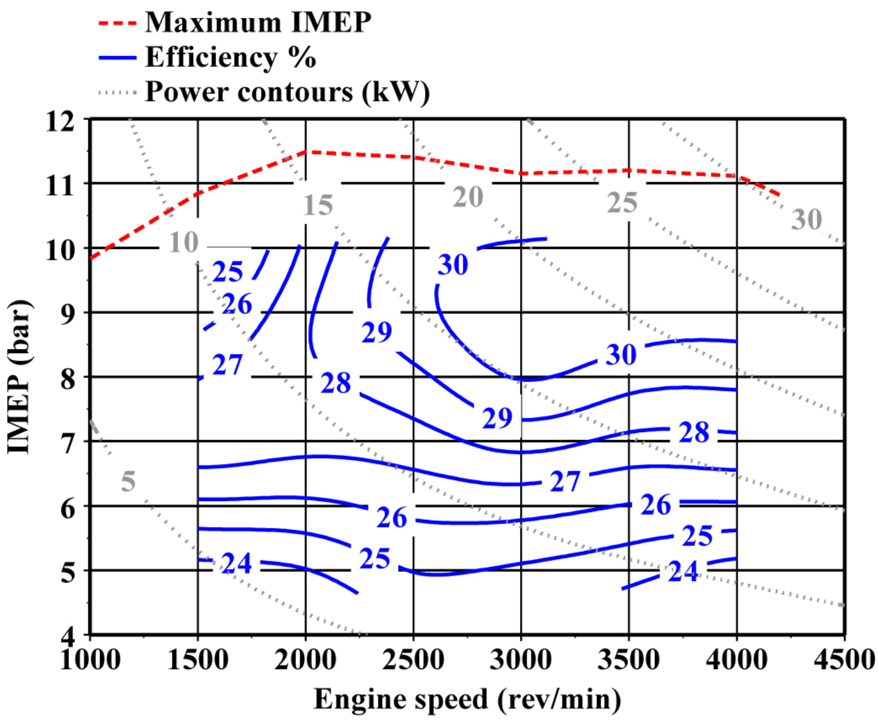

Figure 4.9 : Internal combustion engine map (Bassett et al., 2013).

The range extender logic model is given in Figure 4.10. The range extender has two operating modes such as maximum power and nominal power. The thresholds are calibratible which changes the range extender state.

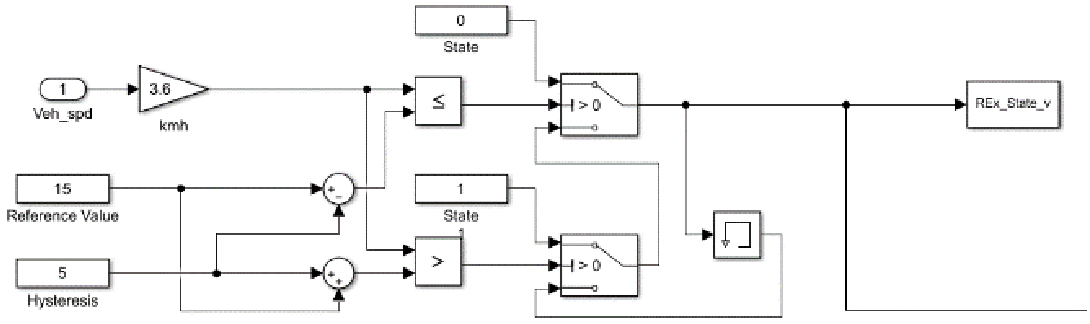

Figure 4.10 : Range extender schedular model.

The range extender operation is also related to vehicle speed. Starts over 20 km/h and stops automatically if the vehicle speed decreases lower than 10 km/h.

4.2.4 Validation

The vehicle is tested on a chassis dynamometer by using determined coast down parameters obtained by coast down tests. By using the same environment parameters, the same speed inputs are used to simulate the model. As the first step, the vehicle is tested on charge depleting mode. As given in Figure 4.11 the vehicle test and simulation are performed on WLTC.

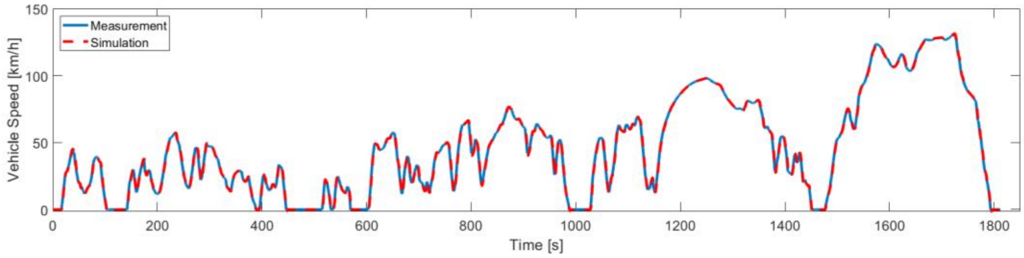

Figure 4.11 : Validation test speed profile (WLTC).

The power comparison of the measurement and simulation is provided in Figure 4.12. The simulation outputs are parallel with measurements.

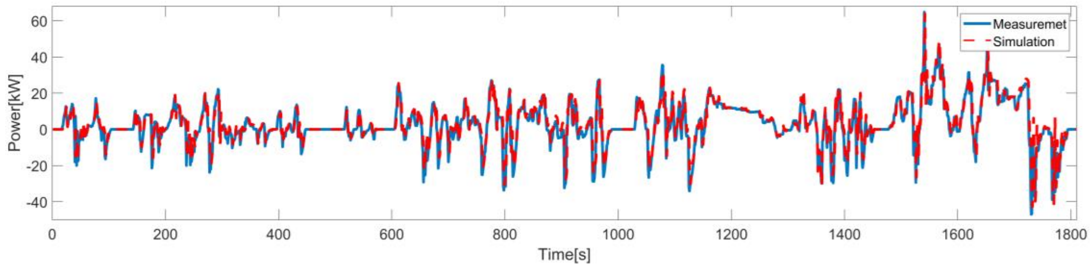

Figure 4.12 : Simulated and measured power values.

The data rate for battery SOC measurement on the vehicle is quite low. For this reason, there are divergences between measurement and simulation outputs in Figure 4.13. Nevertheless, the battery SOC at the end of the cycle is approximately the same for the simulation and test.

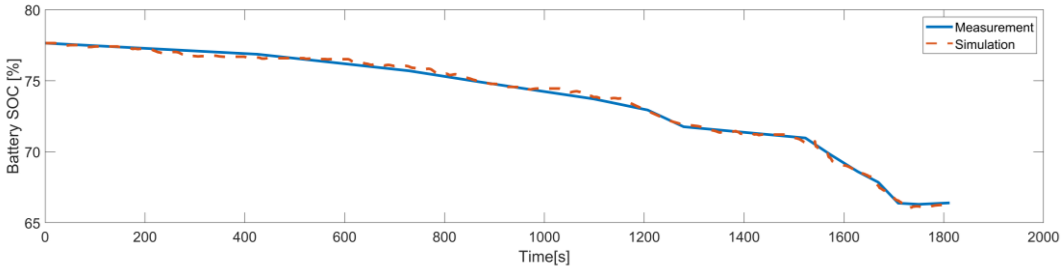

Figure 4.13 : Battery state of charge comparison for charge deppletting mode.

To validate the REx operation, the tests are repeated in charge sustaining mode.

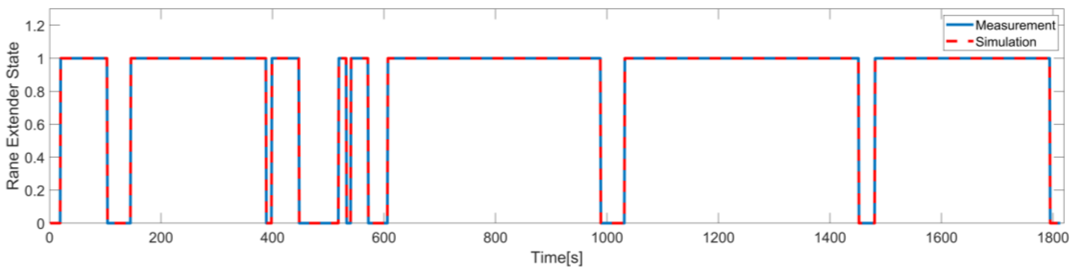

Figure 4.14 : Range extender states for charge sustaining mode.

The battery SOC levels are obtained to be approximately the same at the end of the cycle for both measurement and simulation when compared to the initial levels Figure 4.15. The REx state indicates the REx operation demand by controller which is needed for decision making according to vehicle speed and the battery SOC at that moment.

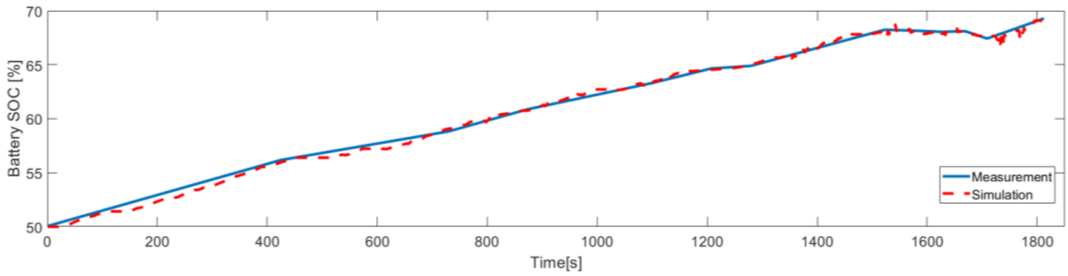

Figure 4.15 : Battery state of charge comparison for charge sustaining mode.

The correlation coefficient between the measured power and the simulated power values are calculated using equation 4.8, where p_m is the measured power, p_s is the simulated power and r is the correlation coefficient.

$$r = \frac{\sum_{i=1}^{n}(p_{m_i} - \overline{p_m})(p_{s_i} - \overline{p_s})}{\sqrt{\sum_{i=1}^{n}(p_{m_i} - \overline{p_m})^2 \sum_{i=1}^{n}(p_{s_i} - \overline{p_s})^2}} \tag{4.8}$$

The correlation coefficient is calculated to be 0.978. Since r=1 refers that the vectors match perfectly, the obtained correlation between measured and simulated values is considered quite good.

4.3 Vehicle Level Emission Map Generation

For the use case where the vehicles are platooning in a mixed traffic in terms of powertrains the developed engine emission models are used. The vehicles are tested on the chassis dynamometer to generate vehicle emission maps. An electric, a gasoline and a diesel vehicle are used. The vehicle spesifications are given in Table 4.3.

