ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

OPTIMUM ENERGY MANAGEMENT STRATEGY OF A HYBRID ELECTRICAL VEHICLE BASED ON EFFICIENT POWER DISTRIBUTION AND BATTERY DISCHARGE CAPACITY

M.Sc. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

VERİMLİ GÜÇ DAĞITIMI VE AKÜ DEŞARJ KAPASİTESİNE DAYALI HİBRİT ELEKTRİKLİ ARACIN OPTİMUM ENERJİ YÖNETİMİ STRATEJİSİ

YÜKSEK LİSANS TEZİ

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Behnam GHADIMI, an M.Sc. student of ITU Graduate School student ID 503191713 successfully defended the thesis/dissertation entitled “OPTIMUM ENERGY MANAGEMENT STRATEGY OF A HYBRID ELECTRICAL VEHICLE BASED ON EFFICIENT POWER DISTRIBUTION AND BATTERY DISCHARGE CAPACITY”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 02 August 2022
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To my parents and son,

FOREWORD

This thesis is written as the main requirement for my graduation in MSc. Automotive Engineering program. The subject is based on comprehensive research on designing an efficient, intelligent energy management strategy for a light-duty commercial hybrid electrical vehicle. A sophisticated, intelligent energy management strategy that employs traffic information from available sources plays a significant role in achieving strict targets to improve the energy efficiency of either hybrid, battery, or fuel cell electric vehicles.

I want to thank Prof. Dr. Özgen AKALIN for his helpful instructions and feedback during this research. This work would not have been appropriately accomplished without his astute observations and sensible recommendations.

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(Mechanical Engineer)

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ABBREVIATIONS

LCV	: Light-duty commercial vehicle
WLTC	: Worldwide harmonized light vehicles test cycles
ICE	: Internal combustion engine
ICE4	: Four-cylinder vehicle
ICE3	: Three-cylinder vehicle
ICEV	: Vehicle with an internal combustion engine
HEV	: Hybrid electric vehicle
PHEV	: Parallel hybrid electrical vehicle
SHEV	: Series hybrid electrical vehicle
CHEV	: Combined hybrid electrical vehicle
HEVP2	: Hybrid electric vehicle in P2 configuration
HEVP4	: Hybrid electric vehicle in P4 configuration
EM	: Electric machine
EM Ratio	: Power split ratio between ICE and EM
SOC	: Battery state of charge
EMS	: Energy management strategy
V2V	: Vehicle-to-vehicle communication
V2I	: Vehicle to infrastructure communication
GPS	: Global positioning system
ITS	: Intelligent transportation system

SYMBOLS

u	: Power split ratio [-]
P_{ice}	: Engine power (kW)
P_{em}	: Electric machine power (kW)
P_{dem}	: Demanded power from powertrain (kW)
F_a	: Aerodynamic force (N)
F_r	: Rolling resistance (N)
F_g	: Gravitational force (N)
F_d	: Disturbance force (N)
F_t	: Traction force (N)
α	: Road gradient (rad)
α_{max}	: Road maximum gradient (rad)
m_v	: Vehicle mass (kg)
m_r	: equivalent mass of rotational parts (kg)
ρ	: Air density (kg/m^3)
A_f	: Vehicle frontal area (m^2)
C_d	: Aerodynamic drag coefficient [-]
C_r	: Friction coefficient [-]
v	: Vehicle velocity (m/s)
v_{max}	: Vehicle maximum velocity (m/s)
v_i	: Vehicle discretized velocity (m/s)
a	: Vehicle acceleration (m/s^2)
a_i	: Vehicle discretized acceleration (m/s^2)
p	: Tire pressure (bar)
g	: gravity (m/s^2)
r_w	: Wheel radius (m)
θ_w	: Total moment of inertia of wheels
θ_e	: Total moment of inertia of rotating parts
γ	: Total gear ration [-]
P_{max}	: Maximum traction power (kW)

$\overline{F}_{trac}$: Mean tractive force (N)

$\overline{F}_{i}$: Mean discretized dissipative force (N)

$\overline{F}_{a}$: Mean discretized aerodynamic force (N)

$\overline{F}_{r}$: Mean discretized rolling resistance force (N)

$\overline{F}_{m}$: Mean discretized mass force (N)

x_{tot} : Total distance of test cycle (m)

h : Time step (s)

t : Time (s)

i : Discretized time [-]

$\overline{E}_{diss}$: Average dissipative energy (kJ)

$\overline{E}_{circ}$: Average circulative energy (kJ)

$\overline{E}_{f}$: Average fuel energy consumption (kJ/km)

H_{l} : Lower heating value of fuel (kJ/kg)

η_{g} : Gearbox efficiency [%]

η_{a} : Efficiency of auxiliary devices [%]

η_{e} : Engine efficiency [%]

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OPTIMUM ENERGY MANAGEMENT STRATEGY OF A HYBRID ELECTRICAL VEHICLE BASED ON EFFICIENT POWER DISTRIBUTION AND BATTERY DISCHARGE CAPACITY

SUMMARY

LCVs are an essential part of goods and passenger transportation in the cities. Based on the studies published by international institutions, the market share of LCVs in EU-27 + UK countries has been reported as 12% for the year 2020, accounting for 1.63 million vehicles. LCVs have high annual mileage in European countries, especially in the first three years of their operation, accounting for an annual mileage of about 34 thousand km. In the Turkish market, however, in 2019, the average mileage of minibuses and small trucks are 24,636 and 16,562 km, respectively. This information emphasizes the importance of LCVs in the economy of these countries. In addition, the annual mileage of LCVs indicates the potential for high yearly fuel consumption and propagation of greenhouse gases. Therefore, electrification of the LCVs is critical to minimize fuel consumption and limit the production of CO_2, which has a high impact on global warming and climate change.

To benefit from the advantages of both the internal combustion engine and the electric powertrain, designing a hybrid LCV with efficient energy consumption is vital. In hybrid electrical vehicles (HEV), efficient power distribution between prime movers, the internal combustion engine, and the electric motor plays a significant role in its energy management strategy to reduce the overall fuel consumption and CO2 emissions. The electric motor can operate at points where the operation of the internal combustion engine is not efficient. These operation points are determined when the delivered torque is far away from the optimum torque line. In addition, the electric motor can provide additional torque while the internal combustion engine is in operation to boost the vehicle's traction and acceleration.

On the other hand, the operation of the electric motor is disregarded by the energy management controller when it is not efficient to have the electric motor in the loop. The internal combustion engine solely provides the required torque in these cases. Another benefit of hybrid electric vehicles is that the regenerative braking system can recuperate the vehicle's kinetic energy during the braking.

In this study, the hybridization of a Light Duty Commercial Vehicle, LCV, is evaluated. The target vehicle is the Mercedes-Benz Sprinter with a four-cylinder diesel engine with a maximum power of 125kW at 3800 rpm and a maximum torque of 360 Nm in a range of engine speeds from 1400 rpm to 2400 rpm. The gross vehicle weight is 3500 kg.

In the first part of this study, the modeling and simulation of the base vehicle with a diesel engine are done using AVL Cruise Software. The necessary design and engine performance data are obtained from the Mercedes-Benz Sprinter type approval documents. The detailed fuel map of the diesel engine is built based on the instructing documents from EPA. The vehicle model is simulated using the AVL Cruise Software, and the overall fuel consumption of 9.6 L/100 km is achieved in the WLTC Class-3b

test cycle. The achieved fuel consumption is identical to the fuel consumption of the target vehicle, which is mentioned in the type approval document. This part of the study will be the basis for comparing the effectiveness of the hybridization of the target vehicle to improve fuel economy and limit CO_2 emissions. In addition to the fuel consumption as the main comparison criteria, the maximum gradeability of the target vehicle is evaluated in AVL Cruise Simulation software which finally accounts for 23.5% while the vehicle is fully loaded.

Furthermore, AVL Cruise Simulation software investigates the ultimate vehicle velocity of the LCV with an internal combustion engine. The simulation results reveal that the base vehicle has a maximum velocity of 158.6 km/h at fifth gear. As an additional constraint besides the fuel consumption and CO_2 emission, the designed hybrid LCV should meet the gradeability and ultimate velocity targets which are 23.5% and 158.6 km/h, respectively.

This study uses AVL Cruise Software and MATLAB R2021b to analyze the overall fuel consumption of the target light-duty commercial vehicle in two different hybrid configurations known as P2 and P4 in the literature. In the P2 configuration, the internal combustion engine and the electric machine are connected to the front axle through a common six-speed gearbox. In contrast, in the P4 configuration, the internal combustion engine drives the front axle through a six-speed gearbox. Still, the electric machine is connected to the rear axle via a two-speed small gearbox.

The four-cylinder diesel engine is downsized to a three-cylinder engine. In the downsizing procedure, the engine's performance is reduced by 25% in all engine speeds and torques. P2 and P4 models are built in AVL Cruise and simulated in WLTC Class-3b in a sustainable charge strategy. The simulation result shows that the fuel consumption can be improved by 17.7% using the P2 configuration compared to the base vehicle with the four-cylinder diesel engine. The overall fuel consumption of the P2 design in the WLTC Class-3b test cycle is dropped to 7.90 L/100km. In contrast, the P4 design accounts for only a 15.6% improvement in fuel economy in a sustainable charge WLTC Class-3b test compared to the base vehicle with an overall fuel consumption of 8.10 L/100km.

In addition, both P2 and P4 configuration satisfies the maximum gradeability and top velocity constraints. The maximum gradeability of the P2 design reached 58%. In contrast, the maximum gradeability of the P4 design is 60%. Furthermore, the maximum vehicle velocity of the P2 design reached 160 km/h, while it is 159 km/h for the P4 design. Since fuel economy and reducing CO_2 emission is the primary goal of this study, the P2 hybrid configuration is decided to be the base hybrid design for the continuation of this study.

The designed P2 hybrid configuration consists of five distinct operation modes. In the eDrive mode, the driver-demanded torque is solely provided by the electric machine in drive mode (called an electric motor). The mode in which the demanded torque is supplied only by the internal combustion engine is called cDrive. The vehicle braking course consists of two steps. At first, when the brake pedal is pressed, the electric machine in generation mode (called a generator) is activated to recuperate the vehicle's kinetic energy to generate electricity for charging the battery. This mode is then called as eBrake. When the braking torque exceeds the regeneration torque limit of the generator, the conventional braking system is activated. This mode is named as mBrake stands for the mechanical brake. When the controller demands the charging of the battery, the generator is activated while the internal combustion engine operates and drives the vehicle. To satisfy the driver torque, the internal combustion engine should deliver more torque, part of which is a supplier to the generator for electricity generation. This mode is called eLPM, which stands for load point movement.

Finally, the eBoost mode is a hybrid vehicle’s operation mode when both the internal combustion engine and the electric motor operate concurrently to provide the driver demanded torque. The electric motor delivers part of the requested torque by the driver, and the remaining torque is delivered by the internal combustion engine. The torque allocation division is done according to a predefined ratio called the power split ratio. Power split ratio is a ratio of the electric motor’s torque to the total demanded torque of the driver. eBoost mode is a hybrid electric vehicle's most challenging operation mode, which needs exact consideration.

To find an optimum power split ratio between the internal combustion engine and the electric motor, research is continued on the P2 configuration. After extensive simulations with different power split ratios in the WLTC Class-3b test cycle, it is revealed that for each velocity phase of WLTC, a particular power split ratio results in the most efficient fuel economy. In addition, the massive investigation for evaluating the impact of the battery maximum discharge power showed that by limiting the battery discharge power to certain levels in different WLTC phases, the fuel consumption could be further improved. Therefore, an adequate pair of power split ratio and battery maximum discharge power is defined for each velocity phase of the WLTC Class-3b test cycle for the final simulation in this part of the study.

The simulation result revealed that by allocating a particular power split ratio paired with a specific maximum permissible battery discharge power capacity, the fuel economy is improved further. This part of the study shows an additional 5.1% improvement in the vehicle’s overall fuel consumption accounting for 7.50 L/100km.

In the next part of this study, the research concentrates on incorporating the online traffic data, which is obtained via V2V, V2I, ITS, and GPS communication, into the energy management strategy of the P2 hybrid LCV to determine an efficient hybrid mode for the current operation of the vehicle. In other words, the current hybrid mode of the P2 hybrid vehicle is defined based on the traffic situation in the future time frame. A 60-second future zone is defined, and the velocity and acceleration of the future traffic in this zone are evaluated. An algorithm is developed to select the most efficient hybrid mode for the current operation of the P2 hybrid vehicle based on the future traffic congestion, the instantaneous velocity, instantaneous acceleration, and the current SOC level of the battery. The simulation of the P2 hybrid vehicle in sustainable charge WLTC Class-3b test shows that the fuel economy is improved by 2.7% compared to the model without the application of this algorithm.

In the final part of this study, an optimum velocity trajectory function is used and instructs the driver on an eco-driving procedure. The fluctuating velocity at the 60 seconds prediction horizon is processed and smoothened using Savitzky–Golay filter with a polynomial order of three. A velocity trajectory is generated, proposing the driver maintain an efficient driving velocity as much as possible. The result showed an additional 6.1% further improvement in fuel efficiency is achieved in the sustainable charge WLTC Class-3b test. At the end of this study, by incorporating all of the solutions, the overall fuel consumption of the P2 hybrid vehicle reaches 7.04 L/100km, accounting for 26.7% fuel saving compared to the based LCV vehicle with a four-cylinder diesel engine.

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ÖZET

Hafif ticari araçlar, şehirlerdeki mal ve yolcu taşımacılığının önemli bir parçasıdır. Uluslararası kuruluşlar tarafından yayınlanan çalışmalara göre AB-27 + İngiltere ülkelerinde hafif ticari araçların pazar payı 2020 yılı için 1,63 milyon araç ile %12 olarak raporlanmıştır. LCV'ler, Avrupa ülkelerinde, özellikle faaliyete geçtikleri ilk üç yılda, yıllık yaklaşık 34 bin km'lik bir kilometreye karşılık gelen yüksek bir yıllık kilometreye sahiptir. Türkiye pazarında ise 2019 yılında ortalama minibüs ve kamyonetlerin ortalama kilometreleri sırasıyla 24.636 ve 16.562 km'dir. Bu bilgiler, LCV'lerin bu ülkelerin ekonomisindeki önemini vurgulamaktadır. Ek olarak, hafif ticari araçların yıllık kilometre performansı, yüksek yıllık yakıt tüketimi ve sera gazlarının yayılması potansiyelini gösterir. Bu nedenle, LCV'lerin elektrifikasyonu, yakıt tüketimini en aza indirmek ve küresel ısınma ve iklim değişikliği üzerinde yüksek etkisi olan CO2 üretimini sınırlamak için kritik öneme sahiptir.

Hem içten yanmalı motorun hem de elektrikli güç aktarma sisteminin avantajlarından yararlanmak için verimli enerji tüketimine sahip bir hibrit LCV tasarlamak hayati önem taşıyor. Hibrit elektrikli araçlarda (HEV), ana taşıyıcılar, içten yanmalı motor ve elektrik motoru arasındaki verimli güç dağıtımı, toplam yakıt tüketimini ve CO2 emisyonlarını azaltmak için enerji yönetimi stratejisinde önemli bir rol oynar. Elektrik motoru, içten yanmalı motorun çalışmasının verimli olmadığı noktalarda çalışabilir. Bu çalışma noktaları, iletilen tork optimum tork çizgisinden uzakta olduğunda belirlenir. Ayrıca elektrik motoru, aracın çekişini ve hızlanmasını artırmak için içten yanmalı motor çalışırken ek tork sağlayabilir.