The test results are processed to get equivalent CO_2 emissions for operating points based on vehicle speeds and tire forces. This is the force applied on the roller surface and measured with a load cell that is mechanically connected to the cradled machine.

Coast-down tests are performed to determine the road loads by speeding up the vehicle to a certain speed and analyzing the vehicle behavior during the deceleration with the engine ungeared. With the help of the coast-down tests, the force coefficients are determined. The coast-down tests are performed few times until the correlation is obtained for the parameters.

Table 4.3 : Test vehicle spesifications.

Parameter	Electric Vehicle	Gasoline Vehicle	Diesel Vehicle
Engine	125 k	71 kW 1.4 lt	70 kW 1.5 lt
Net Weight	1350 kg	1070 kg	1050 kg
Test Weight	1550 kg	1270 kg	1250 kg

Static friction coefficients are independent of vehicle speed, coulomb friction coefficients increase linearly by the vehicle speed and aerodynamic friction coefficients are dependent to square of the vehicle speed. The test chamber schematics is represented in Figure 4.16.

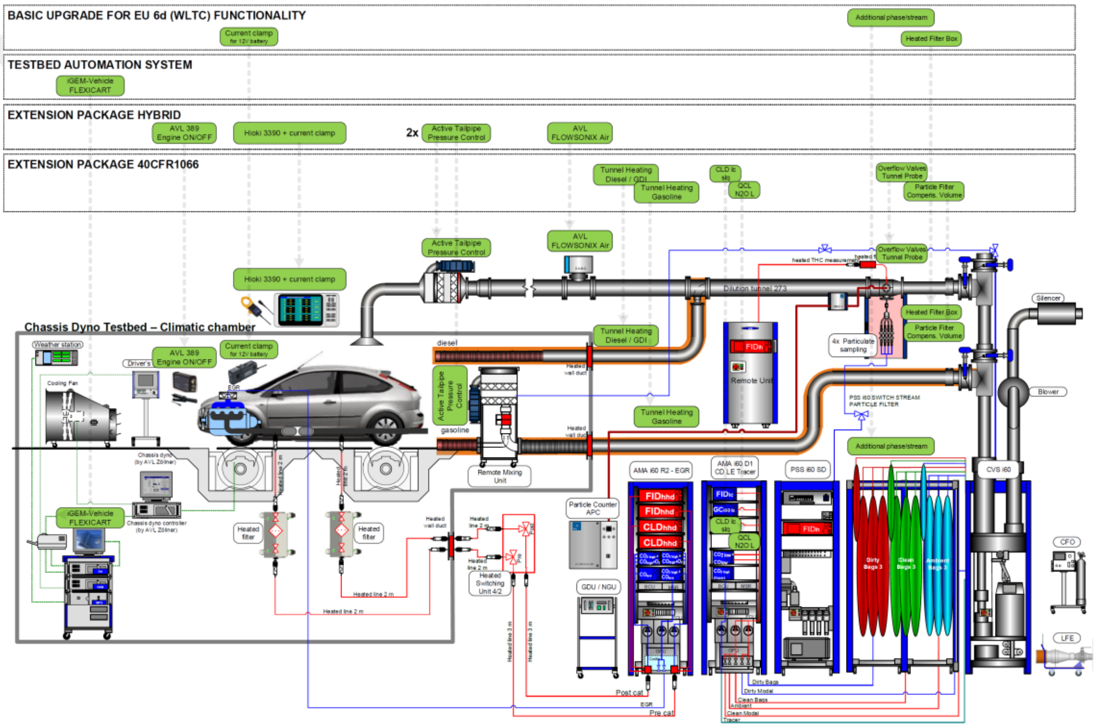

Figure 4.16 : Vehicle dynamometer testrig schematics.

EV emission map is generated by measuring the energy consumption of the vehicle as shown in Figure 4.17. Energy consumption is measured by using a power analyzer which is mounted to battery and electric motor inputs and outputs. Alternatively, Controller Area Network (CAN) signals are used. The operating points based on vehicle speed and tire force are tested by setting the vehicle speed to desired values by using chassis dynamometer speed control. The tire force is measured by the load cell and changed by controlling vehicle accelerator and brake pedal positions and. First, the energy consumption map of the EV is obtained then the WTW emission map of the vehicle is generated by using electric carbon intensity. The electric carbon intensity of the region, where the use case is performed is 520.3 g CO_{2eq}/kWh (Ozdemir et al., 2020). As given in Figure 4.18 there are negative emission points for the vehicle where the vehicle is regenerative braking.

Figure 4.17 : Electric vehicle emission map model developmet tests.

The WTW pathway consists of WTT and TTW pathways for conventional vehicles, where WTT include extraction, transportation, conditioning and transformation processes for fossil fuels (Matteo Prussi et al., 2020).

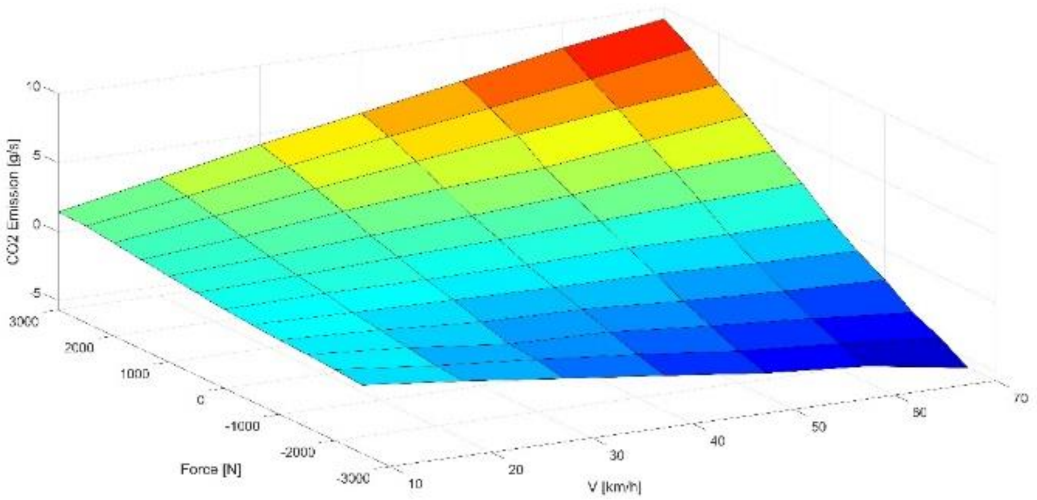

Figure 4.18 : Electric vehicle emission map.

According to JEC Well-to-Tank Report by European Comission Joint Research Centre the average WTT emission factor of gasoline and diesel are 17 g CO_{2eq} per MJ and 18.9 g CO_{2eq} per MJ respectively (Matteo Prussi et al., 2020).   As energy density of gasoline is 43.2 MJ/kg and energy density of diesel is 43.1 MJ/kg, the WTT emissions of gasoline and diesel are 0,73 g $CO_{2eq}/g_{gasoline}$ and 0,82 g CO_{2eq}/g_{diesel} respectively(M. Prussi et al., 2020).

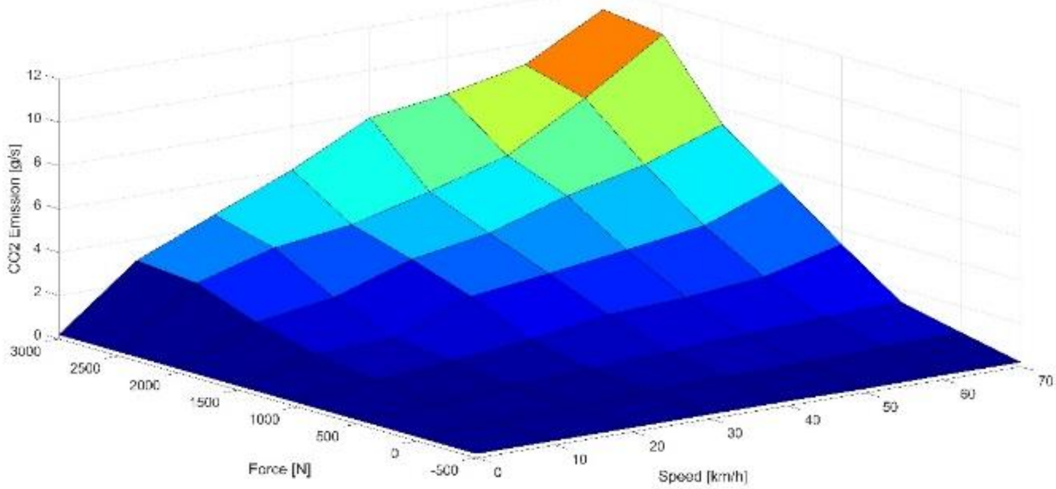

Figure 4.19 : Gasoline vehicle quivalent emission map.

TTW emisions of of ICEVs are measured by using emission bags, constant volume sampler, emission bench and dilution tunnel. Equivalent TTW equivalent emissions are calculated by using the constansts which are 265 for N_2O, 28 for CH_4 and 1 for CO_2 (Myhre et al., 2013). WTW emission maps of ICEVs are generated by using the TTW and WTT measurements and calculations. Figure 4.19 represents the equivalent CO_2 emission map of the gasoline vehicle.

5. ENERGY MANAGEMENT STRATEGY DEVELOPMENT FOR SINGLE VEHICLE: A CASE STUDY FOR HYBRID ELECTRIC VEHICLE

5.1 Introduction

Environmental concerns and technological progress evolve the transportation technology and habits (Huang et al., 2017). There are incentives in most of the developed and developing countries to increase market penetration of electric vehicles and vehicles with alternative power sources. Hybrid electric vehicles can be accepted as a stepping stone for electric vehicles. Especially, due to the low energy density of batteries compared to internal combustion engine fuels, charging time and battery costs, series hybrid solutions are considered in electric vehicles to increase vehicle range (Pozzato et al., 2020). EVs battery charging still takes a longer time in comparison with the tank refueling time of internal combustion engine vehicles (ICEVs). For instance, 72 minutes is required to add approximately 320 kilometers depending on the cycle and the vehicle by using a 50 kW DC fast charging station (Tu et al., 2019). The REEVs use an additional energy source such as internal combustion engine (ICE) or fuel cell to extend the vehicle range.

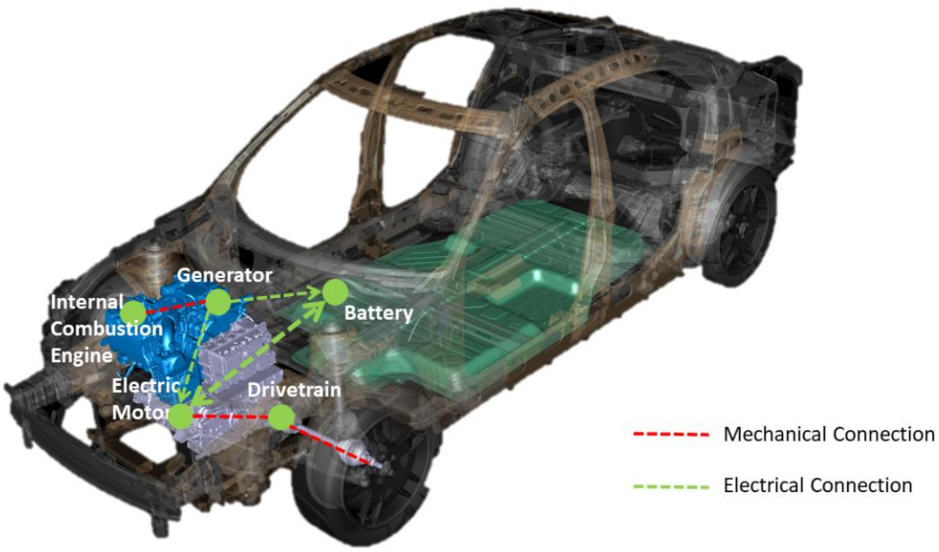

Figure 5.1 : Range extended electric vehicle powertrain architecture.

As shown in Figure 5.1, the internal combustion engine, is not mechanically connected to the drivetrain in the series hybrid powertrain topology. The traction motor is powered by the battery while the REx and generator supply energy for charging the battery or driving the electric motor. The REEVs offer modes such as “charge mode”, “full electric mode” and “keep charge mode”. On the charge mode, REx runs at maximum power to charge the battery while on the “full electric mode” REx runs only if the battery state of charge (SOC) is less than the threshold. “Keep charge mode” aims to keep the battery SOC at a certain level by running the ICE at minimum specific fuel consumption (SFC).

As illustrated in Figure 5.2, the working mode of a REEV vehicle can be battery powered, regenerative braking, range extender powered, driving and charging, REx and battery powered depending on the power demand and operation mode (Y. Yang et al., 2020). Apart from SOC and selected mode, the REx operation is also calibrated according to vehicle speed to improve noise, vibration and harshness(NVH) characteristics (Jeong et al., 2017). As the REx can be the dominant source of NVH, an improvement at low vehicle speeds is possible by disabling the REx (Jeong et al., 2017).

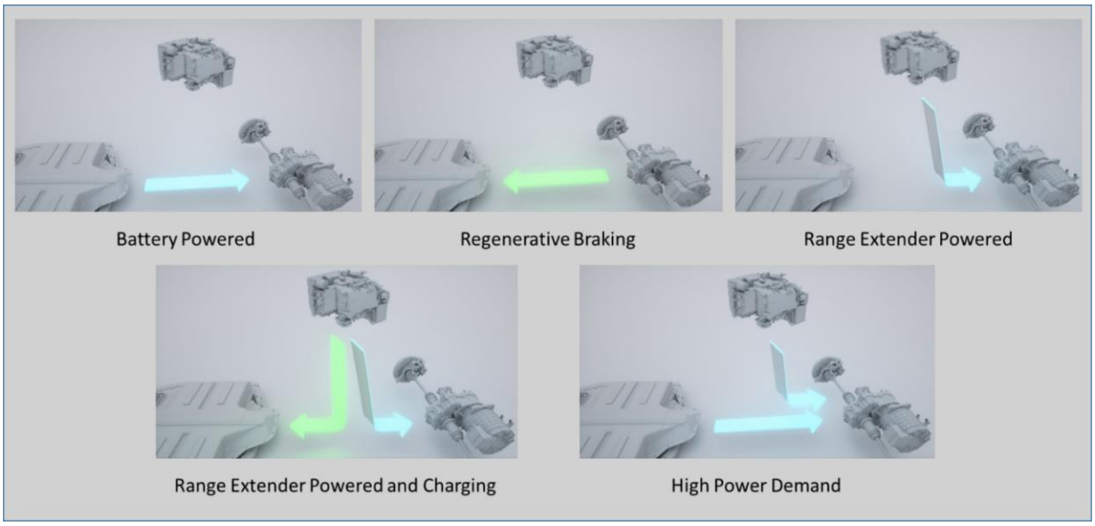

Figure 5.2 : Range extended electric vehicle power flow.

Energy management algorithms are used to increase system level efficiency of HEVs and EVs (Hartavi et al., 2016). There are several studies on the energy management system development for HEVs and EVs. The studies based on single-vehicle and multi-vehicle scenarios show that; the optimization of energy management strategies can have a positive contribution to fuel economy, lifecycle and NVH parameters of the vehicle (Martinez et al., 2017). Zhang et al. (2019) analyzed the energy management strategies of hybrid electric vehicles and categorized as route based, eco driving based and predictive strategies (Zhang et al., 2019). M. Martinez et al. (2017) provides a systematic literature review of energy management strategies of plug-in hybrid vehicles where the main approaches are considered as dynamic programming, equivalent minimization strategy, model predictive conrol, derivative-free algorithm, neural networks, game theory and convex programing(Martinez et al., 2017).

Huang et al., (2017) analyzed the studies on power management strategies in HEVs where they are classified as optimization-based and heuristic (Huang et al., 2017). Heuristic strategies are defined as rule-based algorithms while optimization-based strategies can be classfied as offline and online including model predictive control (Huang et al., 2017). Rodrigues et al. (2015) studied the management strategy for REEVs to improve the NVH characteristics, battery sustainability and fuel economy (Rodrigues et al., 2015). On the other hand, for parallel HEVs, the studies concentrate on driving the subsystems to improve the ICE efficiency by learning algorithms (Xu, Hou, et al., 2020; Xu, Hu, et al., 2020). The conducted studies show that there is a potential for energy consumption improvement for REEVs by using predictive energy management strategies (Johannesson et al., 2015; Shen et al., 2015; Zhou et al., 2015),

Another aspect of the energy management of HEVs is the communication between the Infrastructure to Vehicle (I2V) and Vehicle to Infrastructure (V2I). Connected driving can contribute to the improvement of energy management, platooning, intersection management, lane departure and road friction estimation aspects (Montanaro et al., 2019). Besides, an energy management strategy for HEVs by I2V communication has significant improvement on fuel-saving (HomChaudhuri et al., 2016). The traffic density information based energy management system has key advantages such as globally planning of the optimal trace and low computational load (Zhang et al., 2019).

In this study, for a REEV an energy management strategy based on planning of the REx operation according to driving cycle is developed. The benefit of the proposed strategy on the fuel consumption, the vehicle range and emission are investigated. A validated vehicle model is developed by subsystem testing for model based energy management of REEVs. The optimisation of range extender operation is studied under different operation conditions such as light, moderate and heavy traffic on highways and inner roads. The benefit of the model based energy management strategy is discussed for the different operation conditions. An optimisation process is performed to minimise REx start events to decrease emission and to increase the equivalent range.

5.2 Methodology

5.2.1 Modelling and validation

The test rigs are prepared and the test data is used for subsystem modelling. The battery, electric motor, inverter and REx are tested in the laboratory. The electric motor engine map and inverter efficiency map is obtained by testing both systems on the engine dynamometer. Battery modules in the battery package consist of battery cells. The battery cell efficiency, which affects vehicle performance depends on operation conditions (Hamut et al., 2013). The aging characteristics and battery cell efficiencies are tested at the battery test laboratory. The test data is used in the model for the internal combustion engine which is used as REx. The test data is implemented in to the model as look up tables. The model is developed by using Matlab Simulink. The mathematical models are used for the drivetrain and the vehicle dynamics as introduced before.

A Chassis dynamometer is used for the validation of the model. The coast down test is performed few times to get road loads that are essential for resistive forces on the dynamometer. The validation tests are performed by using the measured static friction (N), first-order (N/(km/h)) and second-order ($N/(km/h)^2$) coefficients. The World-Wide Harmonized Light Duty Test Cycle (WLTC) is used for the validation of the model (Tutuianu et al., 2015). The WLTC is a transient cycle that is obtained from real-world data and includes various speed phases (Tutuianu et al., 2013).

5.2.2 Range extender operation strategy optimizer

For serial hybrid electric vehicles the range extender operation depends on vehicle speed (Jeong et al., 2017). Due to the comfort requirements of the used test vehicle, the REx starts at 20 km/h and stops at 10km/h during deceleration that may cause inefficiency especially in stop and go traffic conditions. As provided in equation (5.1)(5.1) and equation (5.2), there is a hysteresis for REx operation due to vehicle speed where R_{v-} is the REx operation permit during deceleration while R_{v+} is for acceleration.

$$R_{v-} = \begin{cases} 0, & v < 10 \\ 1, & v \geq 10 \end{cases} \tag{5.1}$$

$$R_{v+} = \begin{cases} 0, & v < 20 \\ 1, & v \geq 20 \end{cases} \tag{5.2}$$

To avoid inefficiency, a REx operation strategy is developed to minimize engine start events since minimizing engine start events decreases the emission and increases the equivalent range. By internet of things and vehicle-to-everything communication applications, the cycle data can be obtained to use for energy management strategy development (Montanaro et al., 2019). The speed profiles for planned routes can be obtained from the lead vehicles, sensors or processed images.

For Istanbul, the Transport Management Center of Istanbul produces and publishes instant traffic data for determined routes (IBB, 2020). In this study, road data measured on predefined routes under different traffic conditions such as heavy, moderate and light traffic is used (Table 5.1). The benefit of the optimized REx operation strategy is determined for equivalent range and emissions. The comparative study is performed for keep charge mode where REx operates to keep the charge at 70%.

Table 5.1 : The average speed values of the used road data for the use cases.

	Heavy Traffic	Moderate Traffic	Light Traffic
Use Case			
Average Speed	13.7 km/h	32.6 km/h	60.1 km/h

Figure 5.3 illustrates the REx optimal operation flow chart. The traffic data is collected on predefined routes according to use cases. The collected data includes vehicle speed, coordinates, altitude, etc. used as cycle input for the simulations. As the first step, the simulation is performed for the baseline strategy. By ensuring the same state of charge at the end of the simulation (SOC_{end}), the results of both optimized and baseline

strategies simulations for each case are compared and discussed.