Öte yandan, elektrik motorunun döngüde olması verimli olmadığında, elektrik motorunun çalışması enerji yönetimi kontrolörü tarafından göz ardı edilir. Bu durumlarda yalnızca içten yanmalı motor gerekli torku sağlar. Hibrit elektrikli araçların bir diğer faydası da rejeneratif fren sisteminin frenleme sırasında aracın kinetik enerjisini geri kazanabilmesidir.

Bu çalışmada, Hafif Ticari Ticari Araç (LCV) hibridizasyonu değerlendirilmektedir. Hedef araç, 1400 dev/dak ile 2400 dev/dak arasında değişen motor devirlerinde 3800 dev/dak'da 125 kW maksimum güce ve 360 Nm maksimum torka sahip dört silindirli dizel motora sahip Mercedes-Benz Sprinter'dir. Brüt araç ağırlığı 3500 kg'dır.

Bu çalışmanın ilk bölümünde, dizel motorlu baz aracın AVL Cruise Yazılımı kullanılarak modellenmesi ve simülasyonu yapılmıştır. Gerekli tasarım ve motor performans verileri Mercedes-Benz Sprinter tip onay belgelerinden elde edilir. Dizel motorun ayrıntılı yakıt haritası, EPA'nın talimat belgelerine dayanılarak oluşturulmuştur. Araç modeli, AVL Cruise Yazılımı kullanılarak simüle edilir ve WLTC Sınıf-3b test döngüsünde toplam 9,6 L/100 km yakıt tüketimine ulaşılır. Elde edilen yakıt tüketimi, tip onay belgesinde belirtilen hedef aracın yakıt tüketimi ile

aynıdır. Çalışmanın bu kısmı, yakıt ekonomisini iyileştirmek ve CO2 emisyonlarını sınırlamak için hedef aracın hibridizasyonunun etkinliğini karşılaştırmak için temel olacaktır. Ana karşılaştırma kriteri olan yakıt tüketimine ek olarak, hedef aracın maksimum tırmanabilirliği, araç tam yüklüyken son olarak %23,5 olan AVL Cruise Simulation yazılımında değerlendirilir.

Ayrıca, AVL Cruise Simulation yazılımı, içten yanmalı bir motora sahip LCV'nin nihai araç hızını araştırır. Simülasyon sonuçları, temel aracın beşinci viteste maksimum 158,6 km/s hıza sahip olduğunu ortaya koymaktadır. Yakıt tüketimi ve CO2 emisyonunun yanı sıra ek bir kısıtlama olarak, tasarlanan hibrit LCV, sırasıyla %23,5 ve 158,6 km/s olan tırmanabilirlik ve nihai hız hedeflerini karşılamalıdır.

Bu çalışmada, literatürde P2 ve P4 olarak bilinen iki farklı hibrit konfigürasyonda hedeflenen hafif ticari aracın toplam yakıt tüketimini analiz etmek için AVL Cruise Yazılımı ve MATLAB R2021b kullanılmıştır. P2 konfigürasyonunda, içten yanmalı motor ve elektrikli makine, ortak bir altı vitesli şanzıman aracılığıyla ön aksa bağlanır. Buna karşılık, P4 konfigürasyonunda, içten yanmalı motor, ön aksı altı vitesli bir şanzıman aracılığıyla tahrik ediyor. Yine de elektrikli makine, iki vitesli küçük bir şanzıman aracılığıyla arka aksa bağlıdır.

Dört silindirli dizel motor, üç silindirli bir motora indirgenmiştir. Küçültme prosedüründe, motorun performansı tüm motor devir ve torklarında %25 oranında azaltılır. P2 ve P4 modelleri, AVL Cruise'da üretilmiştir ve sürdürülebilir bir şarj stratejisinde WLTC Class-3b'de simüle edilmiştir. Simülasyon sonucu, dört silindirli dizel motorlu temel araca kıyasla P2 konfigürasyonu kullanılarak yakıt tüketiminin %17,7 oranında iyileştirilebileceğini göstermektedir. P2 tasarımının WLTC Class-3b test döngüsündeki toplam yakıt tüketimi, 9,60 L/100km olan temel araca kıyasla 7,90 L/100km'ye düşürüldü. Ayrıca dört silindirli dizel motora sahip temel aracın CO2 emisyonu, P2 aktarma organı konfigürasyonuna sahip hibrit araçta 252 g/km'den 207 g/km'ye düşürülmüştür. Buna karşılık, P4 tasarımı, geleneksel bir aktarma organına (ICE) sahip temel araca kıyasla, sürdürülebilir bir şarj WLTC Sınıf-3b testinde yakıt ekonomisinde yalnızca %15,6'lık bir iyileşme sağlar. WLTC Sınıf-3b test döngüsündeki P4 tasarımının toplam yakıt tüketimi, CO2 emisyonu 213 g/km ile 8,10 L/100km'dir.

Ek olarak, hem P2 hem de P4 konfigürasyonu, maksimum tırmanabilirlik ve en yüksek hız kısıtlamalarını karşılar. P2 tasarımının maksimum derecelendirilebilirliği %58'e ulaştı. Buna karşılık, P4 tasarımının maksimum derecelendirilebilirliği %60'tır. Ayrıca, P2 tasarımının maksimum araç hızı 160 km/s'ye ulaşırken, P4 tasarımı için 159 km/s'dir. Yakıt ekonomisi ve CO2 emisyonunun azaltılması bu çalışmanın birincil amacı olduğundan, bu çalışmanın devamı için P2 hibrit konfigürasyonunun temel hibrit tasarım olmasına karar verilmiştir.

Tasarlanan P2 hibrit konfigürasyonu, beş farklı çalışma modundan oluşmaktadır. eDrive modunda, sürücü tarafından talep edilen tork, yalnızca elektrikli makine tarafından sürüş modunda (elektrik motoru olarak adlandırılır) sağlanır. Talep edilen torkun sadece içten yanmalı motor tarafından sağlandığı moda cDrive denir. Araç frenleme kursu iki adımdan oluşur. İlk önce, fren pedalına basıldığında, elektrik makinesi, aküyü şarj etmek için elektrik üretmek üzere aracın kinetik enerjisini geri kazanmak için üretim modunda (jeneratör olarak adlandırılır) etkinleştirilir. Bu mod daha sonra eBrake olarak adlandırılır. Fren torku, jeneratörün rejenerasyon torku sınırını aştığında, geleneksel fren sistemi devreye girer. Bu mod, mekanik fren anlamına gelen mBrake olarak adlandırılmıştır. Kontrolör akünün şarj edilmesini talep ettiğinde içten yanmalı motor çalışırken ve aracı sürerken jeneratör devreye girer. Sürücü torkunu karşılamak için içten yanmalı motor, bir kısmı elektrik üretimi için jeneratörün tedarikçisi olan daha fazla tork sağlamalıdır. Bu moda, yük noktası hareketi anlamına gelen eLPM adı verilir.

Son olarak, eBoost modu, sürücünün talep ettiği torku sağlamak için hem içten yanmalı motor hem de elektrik motoru aynı anda çalıştığında hibrit bir aracın çalışma modudur. Elektrik motoru, sürücü tarafından talep edilen torkun bir kısmını sağlar ve kalan tork, içten yanmalı motor tarafından sağlanır. Tork tahsisi bölümü, güç bölme oranı adı verilen önceden tanımlanmış bir orana göre yapılır. Güç bölme oranı, elektrik motorunun torkunun, sürücünün toplam talep edilen torkuna oranıdır. eBoost modu, hibrit bir elektrikli aracın tam olarak dikkate alınması gereken en zorlu çalışma modudur.

İçten yanmalı motor ile elektrik motoru arasında optimum bir güç bölme oranı bulmak için P2 konfigürasyonu üzerinde araştırmalara devam edilmektedir. WLTC Sınıf-3b test döngüsünde farklı güç bölme oranlarına sahip kapsamlı simülasyonlardan sonra, WLTC'nin her hız fazı için belirli bir güç bölme oranının en verimli yakıt ekonomisiyle sonuçlandığı ortaya çıkar. Ek olarak, pil maksimum deşarj gücünün etkisini değerlendirmek için yapılan kapsamlı araştırma, pil deşarj gücünün farklı WLTC aşamalarında belirli seviyelerle sınırlandırılmasıyla yakıt tüketiminin daha da iyileştirilebileceğini gösterdi. Bu nedenle, çalışmanın bu bölümündeki son simülasyon için WLTC Sınıf-3b test döngüsünün her bir hız fazı için yeterli bir çift güç bölme oranı ve pil maksimum deşarj gücü tanımlanmıştır.

Simülasyon sonucu, belirli bir izin verilen maksimum akü deşarj gücü kapasitesiyle eşleştirilmiş belirli bir güç bölme oranı tahsis edilerek, yakıt ekonomisinin daha da iyileştirildiğini ve CO2 emisyonunun azaldığını ortaya koydu. Çalışmanın bu kısmı, bu hususlar olmadan P2 konfigürasyonuna kıyasla, sürdürülebilir bir şarj WLTC Sınıf-3b testinde aracın genel yakıt tüketiminde %5.1'lik ek bir iyileşme olduğunu göstermektedir. P2 hibrit konfigürasyonunun toplam yakıt tüketimi 7,50 L/100km'dir.

Bu çalışmanın bir sonraki bölümünde, araştırma, V2V, V2I, ITS ve GPS iletişimi yoluyla elde edilen çevrimiçi trafik verilerinin, P2 hibrit hafif ticari taşıtın enerji yönetim stratejisine dahil edilerek verimli bir hibrit modun belirlenmesine odaklanmaktadır. aracın mevcut çalışması. Başka bir deyişle, P2 hibrit aracın mevcut hibrit modu, gelecekteki zaman dilimindeki trafik durumuna göre tanımlanıyor. 60 saniyelik bir gelecek bölgesi tanımlanır ve bu bölgedeki gelecekteki trafiğin hızı ve ivmesi değerlendirilir. Gelecekteki trafik sıkışıklığı, anlık hız, anlık hızlanma ve pilin mevcut SOC düzeyine dayalı olarak P2 hibrit aracın mevcut çalışması için en verimli hibrit modunu seçmek için bir algoritma geliştirilmiştir. Sürdürülebilir şarjlı WLTC Sınıf-3b testinde P2 hibrit aracın simülasyonu, bu algoritmanın uygulanmadığı modele kıyasla yakıt ekonomisinin %2,7 oranında iyileştirildiğini göstermektedir.

Bu çalışmanın son bölümünde, optimum hız yörünge fonksiyonu kullanılmış ve sürücüye eko-sürüş prosedürü hakkında talimat verilmiştir. 60 saniyelik tahmin ufkunda dalgalanan hız, polinom sırası üç olan Savitzky-Golay filtresi kullanılarak işlenir ve yumuşatılır. Sürücünün mümkün olduğunca verimli bir sürüş hızını korumasını öneren bir hız yörüngesi oluşturulur. Sonuç, sürdürülebilir şarjlı WLTC Sınıf-3b testinde yakıt verimliliğinde %6,1'lik ek bir iyileştirme elde edildiğini gösterdi. Bu çalışmanın sonunda, tüm çözümler bir araya getirilerek, P2 hibrit aracın toplam yakıt tüketimi 7,04 L/100km'ye ulaşarak, dört silindirli dizel motorlu temel LCV araca göre %26,7 yakıt tasarrufu sağlıyor.

1. INTRODUCTION

1.1. Environmental Concerns and Vehicle Technologies

This study focuses on improving the fuel consumption of a hybrid electrical light-duty commercial vehicle (LCV), mainly used for the city or intercity goods distribution and passenger transportation. Due to their frequent operation during the day, the fuel consumption and CO_2 emission of the LCVs are essential to be addressed and studied.

In a report published in December 2021 by The International Council on Clean Transportation (ICT, 2021), evaluating the European Vehicle Market Statistics, the market share of LCVs in EU-27 + UK countries has been reported as 12% for the year 2020, accounting for 1.63 million vehicles. The details are shown in Figure 1.1.

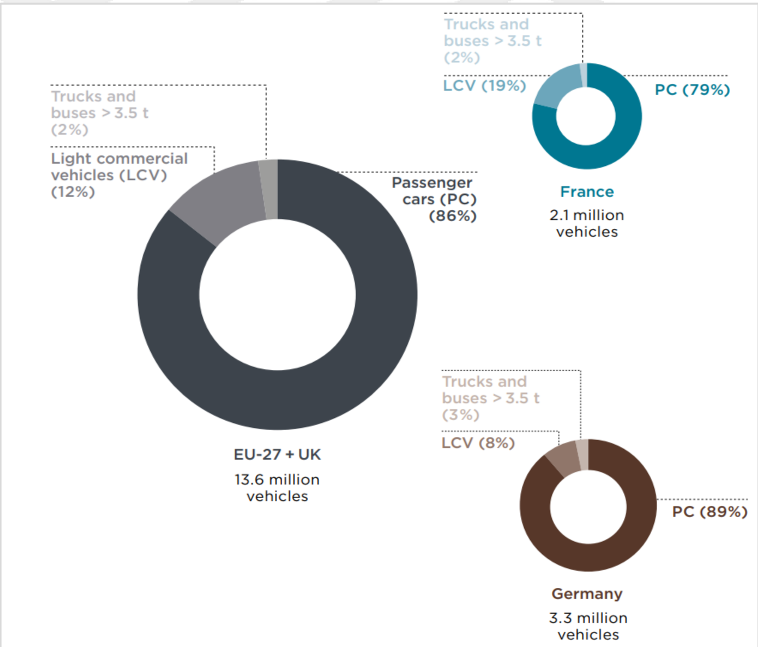

Figure 1.1 : Market shares of passenger cars, light commercial vehicles, trucks, and buses, 2020 **(ICT, 2021)**

A comprehensive report prepared by Ricardo-AEA for European Commission studies the lifetime mileage of all vehicle types. Figure 1.2 from this study shows that LCVs have high annual mileage in European countries, especially in the first three years of their operation, accounting for an annual mileage of about 34 thousand km.

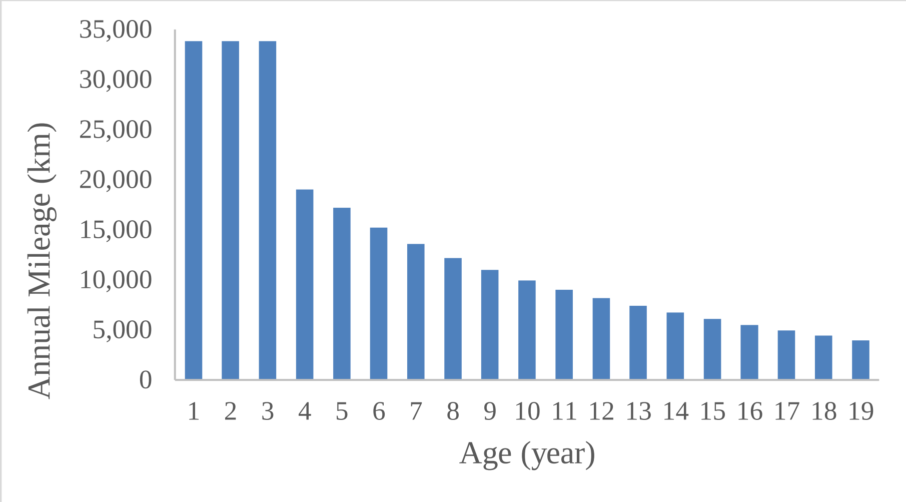

Figure 1.2 : Diesel LCV, annual mileage versus age **(Dun, Horton, & Kollamthodi, 2015)**

Based on the report published by the Turkish Statistical Institute, TUIK, the average mileages of minibuses and small trucks are 24,636 and 16,562 km, respectively, for 2019. (TUIK, 2021) Figure 1.3 shows the average distance traveled by all vehicle types in Turkey for 2018 and 2019.