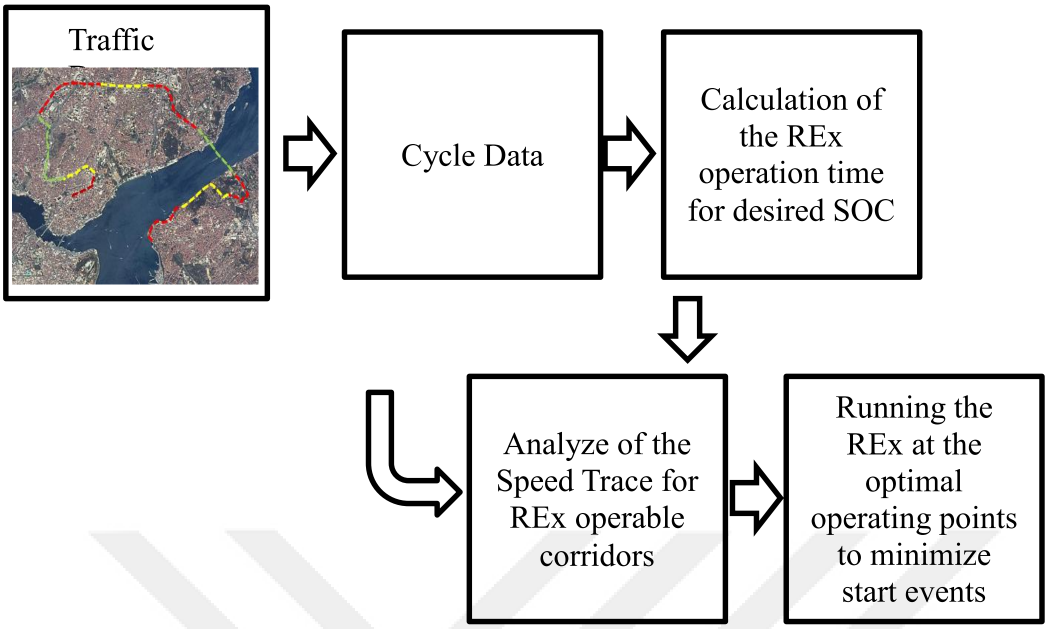

Figure 5.3 : REx optimal operation determination flow chart.

As the REx keeps charge around 70% with 1% hysteresis the SOC_{end} value may be different from the initial SOC (SOC_{in}). The CO_2 effect of the charge or discharge of the battery is taken in to consideration by the Well-to-Wheels (WTW) methodology. For electricity, the WTW pathway includes energy source obtaining process, electricity generation, distribution and the carbon intensity depends on the electricity mix (Moro & Lonza, 2018).

5.3 Energy Management Strategy Development

A series hybrid electric vehicle model is developed by Matlab Simulink and validated by testing on a chassis dynamometer. The subsystem models are developed by testing and mathematical modeling. The technical specifications of the test vehicle are provided in Table5.2. The REx unit consist of internal combustion engine and generator which are connected mechanically. The battery and electric motor are interconnected while the power flow is from the electric motor to the battery during the regenerative braking. Electric vehicles generally use single-stage transmissions so that a one-step gearbox is used in the test vehicle. The total transmission ratio, including the final drive is 8.2. The electric motor, transmission, final drive, differential and wheels are mechanically interconnected.

Table 5.2 : The test vehicle specifications.

System	Details
Vehicle	1750 kg Mass Weight Distribution 56% Front 44% Rear Frontal area 2.28 m^2, Drag Coefficient 0.31
Battery System	35 kWh Capacity 19 Modules Cell Nominal Voltage: 3.2 V
Range-Extender	In-line 2 Cylinder 900 cc 30 kW Max Power 25 Liters Fuel Tank
Electric Motor	8 pole Permanent Magnet Synchronous Motor (PMSM) 70 kW Continuous 170 kW Peak Power 12000 rpm Maximum Speed
Transmission	1 Speed Gearbox Total Transmission Ratio: 8.2

5.3.1 Range extender operation optimizer

The REx operation depends on vehicle speed and battery SOC. As illustrated in Figure 5.4, the upper threshold for REx operation is 20km/h while the lower threshold is 10 km/h. The REx operates at minimum SFC in charge sustaining mode, which indicates that REx operates to keep battery SOC around 70% with 1% precision. The thresholds values are approximately same for range extended eletric vehicles which are being sold and used in the traffic.

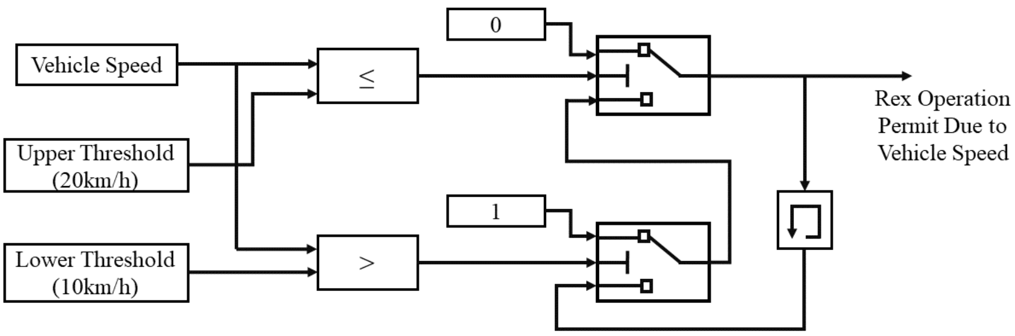

Figure 5.4 : REx operation according to vehicle speed.

The optimization for REx operation is performed for charge sustaining mode where there is a potential for increasing the efficiency by optimizing REx starts.

Table 5.3 : Range Extender Operation Modes and Thresholds.

	Charge Depleting Mode	Charge Sustaining Mode	Charge Mode
Minimum Threshold	0 %	69 %	0 %
Maximum Threshold	30 %	71 %	90 %
Operating Point	Maximum Power	Minimum SFC	Maximum Power
SFC	290 g/kWh	270 g/kWh	290 g/kWh
Vehicle Speed Thresholds	15 km/h (With 5 Km/h Hysteresis)		

REEVs have operation modes such as charging, charge sustaining and charge depleting (Jeong et al., 2017). There is more potential for developing an energy management strategy for REEVs in charge sustaining mode. There may be inefficiency for the REEVs, especially in stop and go traffic conditions since the REx operation also depends on the vehicle speed. For this reason, a predictive REx operation management strategy is developed for charge sustaining mode by using the cycle data.

The REx operation optimizer operates the REx to reach the given SOC at the end of the given cycle by minimizing the engine start events. First of all, for the given SOC_{in}

and SOC_{end} target, required REx operation time is calculated. The optimal REx State matrix is obtained by using the model and inputs as drive cycle SOC_{in} and SOC_{end} target values (Figure 5.5).

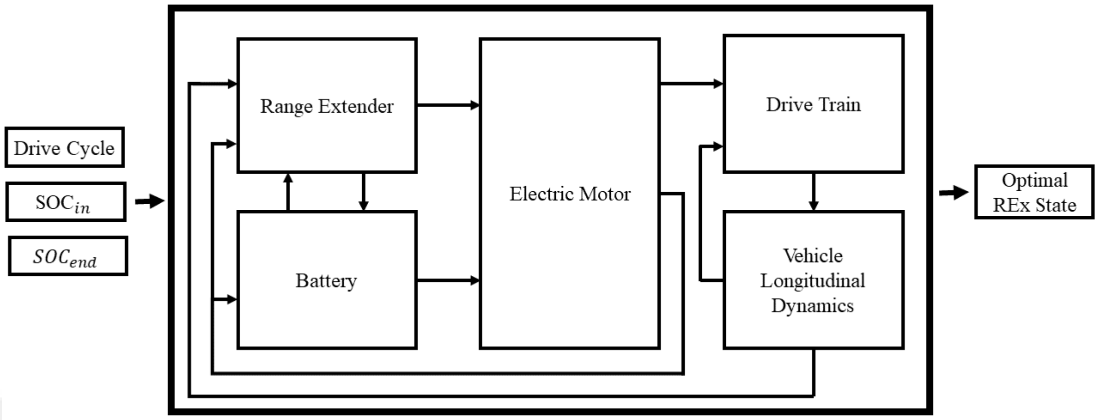

Figure 5.5 : Inputs and Outputs of the REx Operation Optimizer.

The required REx operation time during the cycle(t_{REx}) is a function of the change in SOC(ΔSOC), power demand and power regenerated as provided in equation (5.3); where F_T is the tractive force, η_s is the system efficiency during traction, F_B is the brake force, η_{sR} is the system efficiency during regenerative braking and R_c is the regenerative braking capacity depending on the engine speed and battery current.

$$\Delta SOC = SOC_{end} - SOC_{in} \tag{5.3}$$

$$t_{REx} = f(\Delta SOC.C_{Bat}/100 + \sum v.F_T.\eta_s - \sum v.F_B.\eta_{sR}.R_c) \tag{5.4}$$

The REx operable corridors are detected while the REx operation is reunited in the maximum operable areas. On the other hand, R_{opt} matrix is the REx optimum operation points during the cycle where n depends on the cycle length.

$$R_{opt} = [R_{11}\ R_{12}\ R_{13} \dots R_{1n}] \tag{5.5}$$

R_{opt} consists of arrays that are REx operable points detected according to the rule as illustrated.

The R_{v1} term indicates the longest continuous value of positive values for the R_v. From R_{v1} to R_{vn} the REx operable corridors depending on vehicle speed are sorted according to their lengths.

$$R_{opt} = [R_{v1}] + [R_{v2}] + \cdots [R_{vn}] \tag{5.5}$$

Where,

$$\sum_{i=1}^{n} R_{opt} = t_{REx} \tag{5.6}$$

Depending on the cycle length and battery SOC, the optimization can be processed for separated parts through the cycle.

5.3.2 Results and comparison

For the use cases the model is simulated for optimized and baseline strategies. Tank-to-Wheels (TTW) and WTW CO_2 emissions and extendable ranges are compared with baseline and optimized strategy. Figure 5.6, Figure 5.7 and Figure 5.8 illustrate the REx operation for the cycles according to optimized and baseline strategies. The results show that there is more potential for improvement in CO_2 emission and extendable range for REEVs under heavy traffic conditions.

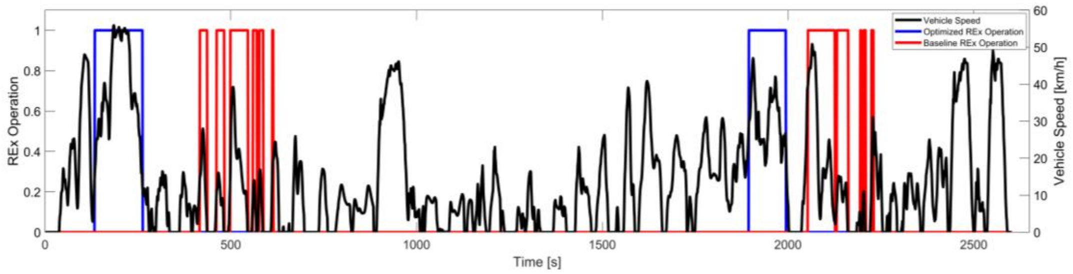

Figure 5.6 : The optimized and baseline rex operation for heavy traffic condition.

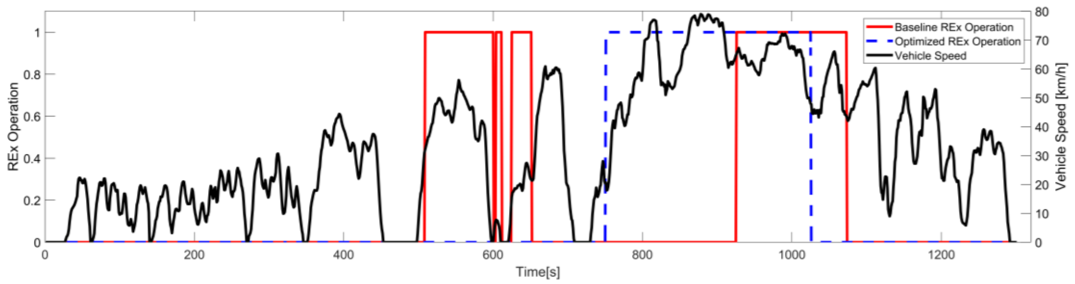

Figure 5.7 : The optimized and baseline rex operation for moderate traffic condition.

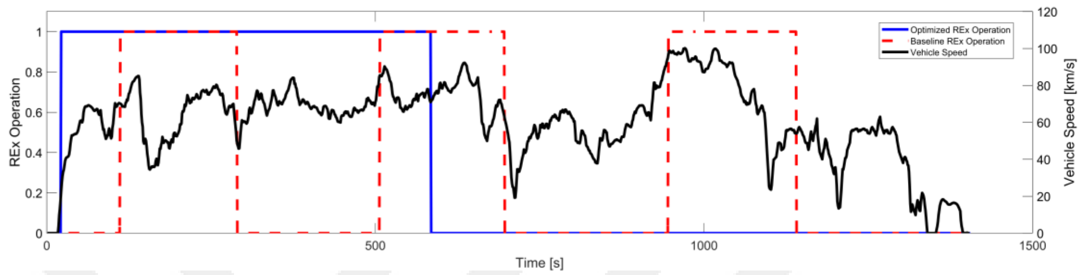

Figure 5.8 : The optimized and baseline rex operation for light traffic condition.

The CO_2 emission benefits are 6.21%, 1.77% and 0.58% for heavy traffic, moderate traffic and light traffic conditions respectively as represented in Table 5.4. There is also improvement in terms of extendable range by using the optimized strategy by consuming the same amount of fuel.

Table 5.4 : The results for CO2 emission and extendable range for strategies.

	Baseline Strategy			Optimized Strategy			Benefit [%]	
	Number of REx Start	TTW CO_2 Emission [g/km]	Total Extendable Range [km]	Number of REx Start	TTW CO_2 Emission [g/km]	Total Extendable Range [km]	CO_2 Emission	Extendable Range
Heavy Traffic	11	139.85	430.82	2	131.18	459.31	6.21	6.61
Moderate Traffic	4	137.24	439.04	1	134.80	446.98	1.77	1.80
Light Traffic	3	140.01	430.38	1	139.18	432.91	0.58	0.59

The Well-to-Tank(WTT) emission of gasoline is the emission caused by the extraction and distribution of the fuel (JEC, 2014). For Istanbul, where the case studies are performed, the WTW emission of the electricity is 391.1 g CO_2/kWh and 520.3 g CO_{2eq}/kWh (Ozdemir et al., 2020). The total emission is calculated by equation (5.7).

$$WTW_{tot} = (SOC_{end} - SOC_{in}).WTW_{el} + WTT_f + TTW_{REx} \quad (5.7)$$

where the WTW_{tot} is the total WTW emission, WTW_{el} is the WTW emission of electricity for the zone, WTT_f is the WTT emission of internal combustion engine fuel and TTW_{REx} is the emission related to the engine operation.

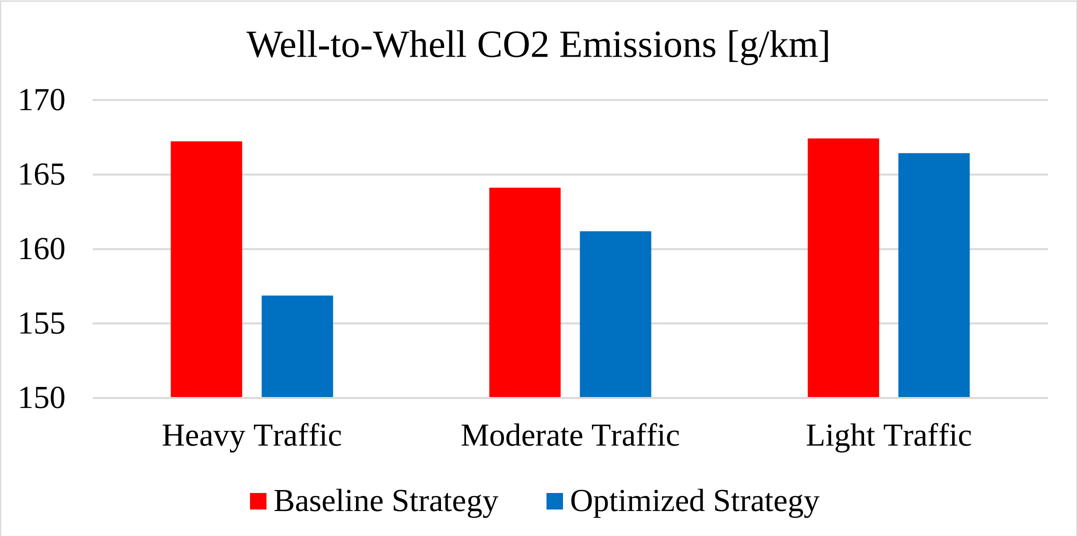

Figure 5.9 : Comparison of WTW emissions of baseline and optimized strategies.

As presented in Figure 5.9, the optimized strategy for REEVs has 10.37 g WTW CO_2 emission per km benefit for heavy traffic while it has 2.92 g and 0.98 g WTW CO_2 emission per km benefits for moderate and light traffic respectively. The results may differ according to use cases, cycles and the driving environment.

5.4 Section Summary

As the vehicle range is one the key parameters, series hybrid solutions are used to increase electric vehicle range by using the REx unit to charge the battery or supply energy for traction system due to low energy density of batteries compared to internal combustion engine fuels. Together with its benefits, operation of REx unit is restricted at low vehicle speeds due to noise and vibration concerns.

To minimize the engine start and stop events, the REx operation can be optimized based on the drive cycle. A driving cycle and model based REx operation optimizer is proposed in this study. A validated vehicle model is developed by subsystem tests to assess the benefit of the developed strategy. The results show that; the proposed strategy that uses the cycle data to manage engine start events, can save 6.21%, 1.77%, 0.58% CO_2 emission for heavy, moderate and light traffic conditions respectively. Moreover, the proposed strategy offers 6.61% vehicle range increase in heavy traffic conditions.

The outcomes indicate that, the usage of the optimized strategy, has significant improvements on emission and vehicle range especially in heavy traffic conditions. Hence the usage of an optimized energy management strategy for series hybrid electric vehicles has benefits in terms of emission and system efficiency.

6. ENERGY MANAGEMENT SYSTEM DEVELOPMENT FOR MULTI VEHICLES: A CASE STUDY FOR MIXED PLATOONING VEHICLES

6.1 Introduction

In the literature, there are several studies on development of energy management system (EMS) for connected vehicles. As mentioned, by the increase of electric vehicle (EV) share in traffic day by day, the traffic is getting mixed in terms of vehicle types. This study examines the situation in which the vehicles in the platoon have different powertrains. In addition, there are various methods to calculate the emitted emissions of the vehicles to determine the benefit of the developed EMS (EEA, 2021). In this study, vehicle emission maps (based on the tire force and vehicle speed) which can also be defined as a vehicle feature are developed by testing the vehicles on a chassis dynamometer. The use of WTW emission values for both conventional vehicles and EVs, by taking into account the emissions caused by electricity production, provides the opportunity of apples to apples comparison. Electric carbon intensity for the region is used to create the emission map for EV.

Conducted studies show that there is a significant improvement potential of transportation efficiency by using the communication based EMS. Connected vehicles can be managed to improve system efficiency with data collection and data analytics (Zhu et al., 2019). Data sources on vehicles and infrastructures are scaling up and big data analytics comes into prominence (Neilson et al., 2019). Yang et al., (2018) performed field tests to evaluate the benefits of vehicle communication based driving strategy and the results show that the fuel consumption can be reduced up to 30% for fast stop-and-go traffic conditions (H. Yang et al., 2018). Ma et al., (2019) developed an adaptive cruise controller for connected autonomous EVs where the simulation results show that the proposed controller has energy saving potential between 6.2% and 16.1% depending on the driving cycle (Ma et al., 2019).

Intersections with traffic lights can cause inefficiencies due to waiting time at the traffic lights and sudden changes in vehicle speed. Adaptive speed controllers for connected autonomous vehicles through signalized intersections can increase the efficiency by avoiding the idle periods at the traffic lights (Ma et al., 2021). He and Wu (2018) developed a speed advisory system for a single intersection to minimize energy consumption of platooning vehicles where the results show that there is a potential for increasing energy efficiency up to 43% (He & Wu, 2018). On the other hand, by considering traffic light states on a planned path an EMS can be developed to increase internal efficiency of a range-extended or a fuel cell vehicle (Neilson et al., 2019; Wei et al., 2022).

In this study a dynamic programing (DP) based optimizer is developed to minimize total equivalent emissions of platooning vehicles. The platoon consists of vehicles with different types of powertrains such as electric, gasoline and diesel. The EV's environmental cost is calculated by considering the energy mix. A multi-layer optimization is studied to find out the optimum speed trace to minimize the emitted WTW GHG emissions by the platoon. DP method is used where the problem is nonconvex and can be defined as deterministic. The results show that there is a considerable benefit of using the developed speed advisory system for mixed conventional and electric platooning vehicles through signalized intersections.