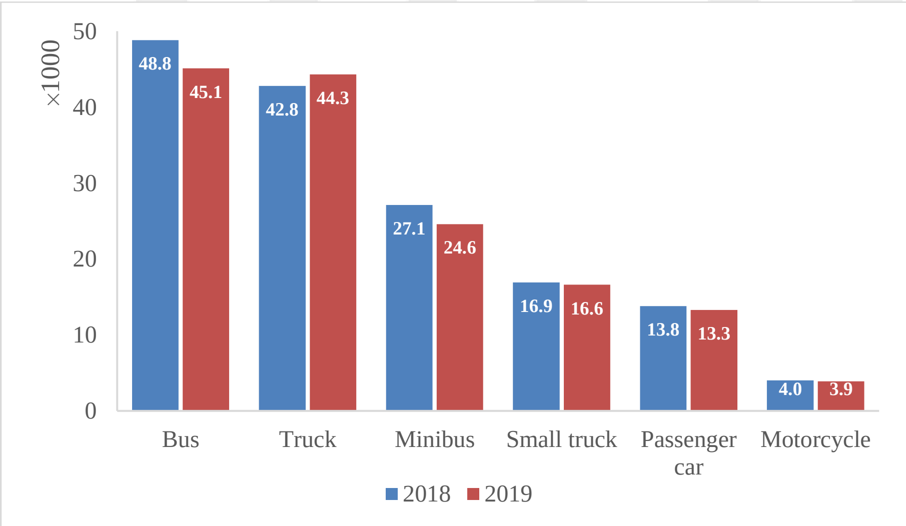

Figure 1.3 : Average distance traveled by vehicle types **(TUIK, 2021)**

The above-presented figures and information verify the importance of studying alternative powertrain solutions for LCVs due to their considerable contribution to road traffic. Due to the nature of the LCV applications and the necessity of high payload for transportation, hybrid electric light commercial vehicles (LHCV) have sensible potential to reduce emissions and improve the fuel economy while maintaining a sufficient payload capacity.

The regulatory institutions are increasingly restricting the value of the CO_2 emitted by LCVs. The report by (Yang & Bandivadeka, 2017) discusses the historic progress in reducing CO_2 emissions in different countries mandated by international standards or national regulations. Figure 1.4 illustrates the advancement of CO_2 emissions reductions in different regions from 2000 to the forecast for the year 2025. For instance, in the US, as the pioneer in regulating the CO_2 emission of LCVs, the NEDC normalized value of CO_2 has been regulated to be reduced from 280 g/km in 2000 to 140 g/km by 2025.

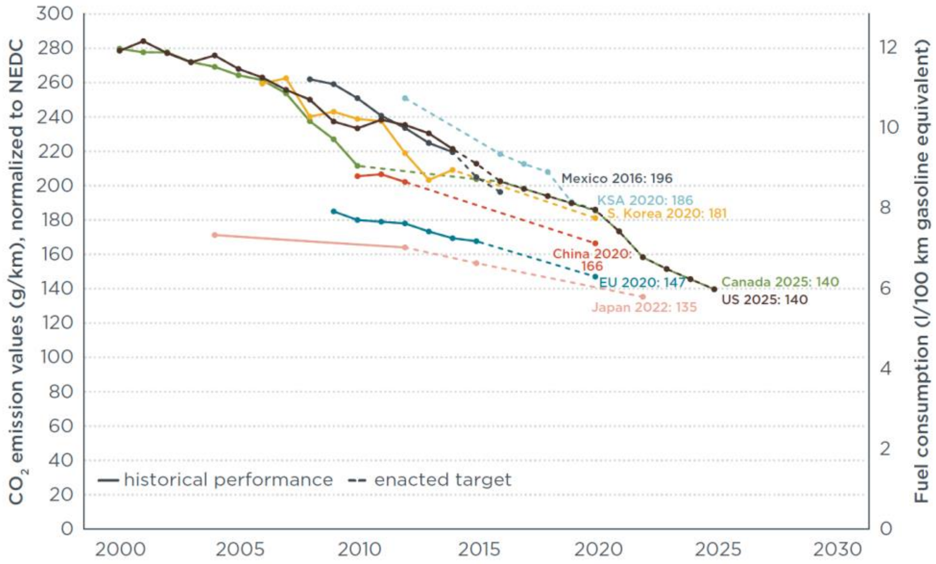

Figure 1.4 : Historical fleet CO_2 emissions performance (g CO_2 /km normalized to NEDC) for LCVs **(Yang & Bandivadeka, 2017)**

In addition, the same report discusses the improvement of the fuel economy of the LCVs through legislative requirements, clearly demanding more efficient vehicles. In Figure 1.5, the development of fuel economy improvement in different countries is depicted. For instance, the US has regulated fuel economy to be improved to 41 mpg by 2025 from 22 mpg in 2000.

Both CO_2 and fuel economy legislations are the main technology-driver to enforce continuous improvement in vehicle’s propulsion systems. Therefore, those targets are achievable solely through innovative engineering solutions using renewable energy sources or hybrid and electric vehicles.

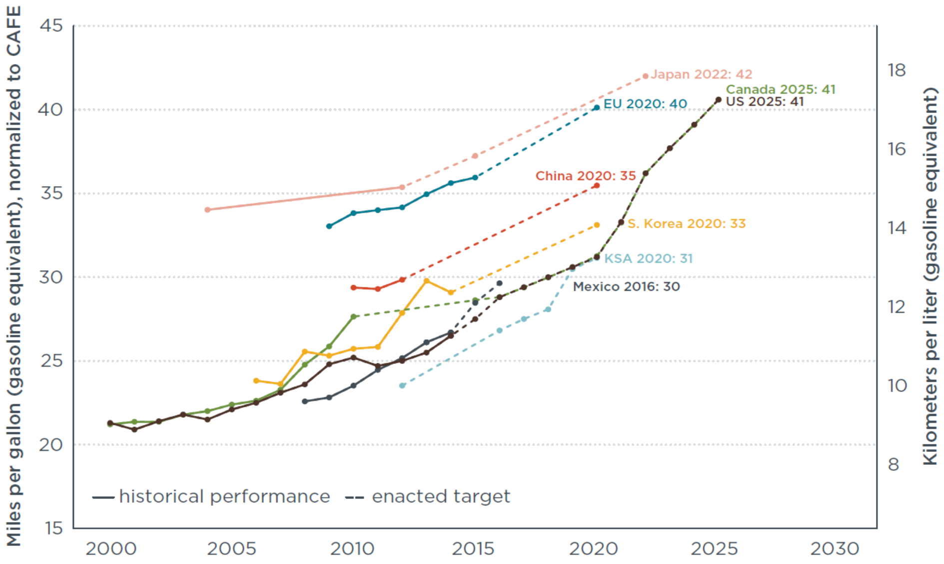

Figure 1.5 : Historical LCVs' fuel economy performance mpg (gasoline equivalent), normalized to CAFE **(Yang & Bandivadeka, 2017)**

1.2. Hybrid Electrical Vehicles

Hybrid electrical vehicles (HEVs) benefit from hydrocarbon fuel's chemical energy and the electrochemical energy of an electrical battery storage system. In these vehicles, as the primary power source, an internal combustion engine (ICE) converts the chemical energy of the fuel to mechanical energy. In addition, an electrical motor (EM) uses the electrochemical energy of the battery to move the vehicle either in a full electric mode where ICE operation is inefficient or by providing additional power to support ICE in acceleration. Moreover, the EM operates as a kinetic energy recuperator during braking and deceleration courses. The advantage of the high energy density of ICE and the privilege of local zero-emission of the electric vehicles (EV) are collected in HEV. Still, the vehicle's overall weight can be increased by about 10-30% based on the vehicle category. (Husted, 2003) By efficient power distribution, the operation of ICE in its low efficient modes can be disregarded by using the electric mode at any driving instant.

Based on the arrangement of ICE and EM, the HEVs are identified into three distinct types known as parallel hybrid (PHEV), series hybrid (SHEV), and combined hybrid (CHEV). In PHEV, ICE and EM have a common mechanical link to the drive axle. In SHEV, ICE has no direct interaction with the drive system and solely provides power to EM for generating electricity either for charging the battery or feeding another EM to move the vehicle. CHEV is a combination of these two main categories. (Guzzella & Sciarretta, 2013), (Lackner, Winter, & Agarwal, 2010)

Comparative studies (Singh, Bansal, & Singh, 2019) and (Butler, Ehsani, & Kamath, 1999) show that PHEVs demonstrate better emission and fuel consumption performance measured in different driving cycles despite having more complexity in the control structure. For this study, the application of a PHEV configuration has been considered in a light-duty commercial vehicle (LCV) to evaluate the effectiveness of either P2 or P4 arrangements. In the P2 design, ICE and EM are connected to the front-drive axle through a conventional gearbox with EM on the input shaft. In contrast, in the P4, also called a robust hybrid, ICE is only connected to the front axle, and EM is connected to the rear axle. Figures 1.6 and 1.7 illustrate the details of these two powertrain setups.

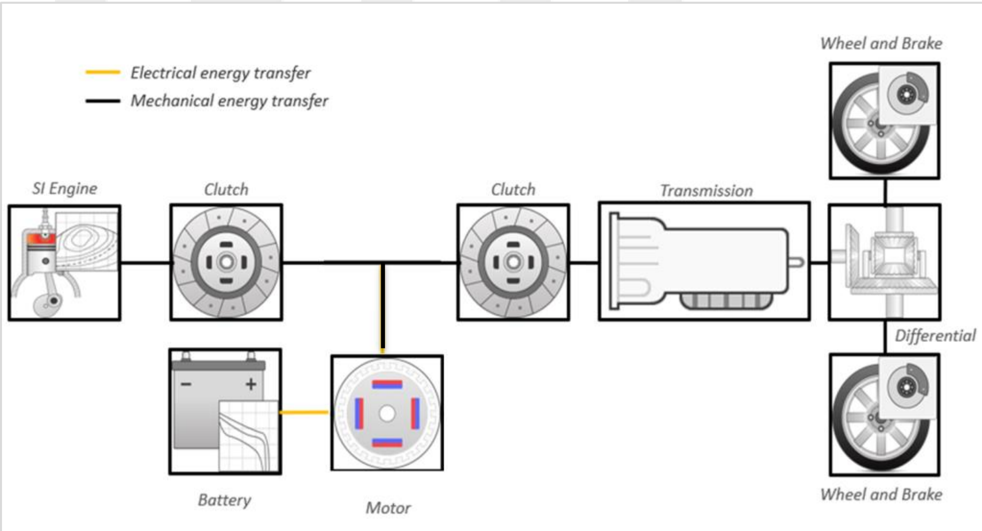

Figure 1.6 : Layout of P2 hybrid electric vehicle (HEVP2) **(MATLAB, n.d.)**

Efficient power distribution and energy management between the power sources are inevitable to get the most out of the HEVs. To this end, the energy management system (EMS) controller provides a control vector – $u(t)$ – with a dimension the same as the number of degrees of freedom of the entire energy flow. In PHEV, the control input is not a vector. Still, a scaler is mainly defined as the ratio of EM power to the total demanded power, called the power-split ratio, as delineated in Equation 1. (Jeon, Jo, Park, Lee, & Dyn, 2002)

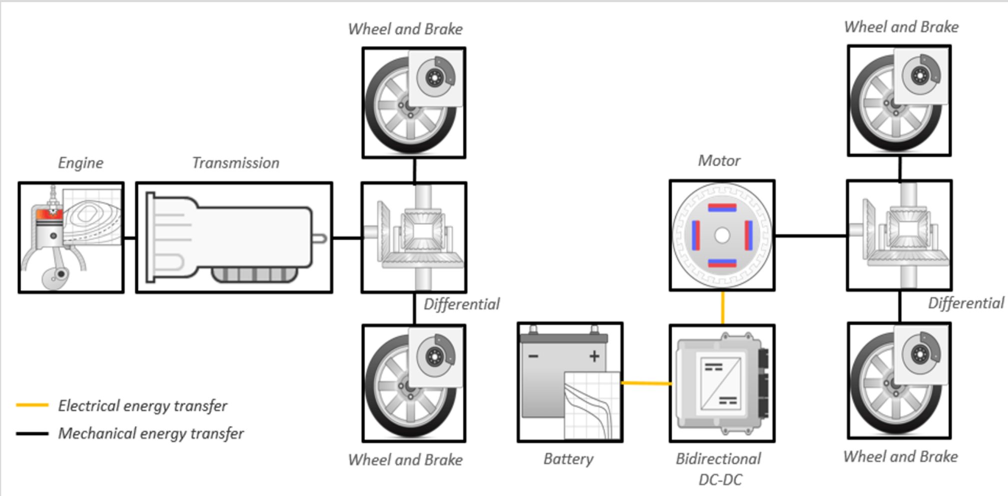

Figure 1.7 : Layout of P4 hybrid electric vehicle (HEVP4) **(MATLAB, n.d.)**

$$u(t) = \frac{P_{em}(t)}{P_{dem}(t)} \quad (1)$$

The primary system constraint is given by Equation 2, which must be fulfilled at all times.

$$P_{dem}(t) = P_{em}(t) + P_{ice}(t) \quad (2)$$

Where $P_{dem}(t)$ is the driver demanded power, $P_{em}(t)$ is the EM power, and $P_{ice}(t)$ is the ICE power at any given time (t). Since the main focus of the HEV energy management strategy is to minimize the overall fuel consumption and CO_2 emission, the only state variable is the battery state of charge (SOC). (Sciarretta & Guzzella, 2007)

In (Guzzella & Sciarretta, 2013), Equation 2 is also known as the degree of hybridization (DOH), and for a full hybrid HEV, DOH is about 50%. DOH has a direct relationship with battery capacity. With lower battery capacity, DOH is also less, while by increasing the battery capacity, DOH (power split ratio) is also increased. In the first part of this study, DOH is considered 50%.

A comprehensive study (Tran, Akinsanya, Panchal, Fraser, & Fowle, 2021) compared five different HEV designs with predefined vehicle performances and energy consumption targets. It revealed that only the P4 HEV powertrain design could satisfy the requirements, hence being the efficient design. In the P4 HEV configuration, the conventional powertrain system is connected to the front axle, while EM is connected to the rear axle. There is no mechanical link between the front and rear axles.

The ultimate goal of this study is to design efficient energy management for the target HEV in traffic. Therefore, the literature review has been done according to this goal. In (Xiuzheng, Liguo, & Kholodov , 2020), a study has been conducted to avoid the downfall of the engine idling at the red light. Therefore, the traffic light state and timing are communicated with the vehicle through a cellular network, advising the driver to arrive at a traffic light when it is green. As a result, a 9.5% improvement in fuel economy is achieved. In another study (Huang, Ng, Zhou, & Surawski, 2018), through V2I communication, improved driving performance has been proposed using the traffic light state and timing to optimize vehicle velocity, potentially improving fuel economy by 60%. In a V2V communication, (Li, Wang, & Song, 2017) have shown that by following the preceding vehicle and velocity optimization of the subject vehicle, a 5% fuel economy improvement is achieved.

In a workshop conducted by the US Department of Energy, it was presented that the potential fuel economy can be over 30% in a simultaneous vehicle and powertrain control optimization. (Atkinson, 2015) Through a fuzzy EMS (Rajagopalan & Washington, 2002), based on the average velocity and slope information of the future road by GPS communication in a time frame of 150s and 300s, the hybrid mode of the current vehicle driving state is decided based on the current SOC level, to either use the battery or save it for future heavier traffic. The fuel-saving is reported as 8.2%. In a similar study by (Kim, Park, Cha, Kim, & Kim, 2009), using GPS communication by DP (Dynamic Programming) algorithm for EMS, a fuel-saving of about 4.5% is achieved.

In (van Keulen, Jager, & Foster, 2010), the designed controller computes the optimal velocity trajectory using online geographical information and vehicle load data, allowing the driver to choose between travel time and fuel consumption. The designed controller could result in a 5% fuel saving. (Saikong, 2019) has evaluated two distinct algorithms, one for investigation of the optimal velocity trajectory and the other one for the analysis of the optimal EMS. This research shows that a 21% saving in energy consumption is achievable.

To obtain minimum fuel consumption (Rabinowitz, Araghi, Gaikwad, & Asher, 2021), velocity has been used as a degree of freedom and HEV power-split and gear shifting in a predictive EMS to optimize the velocity trajectory using dynamic programming. The results reveal 6.8% fuel saving with a negligible increase in travel time. Using a dynamic programming algorithm and GPS information, (Hellstrom, Ivarsson, Åslund, & Nielsen, 2009) have designed a controller for a heavy truck to optimize the velocity trajectory while considering the travel time and overall fuel consumption, a 3.5% fuel saving is achieved without affecting the trip time.

Nonetheless, there are some missing points in the reviewed literature. Firstly, in the literature, it is generally assumed that the power split ratio between the ICE and EM is fixed for the entire test cycle or real-driving test. The author is motivated to evaluate the influence of a variable power split ratio between the ICE and EM on the energy consumption of the HEV. The evaluation framework is based on implementing several simulations of the HEV model with different power split ratios based on the vehicle velocity and acceleration and concluding on the best setup.

Secondly, in most studies, it is assumed that the size of the battery is big enough to deliver the required power to the HEV powertrain, meaning that there is no restriction on the electric power discharge of the battery. Therefore, in this study, the validity of this assumption is also being evaluated by implementing several simulations with different battery discharge power based on the vehicle velocity and acceleration. This evaluation aims to determine if constraining the battery discharge power based on some conditions can avoid inefficient battery discharge and improve energy efficiency.

Last but not least, designing an efficient HEV powertrain controller has been studied a lot, and many solutions and methods have been proposed. However, the optimum velocity trajectory is out of the main focus somehow. Therefore, in this study, it is intended to evaluate the influence of very fluctuating vehicle velocities on the energy consumption of the HEV and design a controller to analyze the future traffic data for generating an optimum velocity trajectory along with choosing the efficient hybrid mode for the vehicle operation, and finally resulting in better energy management.

To proceed with this study, a straightforward procedure is set up. In the first part, a model of the target conventional vehicle, ICEV4, is created in the AVL Cruise simulation tool to determine the fuel consumption, maximum vehicle velocity, and the maximum gradeability of the vehicle. The constraint is that the results should comply with the type-approval documentation of the target vehicle. The objective of this part of the study is to have specific data available from the target vehicle to be the basis for evaluating the effectiveness of the solutions and methods employed in subsequent steps.

By downsizing the ICE from four cylinders (ICE4) to three cylinders (ICE3) in the second part of the study, the HEV models of the target vehicle are created in AVL Cruise to implement a sustainable charge simulation of the models and determine the potential fuel saving. Two distinct configurations are modeled. P2 (HEVP2), in which both EM and ICE are connected to the same gearbox on the front axle. In contrast, P4 (HEVP4), in which ICE is connected to the gearbox on the front axle and EM is connected to the rear axle without having any mechanical link to the front axle. These HEV models' maximum velocity and gradeability should be at least the same as the base vehicle, ICEV4. The vehicle dynamic model should be built up in such a way to fully describe the entire vehicle performance in terms of driver, tire, road interaction, and the other critical dynamic behaviors. It is essential to mention that only the longitudinal vehicle dynamic is considered during the entire study. This part of the study aims to conclude with the most efficient HEV configuration for the target vehicle and continue the succeeding parts of the study using that configuration.

The study is continued in the third part by investigating the influence of a variable power split ratio between ICE and EM on the overall fuel economy of the HEV model in different velocity phases of the WLTC Class-3b. Furthermore, the maximum discharge power of the battery is investigated in conjunction with the power split ratio to assess the correlation between these two parameters and their integrated influence on the energy consumption of the premier HEV configuration. The outcomes of this part of the study are intended to enhance and calibrate the selected HEV model, which will be used in the forthcoming part of the study.

In the final part of the study, it is assumed that the traffic velocity information is available. An algorithm is designed to evaluate this future velocity data in a preset horizon to know whether the traffic ahead is congested or not. The controller checks the battery SOC for congested future traffic to ensure enough electric energy is available during traffic congestion and avoid ICE operation. Force charging is activated if the battery SOC is not within the defined limit. In addition, if the velocity in the prediction horizon is very fluctuating, Savitzky-Golay smoothening function uses that velocity information to design an optimized velocity trajectory avoiding unnecessary acceleration and deceleration, which influence the energy consumption of the HEV.

The four steps explained above are the essence of this study to address the importance of those missing points of the literature and propose considering them as necessary design and calibration parameters in HEVs or battery electric vehicles (BEV). This asseveration will be supported and verified by extensive simulation using the AVL Cruise tool, as discussed in the forthcoming sections.

2. VEHICLE PERFORMANCE ANALYSIS AND ENERGY LOSSES

This study analyzes the longitudinal vehicle dynamics to discuss energy consumption. In addition, the necessary mechanical energy required for the vehicle to follow a given driving cycle is explored.

The basic equation describing the longitudinal vehicle dynamic, corresponding to Figure 2.1, is in the form of Equation 3. In this equation, F_a is the aerodynamic force, F_r the rolling resistance, F_g the grade resistance, F_d the disturbance force representing other non-specified forces, and F_t the traction force which is supplied by the hybrid powertrain. (Guzzella & Sciarretta, 2013)

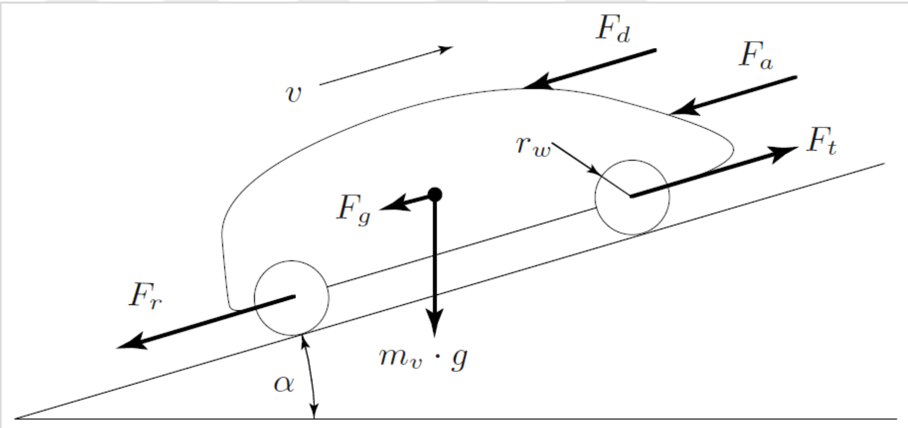

Figure 2.1: Schematic illustration of the forces acting on a moving vehicle **(Guzzella & Sciarretta, 2013)**

$$m_v \frac{d}{dt} v(t) = F_t(t) - \left(F_a(t) + F_r(t) + F_g(t) + F_d(t)\right) \quad (3)$$

The summation of the aerodynamic force, rolling resistance, grade resistance, and other disturbing forces represent the total energy loss of the vehicle in motion, each of which is described by Equations 4, 5, 6, and 7, respectively.

$$F_a(v) = \frac{1}{2} . \rho_a . A_f . C_d . v^2 \quad (4)$$

Where v is the relative vehicle velocity, ρ_a is the air density, A_f is the vehicle frontal area, and C_d is the drag coefficient, a function of vehicle body design.

$$F_r(v, p, \dots) = f_r(v, p, \dots). m_v. g. \cos(\alpha), v > 0 \tag{5}$$

Here, f_r is the rolling resistance coefficient mainly depends on the vehicle velocity, the tire pressure p, and other influencing quantities, m_v is the vehicle mass, and g gravity. The term $\cos(\alpha)$ is due to the road inclination, which is mainly assumed to be unity in the calculations.

$$F_g(\alpha) = m_v. g. \sin(\alpha) \tag{6}$$

In the calculation of gravitational force in Equation 6, for slight inclinations, the term $\sin(\alpha)$ is approximated as α.

The inertial forces from the rotating parts and the entire powertrain from the ICE and EM to the end of the drivetrain at the wheel are another source of power loss. For simplification, longitudinal wheel slip and losses in the drivetrain from the gearbox to the wheel are omitted due to their small contribution to calculation errors. Finally, those inertial forces are described as additional mass named as the equivalent mass, which must be included in m_v on the right side of Equation 3.

$$m_r = \frac{1}{r_w^2}. \mathrm{I}_w + \frac{\gamma^2}{r_w^2}. \lambda_e \tag{7}$$

Where m_r is the equivalent mass of the rotating parts, r_w the wheel radius, I_w the total moment of inertia of the wheels, γ is the gear ratio, and λ_e the total moment of inertia of the rotating parts of the hybrid powertrain.

As for performance and drivability requirements, vehicle top velocity and gradeability have been analyzed in this study. In terms of calculation, by neglecting some unimportant losses, the maximum velocity and gradeability are obtained by solving Equations 8 and 9, respectively.

$$P_{max} = \frac{1}{2}. \rho_a. A_f. C_d. v_{max}^3 \tag{8}$$

$$P_{max} = m_v \, . \, v_{min} \, . \, g \, . \sin(\alpha_{max}) \tag{9}$$

Here, P_{max} is the maximum traction power, v_{max} the maximum vehicle velocity, and α_{max} the maximum gradient.

Since this study is about efficient energy management, the demanded mechanical energy is analyzed. Based on (Guzzella & Sciarretta, 2013), for a straight road profile, the approximated discretized form of the mean traction force in a given test cycle is described in Equation 10. It is essential to know that the mean traction force is subject to traction mode when $F_t > 0$, meaning $i \in trac$ only.

$$\bar{F}_{trac} \approx \frac{1}{x_{tot}} . \sum_{i \in trac} \bar{F}_i \, . \, \bar{v}_i . \, h \tag{10}$$

Where, $v_i = v(t_i), t_i = i.h,$ and $i = 0, \dots, n.$ h is the time step, $\bar{F}_{trac}$ the total mean tractive force, and x_{tot} the total distance of test cycle. $\bar{F}_i$ and $\bar{v}_i$ are calculated by Equation 11 and 12, respectively.

$$\bar{F}_i = \bar{F}_{a,i}(\bar{v}_i) + \bar{F}_{r,i}(\bar{v}_i, \dots) + \bar{F}_{m,i}(\bar{v}_i, \bar{a}_i), \forall t \in [t_{i-1}, t_i] \tag{11}$$

$$\bar{v}_i = \frac{v_i + v_{i-1}}{2}, \bar{a}_i = \frac{v_i - v_{i-1}}{h}, \forall t \in [t_{i-1}, t_i] \tag{12}$$

The acting forces on an HEV are categorized as dissipative forces, like aerodynamic and rolling resistance, which are pure losses, and circulative forces, which can be partially recovered due to their conversion into kinetic and potential energy. Therefore, Equation 10 can be rewritten as a summation of dissipative and circulative forces as Equation 13 (Guzzella & Sciarretta, 2013).

$$\bar{F}_{trac} \approx \frac{1}{x_{tot}} \, . \sum_{i=0}^{n} (\bar{F}_{a,i} + \bar{F}_{r,i}) \, . \, \bar{v}_i \, . \, h + \frac{1}{x_{tot}} \, . \sum_{i \notin trac} - \bar{F}_i \, . \, \bar{v}_i \, . \, h \tag{13}$$

The mean traction energy per distance is described according to Equation 14. Since its unit is $kJ/100\ km$, it can be expressed as $\bar{E} = 100\ .\bar{F}_{trac}$ (Guzzella & Sciarretta, 2013).

$$\bar{E}=\bar{E}_{diss} + \bar{E}_{circ} \tag{14}$$

Where, $\bar{E}_{diss}$ represents the dissipated energy, and $\bar{E}_{circ}$ is the circulated energy. The circulated energy is either kinetic or potential energy, which can be partially recovered through a regenerative braking system or dissipated as heat energy in the friction brake system. As a vital advantage of HEV, the energy consumed to accelerate the vehicle or move it uphill can be partially recuperated during braking.

Last but not least, the average mass of fuel consumption per kilometer is calculated by Equation 15. Here, $\bar{E}_f$ is the average energy consumption per kilometer in the driving test cycle, expressed in Equation 16, and H_l is the lower heating value of the fuel.

$$\bar{m}_f = \frac{\bar{E}_f}{H_l} \tag{15}$$

$$\bar{E}_f = \frac{1}{\eta_g\ .\ \eta_a\ .\ \eta_e}(\bar{E}_{diss} + \bar{E}_{circ}) \tag{16}$$

Where η_g, η_a, and η_e are gearbox efficiency, the efficiency of auxiliary devices, and ICE engine efficiency, respectively.

3. ICE VEHICLE MODEL AND SIMULATION

3.1. Studied Light-Duty Commercial Vehicle

This study focuses on the HEV design of the Mercedes Benz Sprinter with a conventional ICE powertrain, with the specifications provided in Table 3.1. The information has been accessed from the Mercedes Benz Turkey website and Sprinter catalog. Missing data has been calculated based on other available data or estimates. Longitudinal dynamics is the only vehicle dynamic behavior considered in this research; therefore, other inputs are not necessary within the scope of this study.

Table 3.1: Important Parameters of Mercedes Benz Sprinter

Parameter	Value	Unit	Source
Wheelbase	3665	mm	(Benz, 21)
Curb Weight	2310	kg	(Benz, 21)
Gross Vehicle Weight	3500	kg	(Benz, 21)
Frontal Area	4.35	m^2	Calculated
Drag Coefficient	0.36	-	Estimated
Tire	235/65 R16 C	-	(Benz, 21)

This vehicle has a four-cylinder 2143 cc diesel ICE, with a common rail fuel injection system and an emission norm of EURO 6. The engine can deliver a maximum power of 120 kW at 3800 rpm, with a maximum torque of 360 Nm at engine speeds from 1600 rpm to 2400 rpm. The engine's full load engine torque and power are shown in Figure 3.1.