6.2 Dynamic Programing Based Optimization

The study offers a speed advisory system to minimize system level WTW emissions. The objective function contains WTW emissions of the vehicles which contains Well-to-Tank(WTT) and Tank-to-Wheels(TTW) emissions. That means the WTW pathway includes the processes between the well and the wheels for the energy source (Robert et al., 2014). The carbon intensity of electricity is used for EV emission calculations to compare the same variable for EVs and internal combustion engine vehicles(ICEVs) (Ozdemir et al., 2020). The carbon intensity of electricity used in Turkey is calculated in another study as 520.3 g CO_{2eq}/kWh by considering the Turkey's energy mix (Ozdemir et al., 2020). The equivalent carbon dioxide emissions (CO_{2eq}) are calculated by using the constants for global warming potential estimations (Forster et al., 2007; Myhre et al., 2013).

By using the tractive force and vehicle speed values the total emissions are calculated for generated speed traces. The speed optimizer provides the minimize the cost function which includes the travel time and emissions. The contraints of the system are speed limits and traffic light states as given in Figure 6.1.

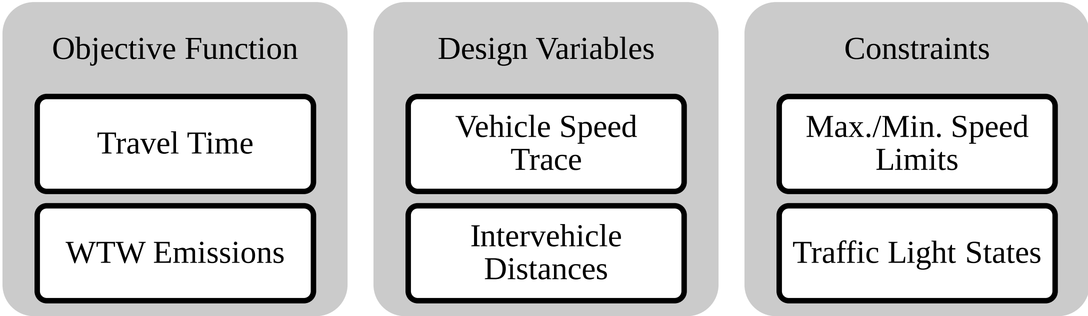

Figure 6.1 : The optimizer objective, constraints and variables.

The methodolgy is given in Figure 6.2. The emission maps of the vehicles are developed by testing on the chassis dynamometer. A platoon of a gasoline, a diesel, and an EV is used to model the heterogeneous traffic in terms of powertrain types. By conducting the tests on chassis dynamometer, vehicle emission maps are produced based on vehicle speed and contact force. Tailpipe emission are measured by the real time emission analyzers. An energy analyzer is used to measure the energy consumption of the EV at the desired operating points.

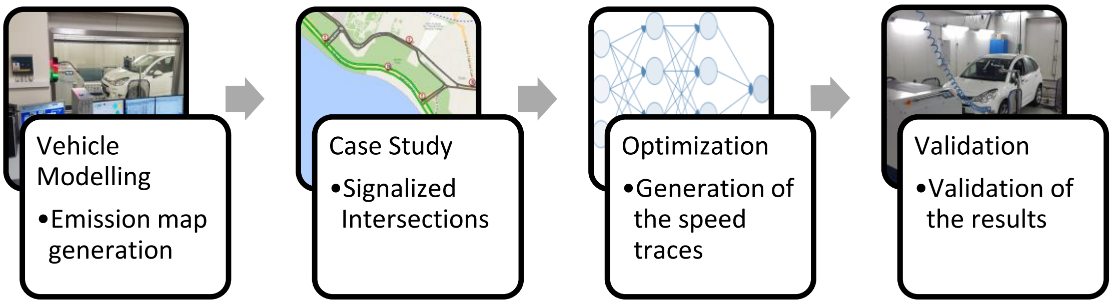

Figure 6.2 : Energy management system development methodology.

The case under study includes signalized intersections. Vehicles with different powertrains help simulate heterogeneous traffic conditions in terms of energy sources. The optimizer offers the best speed profile to minimize the total WTW emissions. The cost function is the system-level emissions, and the main design variables are the speed traces of the vehicles. The constraints of the optimization problem are the traffic light states and speed limits on the selected route.

A DP based multi-layer optimizer is designed to obtain the optimum speed traces of the platooning vehicles. First stage is exploration where the search space is generated by selected check points. The check points are used for velocity profiling which are assigned points in time-distance domain. In exploitation phase the global optimum speed profile is searched between local adjacent optimum points. The simulation outputs and test results are compared by using the vehicle dynamometer.

6.3 Case Study: Mixed Platooning Vehicles

6.3.1 Optimization for signalized route

A vehicle platoon consists of one gasoline vehicle, one diesel vehicle and one EV is simulated on a selected route. The route includes part of the coastal road on the Anatolian side of Istanbul, where the green wave-based control of the signalization systems is not applicable because of the pedestrian buttons and links on the road. As given in Figure 6.3 driving by just considering speed limits causes inefficiency because of stops at traffic lights.

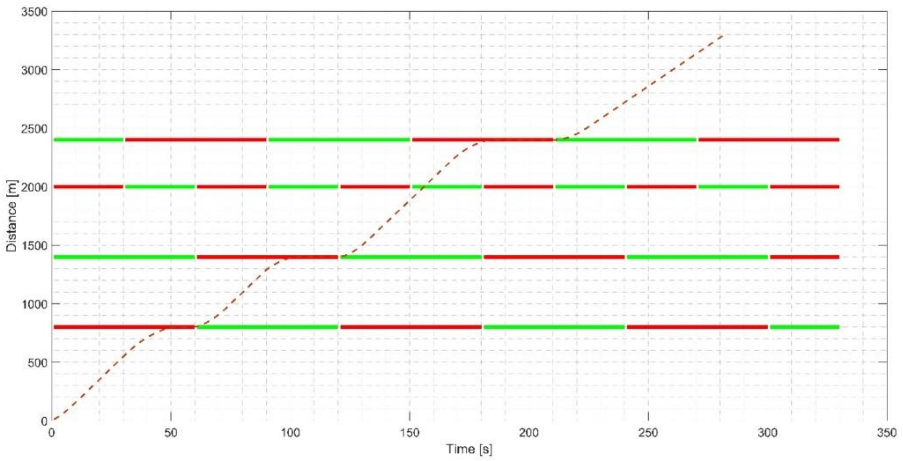

Figure 6.3 : Initial time-distance graph of the platoon.

The route schema is given in Figure 6.4 which includes speed limits and signalized intersections which are the constraints of the optimization problem.

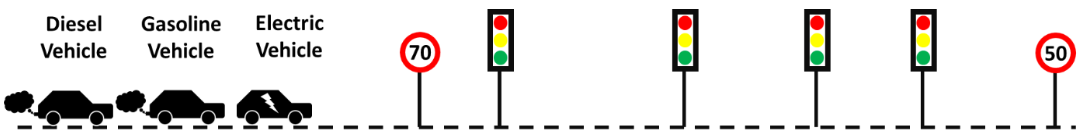

Figure 6.4 : Schematic representation of the defined route.

The optimization includes exploration and exploitation phases. The first layer can be called as exploration phase where the search space is created by defining time and speed points for checkpoints.

The distances of traffic lights from the initial position are D_i, where “i” is the order of the traffic light as given in equation (6.1).

$$D_i, i = \{1,2,3 \ldots n\} \tag{6.11}$$

The traffic light cycles include green light and red light phases. L_{gi} denotes the green light phases of i th traffic light. X_{in} represents the specified checkpoints used to create search space, which are the elements of the green light phase of the traffic lights as defined in equation (6.2)(6.2).

$$X_{in} \in \left[D_i \, \overline{L_{gi}}\,\right] \tag{6.2}$$

For the exploration phase the points are placed on green light phases at specified frequency as represented in Figure 6.5. In the exploitation phase the search space is created by using specified checkpoints as in first stage. In exploitation phase, the points are placed between adjacent local minimums of the first stage as given in Figure 6.6.

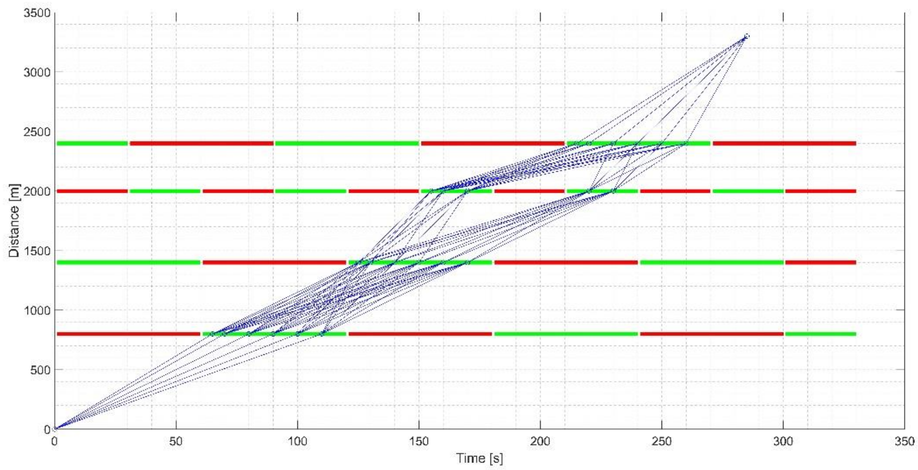

Figure 6.5 : First stage search space of the optimization problem.

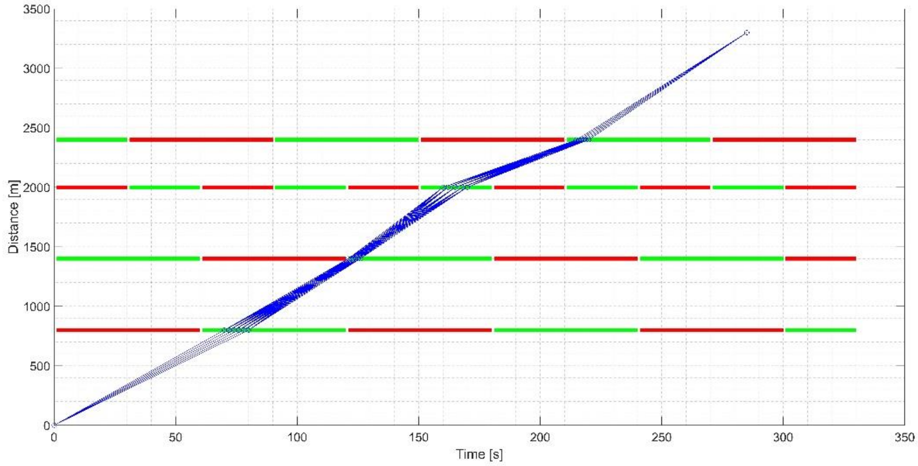

Figure 6.6 : Second stage search space.

The candidate traces include cruising and acceleration or deceleration. The cruise speeds of each section are calculated using equation (6.3) where the difference in distances are divided to difference in T_i, the time for selected points. On the other hand, at the junction points positive change in vehicle speed increases the total WTW emissions and negative change in vehicle speed may decrease the total WTW emissions because of regenerative braking of the EV. The acceleration values are calculated as given in equation (6.4) where t_{ref} is a defined time which is the duration of platoon speed adaption.

$$v_i = \frac{D_i - D_{i-1}}{T_i - T_{i-1}} \tag{6.3}$$

$$a_i = \frac{v_{i+1} - v_i}{t_{ref}} \tag{6.4}$$

The platoon connects to the coastal road from the link road and proceeds on the coastal road for a while and leaves the road from another linking. The initial and final speeds of the platoon are defined as 50 km/h which is the speed limit for residential area (KGM, 2021). The speed limit for the coastal road side is 70 km/h. The speed limits and maximum acceleration of the vehicles are constraints of the problem. The search space is constricted by considering these constraints.

The cost function is total WTW emissions of the vehicles in the platoon and the objective is to minimize it. The WTW emission of the platoon is sum of electric, diesel and gasoline vehicle emissions. The DP is used to calculate the specific WTW emissions. The total emission of each trace is calculated as given in equation (6.5) where J is the minimum total WTW emission of the platoon, E_{ai} is the acceleration or deceleration related emission and E_{vi} is the cruising emission. The cost functions are calculated by using vehicle longitudinal dynamics and emission maps.

$$J = min\left(\sum_{i=1}^{n} E_{ai} + \sum_{i=1}^{n-1} E_{vi}\right) \tag{6.5}$$

$$J(x_{n-k}) = \min_{un-k}\{\hat{f}(x_{n-k}, u_{n-k}) + J_{k-1}(\hat{g}(x_{n-k}, u_{n-k}))\} \tag{6.6}$$

Second layer optimization is processed by defining new checkpoints between X_{in} and X_{in+1} for i=1 to number of traffic lights. As given in Figure 6.7, when the local minimums are not adjacent the checkpoints are relocated for the first stage optimization.

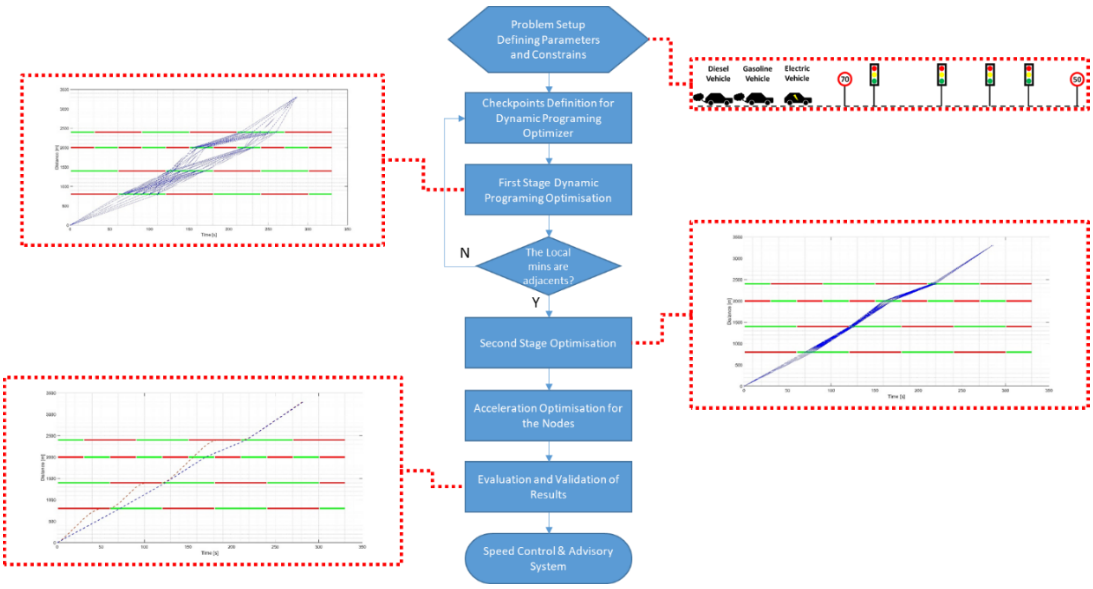

Figure 6.7 : Flow chart of the optimization process.

After second stage optimization the accelerations and decelerations of the global minimum speed trace are optimized. The a_i values are optimized for approaches to the nodes and departures from the nodes. For every node t_{ref} values between specified ranges are simulated.

6.3.2 Testing and evaluation

The optimizer finds out the optimized speed profiles in terms of equivalent CO2 emissions. The baseline and optimized speed profiles are tested on chassis dynamometer as shown in Figure 6.8. All vehicles are tested by using their spesific road load data. Tests are performed by using the target speed bands. The speed bands are ±2km/h of the desired speed traces. The tests are invalid if vehicle speed abides outside the desired speed band for more than one second or goes out of the band more than ten times. The validation tests are repeated until the tests are valid.

Figure 6.8 : Validation tests on chassis dynamometer.

As the same as emission map generation, WTT emissions of conventional vehicles are measured using emission analyzers. The WTW emissions are calculated by using WTT measurement and TTW calculations. The energy consumption of the EV is measured by energy analyzers and CAN signals. The electric carbon intensity is used to transform energy consumption to WTW emissions. The comperative speed profiles between optimized and initial speed traces are given Figure 6.9.

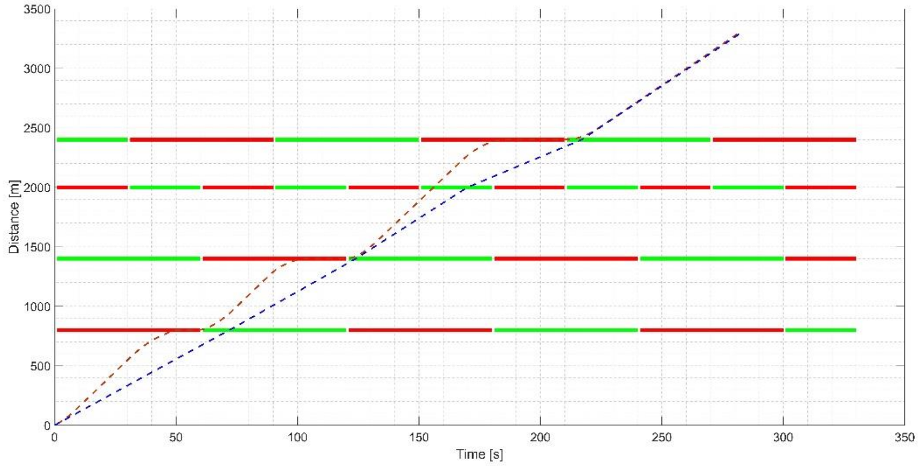

Figure 6.9 : Inıtial and optimized time-distance profiles of the platoon.

The test results and simulation outputs are well-matched with less than 5% relative error. The test results for baseline and optimized speed profiles are given in Table 6.1. The benefit of using the developed optimizer for the use case is around 17% for the EV. For conventional vehicles the offered optimizer can save about 20% CO_{2eq} emissions by avoiding redundant acceleration, deceleration and idling. The optimizer provides an energy-saving potential and better driving comfort by avoiding excessive accelerations and decelerations in the platoon.

Table 6.1 : Baseline and optimized total WTW emissions.

Vehicle	Baseline WTW Emissions [g CO_{2eq}]	Optimized Cycle WTW Emissions [g CO_{2eq}]
Electric	248.82	206.52
Gasoline	487.08	392.04
Diesel	518.76	407.88
Total	1254.66	1006.44

As given in Table 6.1 total WTW emission for the baseline is 1254.66 g CO_{2eq} and 1006.44 g CO_{2eq} for the optimized speed. Total WTW emissions of the platoon decreased by %19.8 for the use case under the developed strategy. It is essential to design optimizer by considering the vehicle mix in traffic. When the speed profile is designed by optimizer for platooning only EVs on the selected route there are more local minimums at first stage. The optimum speed trace varies according to vehicle types in the platoon. The research has also shown that the use of EVs has advantage in terms of WTW emissions comparing to ICEVs on the same route.

6.4 Section Summary

In this study a multi-layer DP based optimizer is designed to minimize platooning WTW emissions of platooning vehicles where the platoon consists of an electric, a gasoline and a diesel vehicle. Vehicle emission maps and longitudinal dynamics are used for vehicle modelling. TTW emission maps of ICEVs are produced by testing the vehicles on a chassis dynamometer. The optimization process has exploration and exploitation layers. The cost function is total WTW emission, design variable is speed trace, constraints are speed limits, traffic light states and vehicle accelerations limits. The test results show that the developed optimizer helps to achieve a 19.8% reduction in total WTW emissions for the defined use case. Thus, there is a significant emission saving potential in using speed advisory system for platooning vehicles through signalized intersections.

Efficiency can be increased with the effective use of data, taking into account the infrastructure and vehicle characteristics in transportation. In the case of using different energy sources, the objective function should include a common variable such as WTW emissions for an optimizer development. As represented in Figure 6.10 if the platoon was consisted of only electric vehicles there was going to be more local minimums.

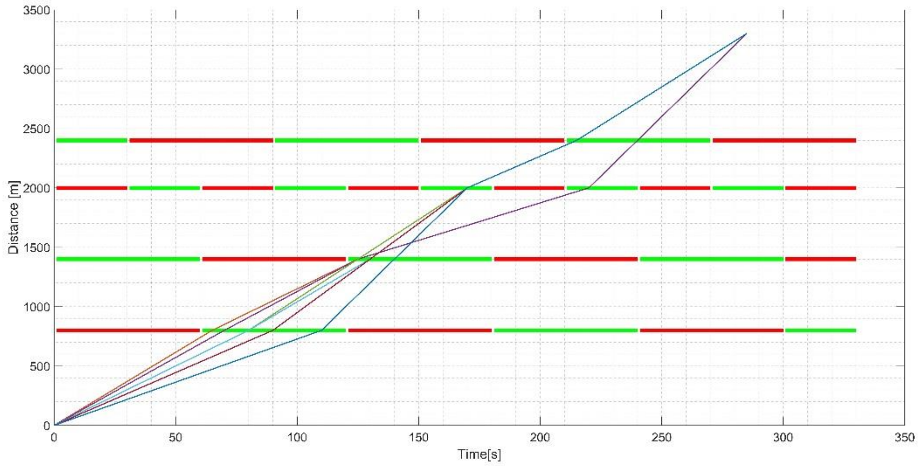

Figure 6.10 : Platooning only electric vehicle scenario.