The engine fuel consumption map is not available. The vehicle’s overall fuel consumption in the WLTC Class-3b cycle is 9.60 liter/100 km based on the type-approval documents of the Mercedes Benz Sprinter.

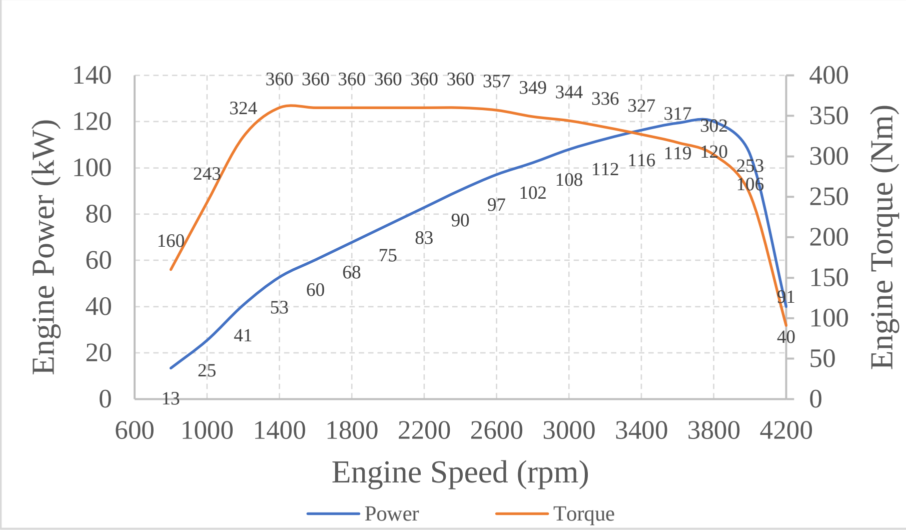

Figure 3.1 : Engine full load torque and power **(Benz Mercedes, 2021)**

3.2. ICE Vehicle Modeling and Simulation in AVL Cruise M

The fuel consumption at the maximum torque of different engine speeds is used to build a generic fuel consumption map to generate the same fuel consumption for the ICEV4 model in the AVL Cruise simulation. This goal is achieved by doing laborious interpolation and simulation work. (EPA, n.d.) The created generic fuel consumption map is shown in Figure 3.2. The most important engine and drivetrain information have been tabulated in Table 3.2.

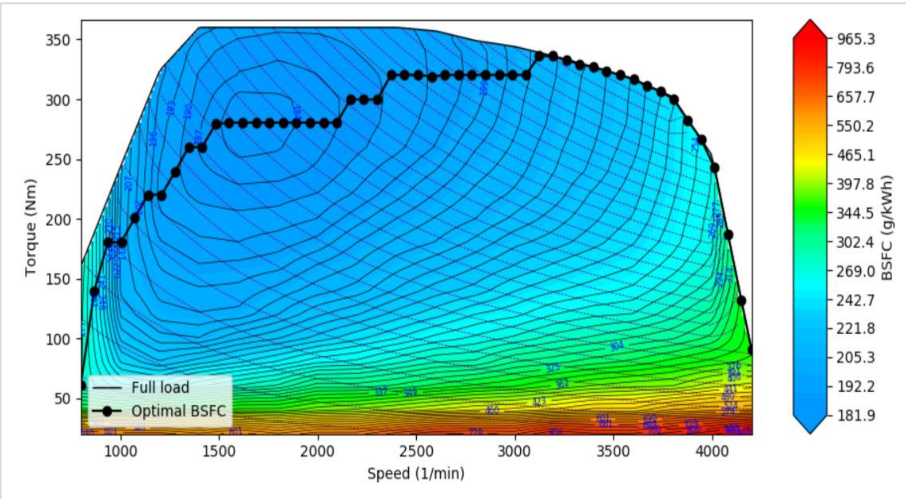

Figure 3.2 : Generic fuel consumption map of ICE4

Table 3.2: Engine and drivetrain data **(Benz, 21)**

Parameter	Value	Unit	Comment
Displacement	2143	cc	
Number of Cylinders	4	-	
Maximum Torque	360	Nm	
Maximum Power	120	kW	
Fuel System	Diesel	-	
Gearbox	Six-speed	-	Ratio (5.08-0.68)
Differential	-	-	3.92

AVL Cruise^{TM} M, a robust multi-disciplinary vehicle system simulation tool, has been used in this study. The available vehicle and engine information, and other calculated, created, and estimated parameters have been used in a model to validate the base vehicle specification for the continuation of the study toward downsizing and hybridization.

The ICE vehicle with a 4-cylinder engine (ICEV4) model has been created in AVL Cruise, illustrated in detail in Figure 3.2. All necessary input has been used in each sub-system block. The shifting procedure is an essential input influencing the vehicle's overall fuel consumption in the WLTC Class-3b cycle. For this purpose, the vehicle traction-velocity relationship is drawn, as shown in Figure 3.3. The gear shifting velocities are extracted at those courses when the engine torque is maximum at that corresponding gear provided in Table 3.3.

Table 3.3: Gear ratios and shifting velocities

Gear	Ratio	Upshifting (m/s)	Downshifting (m/s)	Diff. Ratio	Final Ratio
1	5.08	3.60	2.00	3.92	19.91
2	2.61	6.00	4.00		10.24
3	1.52	9.20	6.50		5.96
4	1	13.90	9.70		3.92
5	0.79	18.10	14.40		3.1
6	0.68	37.00	27.00		2.65

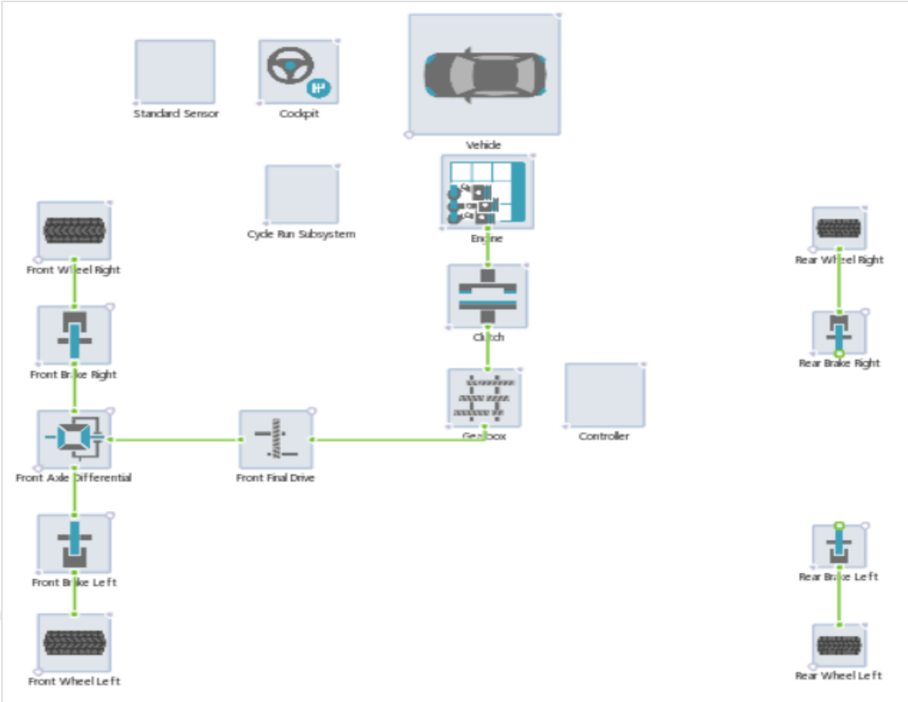

Figure 3.3 : ICEV4 model in AVL Cruise M

In addition, analyzing the traction-velocity graph to understand the ICE vehicle's performance fully, the vehicle's top velocity and maximum gradeability have been extracted. The top velocity is achieved on a straight road with 0% inclination when the vehicle's traction and net resistance forces are equal (Figure 3.4). The total resistance force (F_r) is described by Equation 17 as the summation of aerodynamic force, rolling resistance force, and gradient force. The gravitational force is zero since the top velocity is measured on a mean-level road. The results of these analyses are also written in Table 3.3.

$$\sum F_r = \frac{1}{2}\rho_a \,.\, C_d \,.\, A \,.\, v^2 + f.m.g + m.g.\sin\theta \qquad (17)$$

The ICEV model is simulated by AVL Cruise with a WLTC Class-3b velocity profile (Figure 3.5). The ICEV model fully complies with the velocity profile, and neither deviation nor error occurred during the simulation. The model simulation results are provided in Table 3.4. This information will be the basis for evaluating the performance, fuel consumption, and CO_2 emissions of the hybrid models, which will be discussed in the forthcoming chapters.

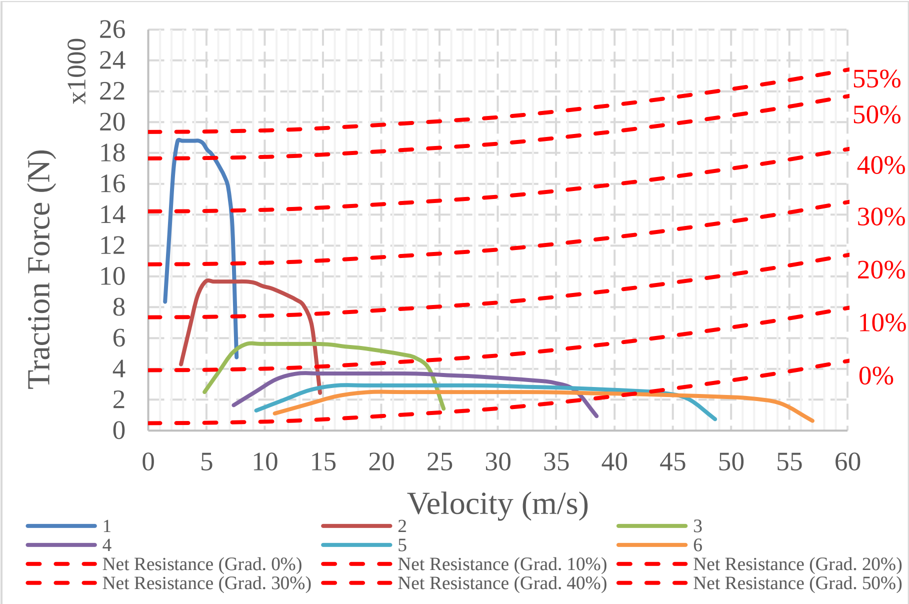

Figure 3.4 : ICEV traction-velocity in different gears and total resistance (x10^3)

It is essential to mention that based on Figure 3.4, the maximum gradeability of the ICE vehicle is expected to be about 54% at the first gear with the vehicle's maximum traction force of 19 kN. However, the model simulation in AVL Cruise revealed that the maximum gradeability could only reach 23.5%. The underlying reason could be that by engaging the clutch, the engine speed starts dropping from the maximum torque speed towards lower speeds where the torque is also lower; therefore, the vehicle model cannot realize a higher gradeability further than 23.5%.

Figure 3.5 : ICEV model simulation and velocity compliance in WLTC Class-3b

In summary, the most crucial part of the simulation results of the ICE model is the vehicle's overall fuel consumption in the WLTC Class-3b test cycle, which has exact compliance with the certified fuel consumption of the target vehicle mentioned in the type-approval document. The fuel consumption is the basis for evaluating the performance of the hybrid models in later chapters. In addition, the ICE vehicle's top velocity and maximum gradeability will also be used to assess the hybrid models.

Table 3.4: Simulation result of ICEV4 model in AVL Cruise over WLTC Class-3b

Parameter	Value	Unit	Comment
Fuel Economy	9.60	l/100 km	
Overall BSFC	247.30	g/kWh	
CO_2 Emission	251.90	gr/km	
Top Velocity	158.60	km/h	In 5th gear with a ratio of 0.791
Gradeability	23.50	%	Loaded with GVW 3500 kg
Gears Shifting	**Upshift**	**Downshift**	
1st Gear	3.6	2.0	Units are m/s
2nd Gear	6.0	4.0	
3rd Gear	9.5	6.5	
4th Gear	14.0	9.7	
5th Gear	18.0	14.5	

4. HEV DESIGN AND SIMULATION

4.1. Benchmark and Target Setting

To design an HEV with reasonable targets and performance, a benchmark is done to collect the design parameters of the existing HEV in the market. Three vehicles from three different OEM manufacturers are considered in this benchmarking, and their essential design parameters are compared and tabulated in Table 4.1. Iveco Eurocargo (IVECO, 2021) is a SHEV and delivers a 30% fuel saving compared to its conventional ICEV counterpart. The fuel-saving of Ford Transit HEV is 15.5% compared to its full ICE version (FORD, 2021). In contrast, the Mercedes Benz eSprinter is a Battery Electric Vehicle (BEV) which delivers a maximum torque of 295 Nm with a battery weight of 990 kg (Benz Mercedes, 2021).

Table 4.1: Comparison of existing HEV and BEV

Parameter	IVECO Eurocargo HEV	FORD Transit	Mercedes Benz eSprinter
ICE	118 kW	90 kW	-
EM	44 kW	30 kW	85 kW
Gearbox	6 Speed	6 Speed	NA
Battery Pack	1.9 kWh	2.4 kWh	47 kWh
Fuel Saving	30%	15.5%	BEV

Benefitting from the benchmark results, the most critical design parameters of the HEV are decided, which are described in Table 4.2. This information is used to build the main structure of the HEV model in the AVL Cruise simulation tool. The HEV is built up in two distinct configurations, P2 with ICE and EM connected to the front axle through a 6-speed gearbox, and P4 with ICE connected to the front axle and EM to the rear axle.

In this study, P4 EHV design is also included for conducting an extensive comparison with P2 HEV design for selecting the most efficient HEV powertrain for the target vehicle and continuing the research towards the energy management strategy analysis.

Table 4.2 : Design target of HEV subject to this study

Parameter	Sprinter ICEV4 Base Vehicle	Sprinter HEV This Study
Engine	Four-cylinder	Three-cylinder
Displacement	2143 cc	1607 cc
Maximum Power	125 kW	88 kW
Maximum Torque	360 Nm	270 Nm
Curb Weight	2310 kg	2500 kg
EM Maximum Power	NA	32 kW
EM Maximum Torque	NA	100 Nm
Electrical Cons.	NA	<=10 kWh/100 km
Battery Capacity	NA	12 kWh

4.2. Hybrid Electrical LCV Design

The ICE is first downsized to a three-cylinder engine. So, a straightforward approach is considered to reduce the engine performance by 25%. No changes are applied to the fuel consumption map, only a 25% reduction in fuel mass flow at engine loads and speeds.

To select the right EM for HEVP2 or HEVP4 design, it is presumed that the total demanded torque from the HEV powertrain equals the total torque produced by the ICE4 engine. Therefore, the ICE4 full load torque is addressed as the maximum demanded torque from the HEV powertrain, which is expected to be satisfied at any required instances.

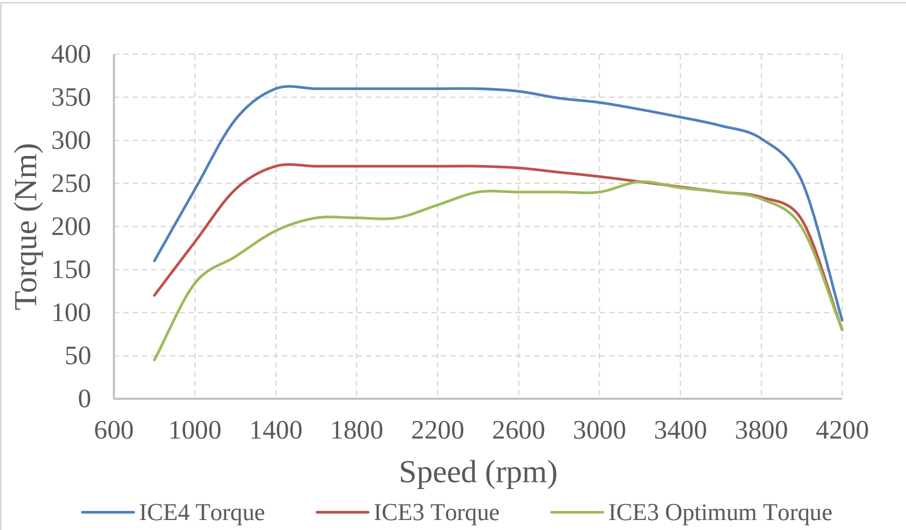

Figure 4.1 : HEVP2 system different torques

In Figure 4.1, the full-load torque of the base four-cylinder engine, ICE4, corresponds to the total demanded torque from the HEV powertrain, and the three-cylinder downsized engine torque ICE3, are depicted. It is worth mentioning that the summation of ICE3 full-load torque and EM full-load torque satisfies the HEV powertrain demanded torque. The optimum torque of the ICE3 is also demonstrated in Figure 4.1. The optimum torque is a crucial parameter in energy management strategy since it matches the engine's minimum BSFC at the given speed. The details of the calculation for selecting the right EM for the HEVP2 powertrain are shown in Table 4.3.

Table 4.3 : Calculation of EM torque for HEVP2

ICE3 Speed (rpm)	Demanded Torque (Nm)	ICE Optimum Torque (Nm)	EM Net Torque (Nm)	EM Efficiency (%)	EM Gross Torque (Nm)
1000	243	134	109	0.89	123
1400	360	195	165	0.92	179
1800	360	210	150	0.91	165
2200	360	225	135	0.90	150
2600	357	240	117	0.88	133
3000	344	240	104	0.87	120
3400	327	245	82	0.85	96
3800	302	232	70	0.83	84
4200	91	80	11	0.81	14

In this table, the demanded torque is the maximum torque to be provided by the HEVP2 powertrain. The difference between required and ICE optimum torque is the maximum net torque to be available at the output shaft of the EM. The EM efficiency has been taken from the data sheet of a Phi271S High-performance Axial Flux Motor from Phi-Power Company. (Phi-Power, 2017) By considering a single drive ratio with the ratio of two on the EM motor output shaft, the details of the EM performance will be known, as shown in Figure 4.2 and Figure 4.3.

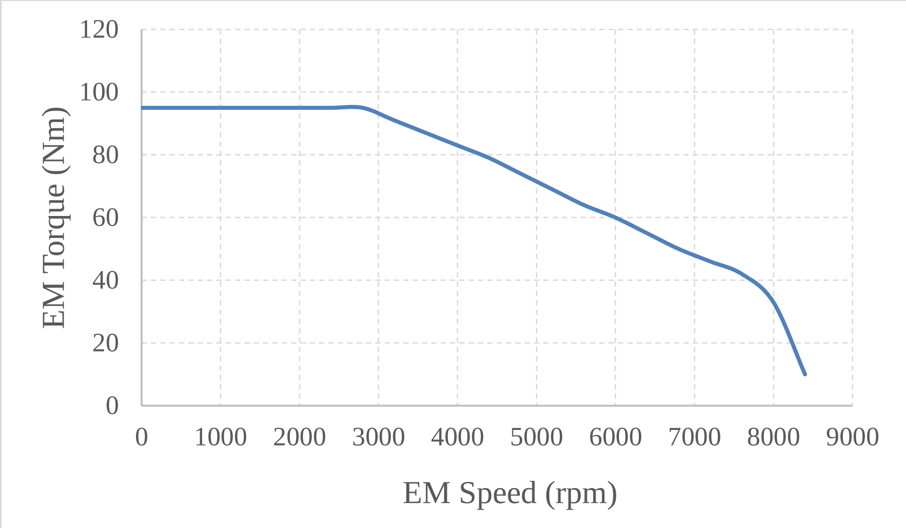

Figure 4.2 : EM full-load torque for HEVP2

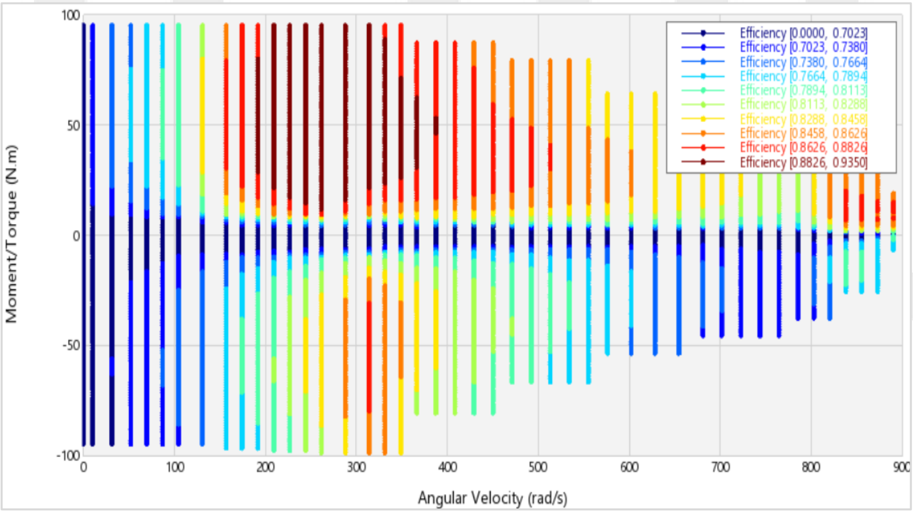

Figure 4.3 : Calculated simulation data for EM efficiency - HEVP2

In HEVP2 design, the EM output shaft is connected to the same gearbox input shaft as ICE3. Hence, the EM output torque is multiplied by the same gear ratios as the ICE3. This facilitates the EM torque amplification between a stepped range of 39.83 at first gear to 5.3 at sixth gear, mentioning that the EM single drive ratio is two and the front axle differential ratio is 3.92. The gear ratios of the HEVP2 drivetrain are provided in Table 4.4. The gearbox and differential gear ratios are carried over from the ICEV4 and taken from the Mercedes Benz Sprinter catalog. (Benz Mercedes, 2021)

Table 4.4: Drivetrain ratios, ICE3, and EM output torque final ratios

EM Drive Ratio	Gear	Ratio	Diff. Ratio	ICE Final Ratio	EM Final Ratio
2	1	5.08	3.92	19.91	39.83
	2	2.61		10.24	20.48
	3	1.52		5.96	11.91
	4	1		3.92	7.85
	5	0.79		3.10	6.21
	6	0.68		2.65	5.3

Before describing the procedure of selecting the appropriate EM performance for HEVP4 configuration, it is vital to emphasize that this study only considers the HEV longitudinal dynamics, meaning that the vehicle is driven on a straight road where differential operation is rarely needed. Controlling vehicle dynamics on the cornering course requires special considerations in torque distribution between ICE and EM longitudinally and between inner and outer wheels laterally. However, since this study focuses on optimum energy management of the HEV, the lateral vehicle dynamics and vehicle cornering motion are not considered.

Despite HEVP2, selecting the right EM for HEVP4 is somewhat different and complicated. The underlying reason is that the EM is directly connected to the rear axle in the HEVP4 design, and the EM torque multiplication by the drivetrain is not identical to the HEVP2. In addition, to avoid wheel slip in longitudinal dynamics originating from different speeds of the front and rear wheels, all wheels should have the same angular velocity when EM is activated on the rear axle in a hybrid mode, and ICE is also engaged on the front axle. Therefore, it can be said that the hybrid modes in which the angular velocity of the front and rear wheels should remain equal are the eBoost and eLPM modes.

In the eBoost mode, the demanded driver torque is provided by ICE and EM simultaneously based on the power-split ratio according to Equation 1 while maintaining the system constraint as per Equation 2. In addition, when the eLPM mode is activated by the hybrid powertrain controller, when a forced charging of the battery is required, the angular velocity of the front and rear wheels should remain equal to avoid wheel slips.

As mentioned earlier, the full-load torque characteristic of ICE4 has been considered as the total demanded torque from the HEV powertrain. The ICE3 torque delivery is limited to its optimum torque level to reach the best possible fuel economy. Therefore, the remaining requested driver torque greater than ICE3 optimum torque is provided by EM according to Equations 18 to 23.

$$\omega_{fw} = \omega_{rw} \tag{18}$$

$$F_{tf} = \frac{T_{ICE3-opt} \cdot \gamma_{tot} \cdot f_{tc}}{r_w} \tag{19}$$

$$F_{dem} = \frac{T_{ICE4} \cdot \gamma_{tot} \cdot f_{tc}}{r_w} \tag{20}$$

$$F_{EM} = F_{dem} - F_{tf} \tag{21}$$

$$T_{EM} = \frac{F_{EM} \cdot r_w}{\gamma_{EM} \cdot f_{tc}} \tag{22}$$

$$\omega_{EM} = \omega_{rw} \cdot \gamma_{EM} \tag{23}$$

Equations 18 to 23 are considered for sizing the required EM of HEVP4. Equation 18 is a constraint for the duration of eBoost and eLPM modes. ω_{fw} and ω_{rw} are the angular velocity of front and rear wheels in a longitudinal motion, respectively, required to be equal to avoid tire slip. Equation 19 describes the traction force of the front axle where F_{tf} is the traction force of the front axle being supplied by ICE3, $T_{ICE3-opt}$ the optimum torque of ICE3, γ_{tot} the total transmission ratio, f_{tc} the traction coefficient, and r_w the tire rolling radii. Equation 20 describes the calculation of the maximum demanded driver torque from the HEV powertrain; here, F_{dem} is the maximum total required traction force, and T_{ICE4} the maximum full-load torque of ICE4, which is considered as the maximum torque needed from HEV powertrain. Equation 21 describes the traction force of the rear axle, F_{EM}, which should be provided by EM. Equation 22 calculates EM torque, T_{EM}, where γ_{EM} is the total transmission ratio from EM to the wheels. Finally, the angular velocity of EM, ω_{EM}, is calculated by Equation 23. Figure 4.4 illustrates the steps for extracting the EM full load torque map according to the above procedure.

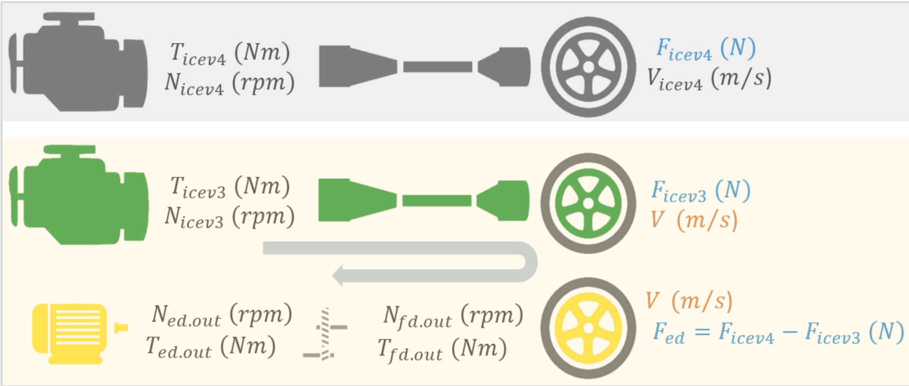

Figure 4.4: EM full-load torque extraction for EM sizing

The worst-case scenario for sizing EM for HEVP4 is when the driver demanded torque exceeds ICE3 optimum torque. In this case, the ICE3 torque is set to optimum torque, and the difference between driver required torque and ICE3 optimum torque is determined as EM torque during eBoost hybrid mode. Therefore, this case has been considered for designing an EM performance map.

For having a clear understanding of the calculation principle, the HEV operation at the first gear and in a specific engine speed is explained as an example. Suppose the base vehicle, ICEV4, with a four-cylinder internal combustion engine, ICE4, is operating at 2000 rpm, and the maximum torque of 360 Nm is required to be delivered by the ICE4 engine. Knowing that the total transmission ratio of the drivetrain at first gear is 19.91, the tyer rolling radii is 0.343 m, and the traction coefficient is 0.9, using Equation 20, the total demanded traction force is calculated as 18,807 N as shown in Equation 24. This is the total traction force that should be supplied by the HEVP4 powertrain as well since it is expected that the HEVP4 should also deliver the same maximum traction force as ICEV4.

$$F_{dem} = \frac{T_{ICE4} \cdot \gamma_{tot} \cdot f_{tc}}{r_w} = \frac{360\ .\ 19.91\ .\ 0.9}{0.343} = 18{,}807\ N \tag{24}$$

The differential output shaft speed is calculated using Equation 25, n_{ice} is the engine speed in rpm. It is essential to mention that the output shaft speed on the front and rear axles should be equal to avoid wheel slip on either axle.

$$\omega_{fw} = \frac{n_{ice}}{\gamma_{tot}} = \frac{2000}{19.91} = 100.5\ rpm \tag{25}$$

The ICE3 engine should partially deliver the calculated traction force of 18,807 N on the front and EM on the rear axle. The summation of traction forces on both axles should equal 18,807. The maximum allowed torque by ICE3 in HEV powertrain is limited to the optimum torque at that given engine speed. The ICE3 optimum torque at 2000 rpm is 210 Nm, as seen in Figure 4.1. By using Equation 26, the maximum traction force on the front axle of HEVP4 is calculated.

$$F_{tf} = \frac{T_{ICE3-opt} \cdot \gamma_{tot} \cdot f_{tc}}{r_w} = \frac{210 \,.\, 19.91 \,.\, 0.9}{0.343} = 10{,}971\ N \tag{26}$$

By subtracting the calculated traction force of the front axle, 10,971 N, from the maximum traction force of ICEV4, 18,807 N, the remaining traction force is calculated by Equation 27, which is the traction force that the EM-driven rear axle should supply.

$$F_{EM} = F_{dem} - F_{tf} = 18{,}807 - 10{,}971 = 7{,}836\ N \tag{27}$$

By knowing the required traction force of the rear axle, the required torque that has to be delivered by EM is calculated by Equation 28.

$$T_{EM} = \frac{F_{EM} \,.\, r_w}{\gamma_{EM} \cdot f_{tc}} = \frac{7{,}836 \,.\, 0.343}{\gamma_{EM} \cdot 0.9} = \frac{2{,}986}{\gamma_{EM}}\ N \tag{28}$$

Maximum vehicle velocity is another constraint in HEV design. The maximum velocity of the base vehicle with an internal combustion engine, ICEV4, is 160 km/h. On the other hand, the maximum shaft speed of the high-performance axial flux electric motor is 12,000 rpm (Phi-Power, 2017). To this end, γ_{EM} should be defined in such a way as o ensure that the required rear wheels' angular speed is achieved for reaching the maximum vehicle velocity target. If γ_{EM} is big, the maximum full-load torque of EM is decreased at the cost of exceeding EM speed beyond the EM speed limit of 12000 rpm. In contrast, if γ_{EM} is small, the required full-load torque of EM is increased, but the maximum EM speed decreases. Therefore, to meet these two requirements simultaneously, a two-speed small gearbox is considered on the rear axle, which is systematically synchronized with the front axle's gearbox during shifting. The defined first gear ratio of the EM gearbox is 5.85, which is activated with the first and second gear of the gearbox on the front axle, and the second ratio of 1.95, which is activated with the third to sixth gears of the front axle gearbox. A differential is also considered for the rear axle with a fixed ratio of five. All the details are tabulated in Table 4.5.