The future research should take the vehicle characteristics in the platoon into account for EMS development. Further research can also be conducted on machine learning based vehicle emission map generation for developing an optimizer. Another possible area of future research would be to investigate the effect of using different optimization methods for the same problem.

7. CONCLUSIONS AND RECOMMENDATIONS

There are estimations for significant increase in the market share of EVs in coming years. The environmental effect of EVs depends on the power sources. When fossil fuels are energy generation sources, the EV usage also has certain environmental costs. In this study by considering global warming potential estimations, WTT emissions of electricity production is estimated as 520. 3 g CO_{2eq}/kWh. By estimation of the environmental cost of electricity production, it is possible to compare same variable for the systems where the electricty and fossil fuels are used together. For example; an optimisation for hybrid electric vehicle which uses fossil fuels and electricity as energy source, the WTT emission values gives the opportunity to optimize energy management strategy by considering environmental effects.

In this study an energy management strategy is developed for hybrid electric vehicles. By using the REx the battery can be charged or energy can be supplied for traction system. A range extended serial hybrid vehicle's energy management strategy is optimised by minimizing the start and stop event for the range extender. To minimize the engine start and stop events, the REx operation can be optimized based on the drive cycle. Together with its benefits, operation of REx unit is restricted at low vehicle speeds due to noise and vibration concerns which causes inefficiency in terms of energy consumption.

A driving cycle and model based REx operation optimizer is proposed in this study. A validated vehicle model is developed by testing subsystems such as electric motor, inverter, battery, range extender to assess the benefit of the developed strategy. The results show that; the proposed strategy that uses the cycle data to manage engine start events, can save 6.21%, 1.77%, 0.58% CO_2 emission for heavy, moderate and light traffic conditions respectively. Moreover, the proposed strategy offers 6.61% vehicle range increase in heavy traffic conditions.

The outcomes indicate that, the usage of the optimized strategy, has significant improvements on emission and vehicle range especially in heavy traffic conditions.

Hence the usage of an optimized energy management strategy for series hybrid electric vehicles has benefits in terms of emission and system efficiency.

As mentioned above the traffic is getting mixed in terms of vehicle types. The estimations indicates that in ten years there will be more electric vehicles on the roads. Tanks to vehicle communicatipn systems the data can be used to energy cunsumption minimization. As in hybrid electric vehicle energy management startegy development study an energy managegement strategy is developed for mixed platooning vehicles by considering WTW emissions.

A multi-layer DP based optimizer is designed to minimize WTW emissions of platooning vehicles where the platoon consists of an electric, a gasoline and a diesel vehicle. On the othe hand the emission map terminology is offered as a vehicle feature. When the vehicle types differ from each other in a platoon a common vehicle feature must be used such as an emission map.

For optimization process vehicle emission maps and longitudinal dynamics are used for vehicle modelling. TTW emission maps of ICEVs are produced by testing the vehicles on a chassis dynamometer. The bag and analyzer results are used to create vehicle emission maps.

An optimizer is developed which has multi steps. The optimization process has exploration and exploitation layers. The cost function is total WTW emission, design variable is speed trace, constraints are speed limits, traffic light states and vehicle accelerations limits for the optimization problem.

A case is studied which includes traffic lights. A section of Istanbul Anatolian side coastal road is simulated. The optimizer is used to generate best speed profile through signalized intersections. The test results show that the developed optimizer helps to achieve a 19.8% reduction in total WTW emissions for the defined use case. Thus, there is a significant emission saving potential in using speed advisory system for platooning vehicles through signalized intersections.

Thus it is important to use the sensor data and communication systems to optimize the energy consumption in traffic both for vehicle and system level. On the other hand it is also important to take in to account the types of vehicles. When one type of vehicle is selected for the optimization process the optimum speed profile would be different.

The estimation of the electric carbon intensity of electricty gives chance to compare the WTW emissions of electric and gasoline vehicles. The energy consumption and emission values are measured by using generated driving cycle for Istanbul. The driving cycle is generated by using the collected data on traffic. The use cases and the routes are defined for data collection. The collectec data is statistically analyzed for driving cycle development.

The chassis dynamometer test results show that the energy consumption of EV is 0.142 kWh/km and the TTW emissions of gasoline vehicle is 152.7 g CO_{2eq}/km according to proposed drive cycle. The results show that WTW emissions of ICEV is 183.4 g CO_{2eq}/km and for EV it is 73.9 g CO_{2eq}/km.

Thus, introduction EVs to Istanbul on a large scale can reduce the WTW emissions by 60 %, excluding the emissions associated with the vehicle production and power plant construction. Even though this reduction is quite beneficial, it is under the European average due to the current reliance of fossil fuels on the energy generation mix. Hence, the switch the EVs should be reinforced with more widespread usage of renewable energy in the country to realize the full impact of emission reduction generally associated with EVs. At the same time, the results in this thesis can also be a guide for policy makers.

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APPENDICES

APPENDIX A: Map of case study route

APPENDIX B: The distribution of electricity production according to resources

APPENDIX A : Map of case study route

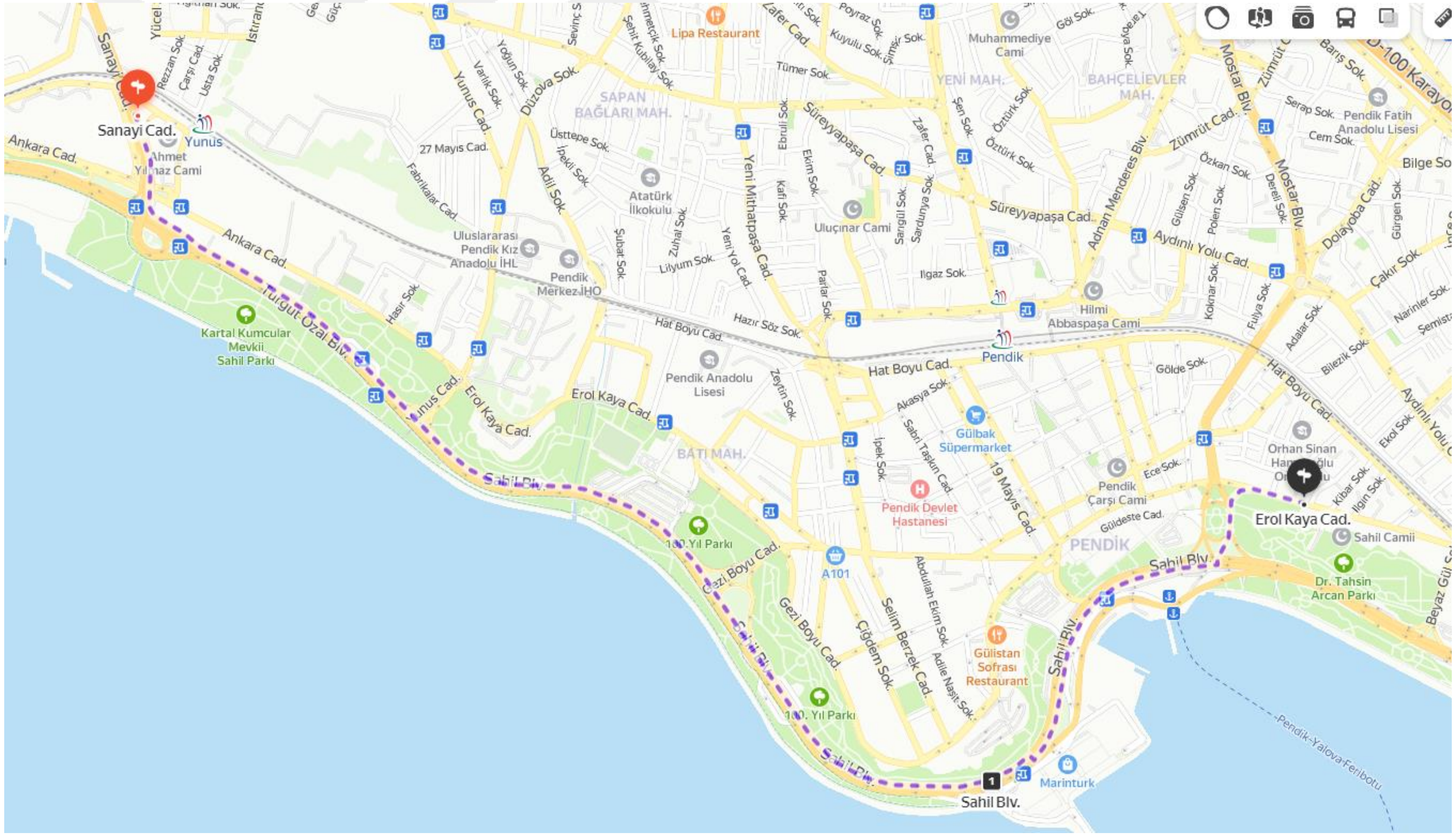

Figure A.1 : The map of case study route for platooning vehicles.

APPENDIX B : The distribution of electricity production according to resources

Table B.1 : The distribution of electricity production according to resources.

Months / Power Resources	January [GWh]	Feb. [GWh]	March [GWh]	April [GWh]	May [GWh]	June [GWh]	July [GWh]	August [GWh]	Sept. [GWh]	Oct. [GWh]	Nov. [GWh]	Dec. [GWh]	Total [GWh]
Hard Coal	5557	5743	4846	3639	3379	4156	6348	6269	6533	6579	6479	6694	66224
Lignite	3586	3407	3756	3501	3602	3581	4464	4282	4100	4191	4043	4382	46894
Liquid Fuels	86	80	79	73	91	45	46	46	42	48	50	48	734
Natural Gas	5535	3663	4390	3203	3026	3169	6202	5405	5127	4968	5615	6399	56703
Waste and Other	373	339	379	348	397	371	364	378	373	389	403	409	4524
Hydraulic	7682	7196	7738	9991	11623	9626	7649	6968	5687	5120	4515	5093	88886
Renewable	3321	3150	3680	3040	2909	3395	3779	4417	3683	2897	2839	3176	40287
Gross Generation	26141	23579	24866	23795	25028	24344	28852	27764	25545	24192	23944	26201	304252
Imports	143	176	259	120	137	155	164	193	129	127	309	299	2212
Exports	252	322	264	293	327	156	181	176	168	260	200	189	2789
Gross Demand	26032	23433	24861	23622	24837	24343	28835	27781	25506	24058	24053	26312	303674

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