Table 4.5: HEVP4 rear axle transmission ratios

Gear	EM Gearbox Ratio	Diff. Ratio	EM Final Ratio
1	5.84	5.0	29.2
2	5.84		29.2
3	1.95		9.75
4	1.95		9.75
5	1.95		9.75
6	1.95		9.75

Implementing the above-explained procedure for all engine speed and gear ratios of the ICE powertrain on the front axle, the required full-load map of the EM for the rear axle at each gear ratio is obtained as depicted in Figure 4.5. These maps are extracted based on the required maximum traction force on the rear axle. The net delivered torque of EM should be greater or equal to the calculated torque needed at each gear ratio. By applying the EM efficiency at each torque and speed, the gross full-load torque map of the EM is also calculated.

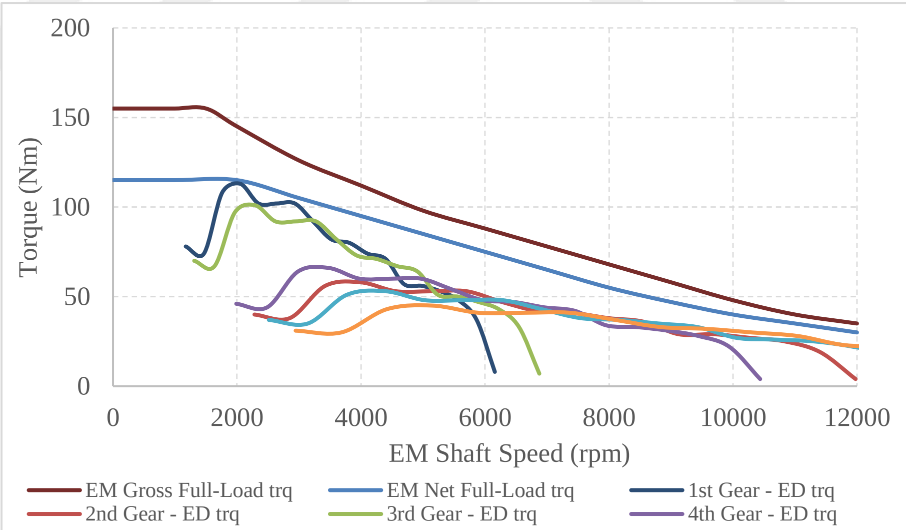

Figure 4.5 : EM Full-Load Torque for HEVP4 Powertrain

The efficiency map of EM for HEVP4 is shown in Figure 4.6. This map is based on the calculated simulation data of the AVL Cruise simulation tool.

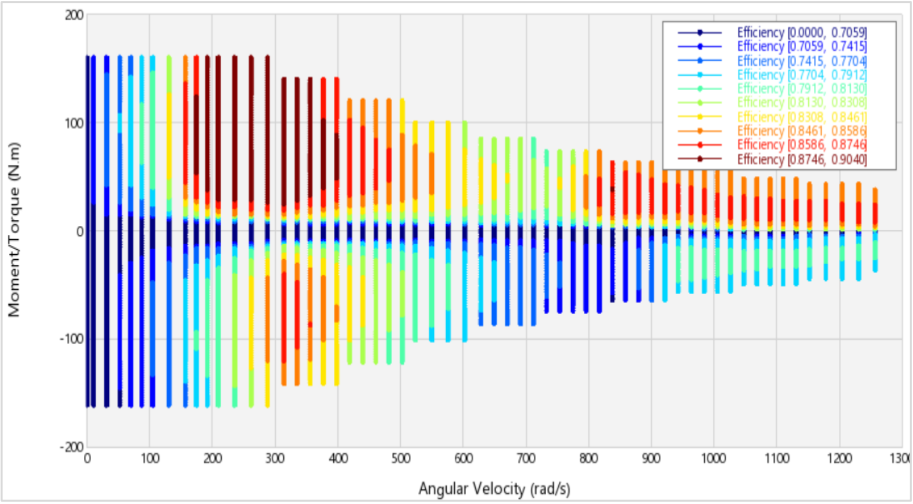

Figure 4.6 : Calculated simulation data of EM for HEVP4

As the outcome of the benchmarking study presented in Table 4.2, the battery capacity is considered as 12 kWh, about 25% of the battery capacity of a BEV Mercedes Benz Sprinter. In (Maruyama, Kono, Sato, Ishizu, & Koseki, 2009), a comprehensive review and road map of batteries for electric vehicles, introduced a lightweight, high-performance battery of the fourth generation from the Hitachi company. Table 4.6 describes the essential specifications of this battery. The fourth-generation battery from Hitachi has an output power density of 4,500 W/kg. (Maruyama, Kono, Sato, Ishizu, & Koseki, 2009)

Table 4.6 : Key specifications and current status of Hitachi battery **(Maruyama, Kono, Sato, Ishizu, & Koseki, 2009)**

	Second Generation	**Third Generation**	**Fourth Generation**
Cathode material	Mn-based	Mn-based	Newly developed Mn-based
Anode material	Amorphous carbon	Amorphous carbon	Amorphous carbon
Capacity (Ah)	5.5	4.4	4.8
Weight (kg)	0.30	0.26	0.24
Cell shape	Cylindrical	Cylindrical	Rectangular
Output density (w/kg)	2,600	3,000	4,500
Status	In production	Readying for production	Under development

A 12-kWh battery pack capacity requires an arrangement of 90 battery cells in series and eight rows in parallel (90S8P), which builds up a 315 V high voltage battery system. The total net weight of the battery pack reaches 173 kg.

4.3. Hybrid LCV Modeling and Simulation

With all the necessary information available, two distinct vehicle models are created in AVL Cruise, one with HEVP2 design and the other with HEVP4. All components are identical except the EM, which was discussed earlier. Both models are simulated in WLTC Class 3b, which regulates a vehicle with PMR (Power to Mass Ratio) greater than 34 W/kg, and a maximum velocity equal to or greater than 120 km/h. (UNECE Committee, n.d.) HEVP2 and HEVP4 designs are in Figures 4.7 and 4.8, respectively.

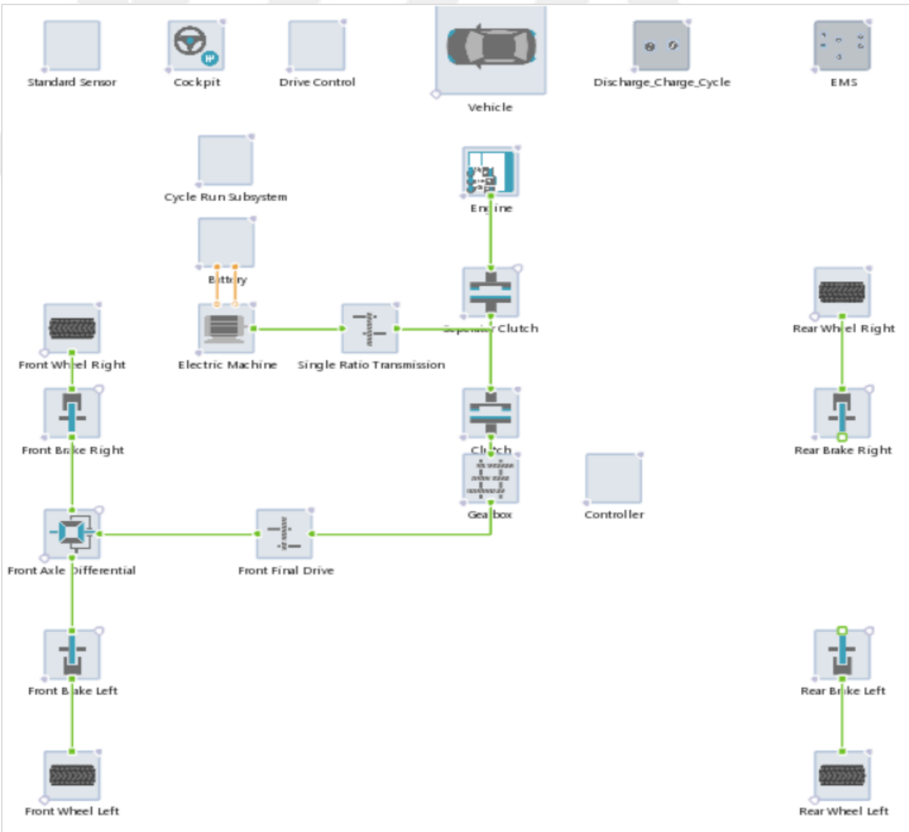

Figure 4.7: HEVP2 design of hybrid LCV

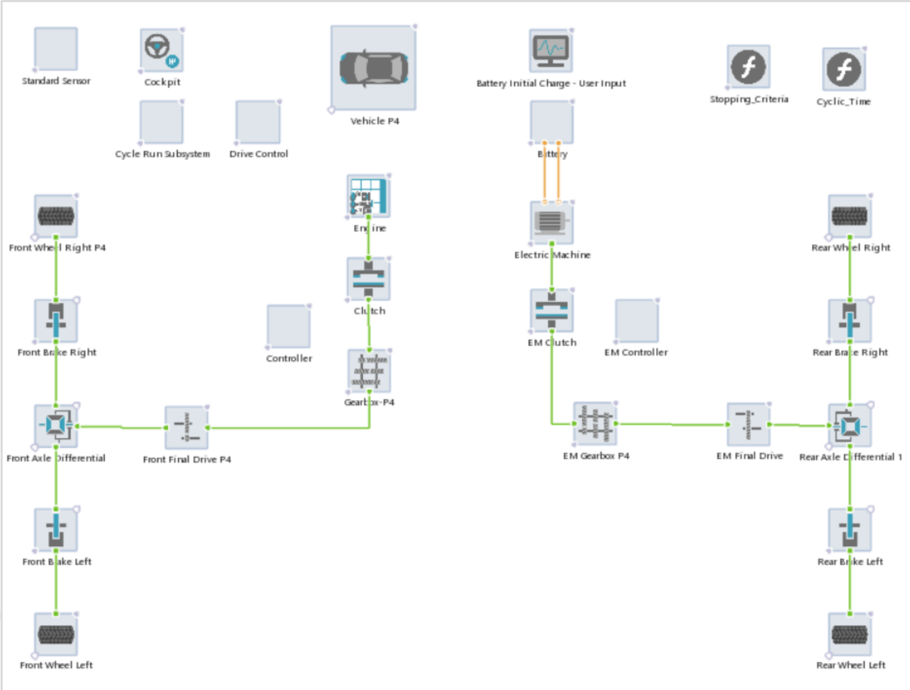

Figure 4.8 : HEVP4 structure of hybrid LCV

In the modeled HEV, drive control decides hybrid functionality based on vehicle state. Table 4.7 describes the relationship between vehicle states and the hybrid modes, where a is the vehicle acceleration, v the vehicle velocity, $eDrive$ the HEV in full-electric mode, $cDrive$ the full ICE mode, $eBoost$ the mode with both EM and ICE involved in traction based on power split ratio, $eLPM$ the load point movement for charging the batteries, $eBrake$ the mode during braking when EM operates as a generator to capture the vehicle kinetic energy to charge battery and $mBrake$ is the conventional braking activated when battery charging is not needed, or the $eBrake$ torque is not sufficient to decelerate the vehicle as desired by the driver.

Both simulations have been executed in a sustainable charge requirement, meaning that the battery state of charge (SOC) at the end of the simulation is equal to the initial SOC. $SOC_{t=0} = SOC_{t=t_f}$, here, t is time, and t_f is the final time and end of the simulation.

According to (Kim, Cha, & Peng , 2011), at the nominal SOC range, $SOC = 50\%\ to\ 90\%$, batteries' parameters do not vary so much, meaning that the open-circuit voltage remains almost constant. Therefore, for sustaining charge simulation of HEVP2 and HEVP4, the maximum and minimum SOC are 90% and 50%, respectively. Figure 4.9 and 4.10 show the sustainable charge simulation of both HEVP2 and HEVP4 hybrid designs.

Table 4.7 : Hybrid modes definition

State\H-mode	eDrive	cDrive	eBoost	eLPM	eBrake	mBrake
Acceleration $\boldsymbol{a >= 0.15}$	✓	-	✓	-	-	-
Constant Vel. $\boldsymbol{-0.15 < a < 0.15}$	✓	✓	-	✓	-	-
Stand Still $\boldsymbol{v < 0.1}$	-	-	-	-	-	✓
Coasting $\boldsymbol{-0.25 < a < -0.15}$	-	-	-	-	-	-
Deceleration $\boldsymbol{a =< -0.25}$	-	-	-	-	✓	✓

With a fixed power split ratio of 50% and a maximum charge/discharge power of battery as 20 kW, the simulation is started from a $SOC = 90\%$ without any forced charging during the simulation, except during $eBrake$ mode and constant velocity state of the vehicle. Due to the very transient characteristics of the WLTC Class-3b, the contribution of constant velocity to battery charging is negligible. When the battery charge drops to $SOC = 50\%$, forced charging of the battery is activated when the vehicle velocity is greater than $15\ m/s$ or the ICE operates at around $\pm15\%$ of optimum torque.

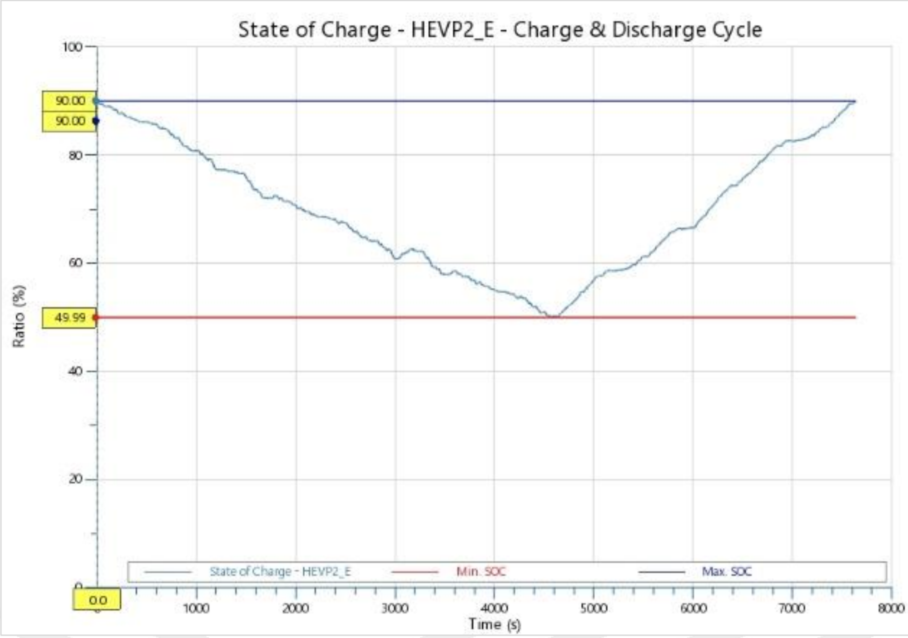

Figure 4.9: HEVP2 sustainable charge simulation

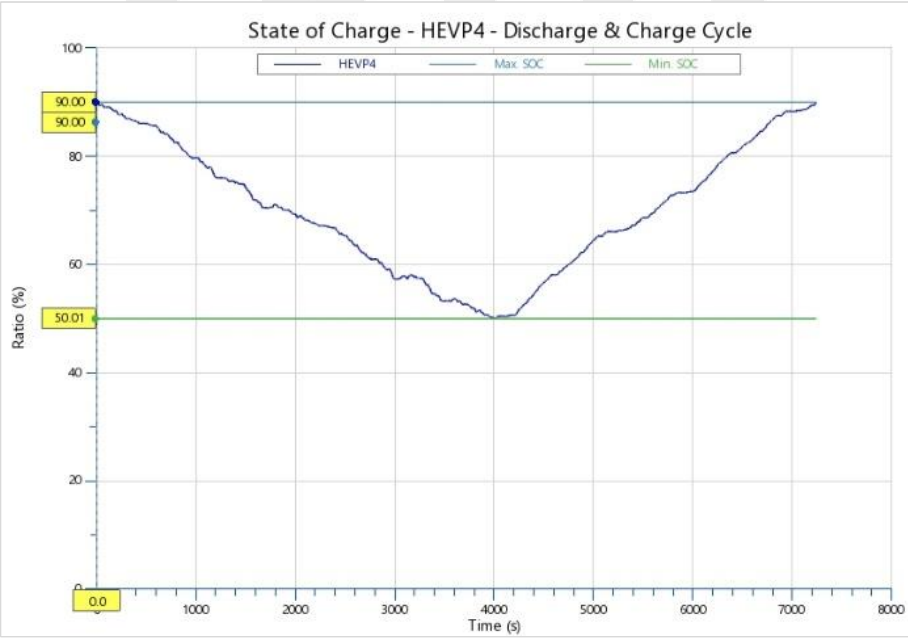

Figure 4.10: HEVP4 sustainable charge simulation

And finally, the fuel consumption, CO_2 emissions, and overall BSFC are depicted in Figures 4.11, 4.12, and 4.13, respectively. In the HEVP2 design, the overall fuel consumption in a sustainable charge simulation is decreased by about 17.7%; in contrast, the HEVP4 improves the fuel economy only by 15.6% for the same in comparison with ICEV4. The overall BSFC is also enhanced in both hybrid designs to the same extent.

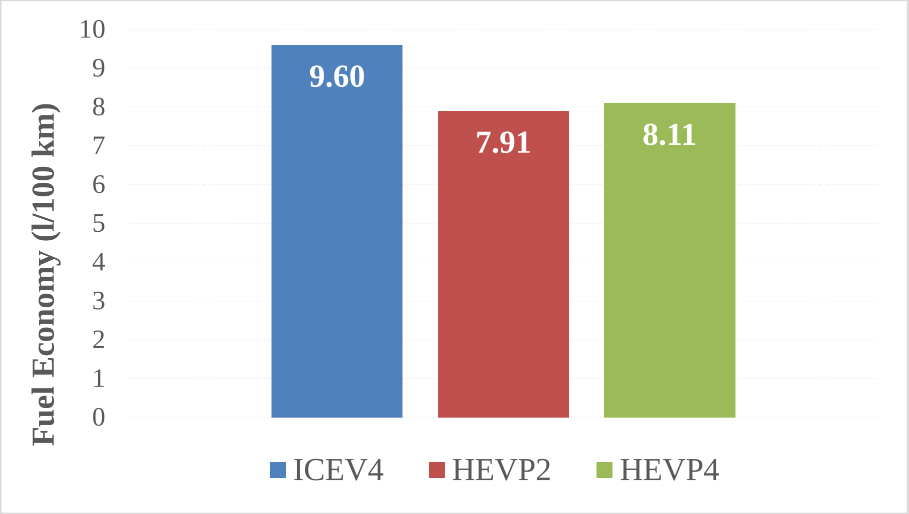

Figure 4.11 : Overall fuel consumption comparison

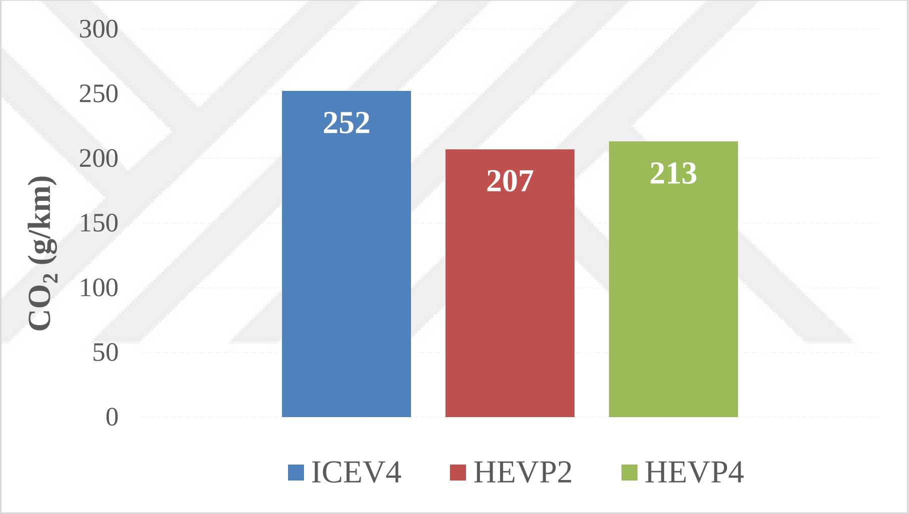

Figure 4.12 : Overall CO_2 emission comparison

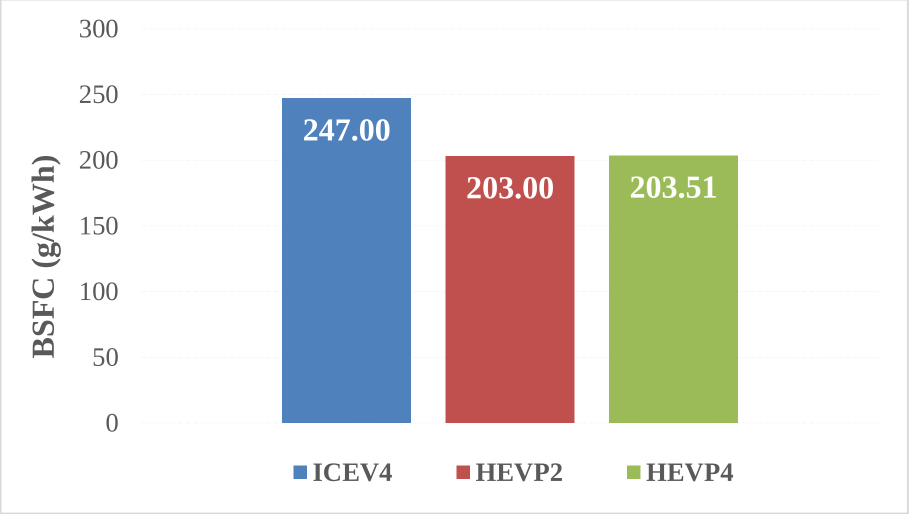

Figure 4.13 : BSFC comparison

Despite the author’s expectations based on the literature review (Tran, Akinsanya, Panchal, Fraser, & Fowle, 2021), HEVP2 reveals better performance than the HEVP4 design. The author assumes that the underlying reason will most likely be concerning the eBrake efficiency in HEVP4 since the BSFC of both models is almost the same, meaning that in eBoost, cDrive and eLPM modes, the ICE3 shows the same performance in both scenarios.

In conclusion, as expected, both hybrid designs, HEVP2 and HEVP4, improve the overall fuel consumption compared to ICE4. However, the performance of HEVP2 is better than the HEVP4 design for the intended LCV application; therefore, in the continuation of the study toward an efficient energy management strategy, the research is focused only on the HEVP2 design. It is essential to mention that the obtained results are based on the Mercedes Benz Sprinter design parameters, and they may differ for other applications. However, the procedures explained in this study can be followed to study other vehicles.

5. HEV ENERGY MANAGEMENT IN TRAFFIC

5.1. Technological State-of-the-Art

With the rapid advancement of telecommunication systems, and the tendency of online communication of the drivers/vehicles with the available infrastructure for decreasing driving time and using less congested roads, the advantages of BEV and HEVs can be even boosted further by incorporating an intelligent energy management system (EMS) in communication with Intelligent Transportation System (ITS), Geographical Information System (GIS), Global Positioning System (GPS), Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V).

In a single-vehicle communication with the infrastructure, the goal of EMS is to choose better routes or decide on the current vehicle hybrid mode and state based on future traffic information to minimize the energy consumption as much as possible while maintaining driving comfort. In double-vehicle communication, EMS aims to satisfy the driving safety requirements while seeking optimum driving to minimize energy consumption. And finally, in the multi-vehicle connected scenario, the EMS performs further by managing the power split between ICE and EM and controlling the velocity for energy-efficient driving. (Zhang, Hu, Langari, & Cao, 2019) (Song, Song, & Zhang , 2019) Figure 5.1 shows a schematic of the multi-vehicle communication.

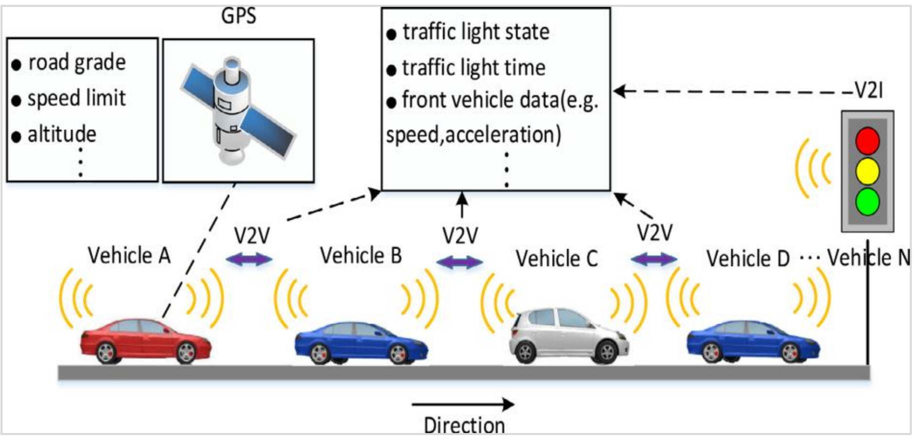

Figure 5.1 : The scenario of multi-vehicle energy management **(Zhang, Hu, Langari, & Cao, 2019)**

The subject vehicle will access the road information, i.e., road grade, velocity limit, and altitude, via GPS communication, and the upfront traffic information is available by V2V and V2I communication. This study assumes that future road information and future traffic data are known to the subject vehicle.

5.2. Power Split Ratio and Battery Discharge Power Analysis

In this study's first part of the energy management of the subject vehicle, the influence of power split ratio and battery maximum permissible discharge power on fuel consumption is extensively evaluated. The outcomes of this section are used to optimize the drive control of the HEVP2 design for the final section, which is about the vehicle's energy management based on future traffic information.

Several HEVP2 model simulations are done in WLTC Class 3b cycle with sustainable SOC constraint, $SOC_{t=0} = SOC_{t=final}$. The power-split ratio varies from 0%, meaning a pure ICE operation, to 70%, as an HEV with DOH of 70. In addition, for each power-split ratio, three different simulation runs are executed with different maximum battery discharge powers from 10kW to 20kW with an interval of 5kW.

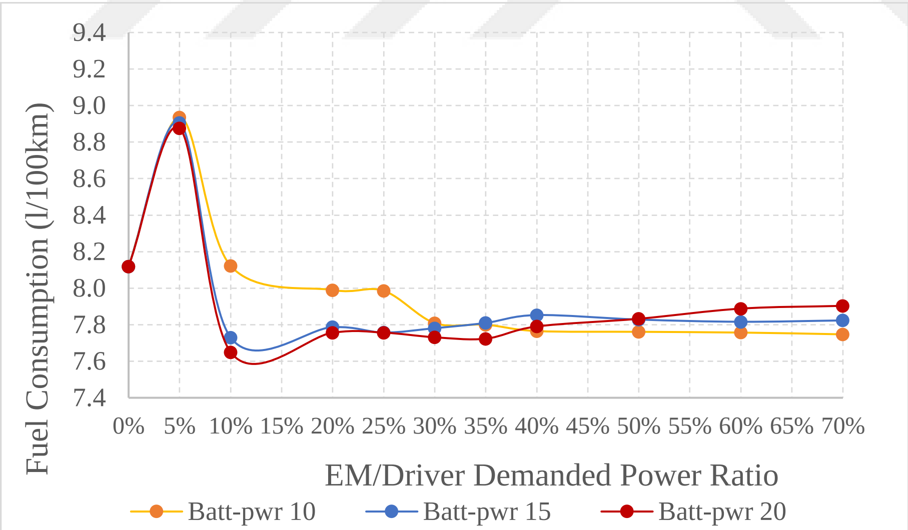

Figure 5.2 : Influence of power split ratio & battery maximum discharge power on fuel consumption

Figure 5.2 shows the results of these comprehensive simulations. As seen on the graph, with a battery maximum discharge power of 20kW, HEVP2 has the minimum fuel consumption until the power split ratio of 40%. For a more than 40% power split ratio, the minimum fuel consumption is achieved with battery maximum discharge power of

10 kW. This investigation verifies the tradeoff between the power split ratio and battery maximum permissible discharge power for reaching the minimum fuel consumption as follows:

i. A higher battery discharge power is required with a lower power split ratio.
ii. A lower battery discharge power is required with a higher power split ratio.

In addition, this investigation reveals that lack of constraint on battery discharge power will result in high depletion of battery charge in uneconomical instances. Next, the influence of power split ratio and battery maximum discharge power is investigated on fuel consumption based on a vehicle velocity.

The WLTC Class-3b cycle is constructed on four different velocity phases: low, medium, high, and extra high-velocity phases. (UNECE Committee, n.d.) HEVP2 model is simulated in each velocity phase independently in a sustainable charge requirement with different power split ratios and battery maximum discharge power. The power-split ratio varies from 0% to 70%, and battery maximum discharge power ranges between 5kW to 30kW. The results of this broad investigation are depicted in details in Figure 5.3 in which the values in bubbles are fuel consumption in l/100 km in the respective WLTC Class-3b velocity phase. Based on each WLTC Class-3b phase's velocity characteristic, a particular pair of power split ratio and battery maximum discharge power results in minimum fuel consumption of the HEVP2 model in that corresponding phase.

These findings are used for updating the drive control of the HEVP2 model, allocating the pair of optimum power split ratio and battery maximum discharge power to different velocity phases of WLTC Class-3b. The simulation is implemented in a range of $SOC_{min} = 70\%$ and $SOC_{max} = 80\%$. The results reveal a 5.1% saving in overall fuel consumption compared to the primary model of HEVP2 in a sustainable charge simulation, validating the findings of the investigations.

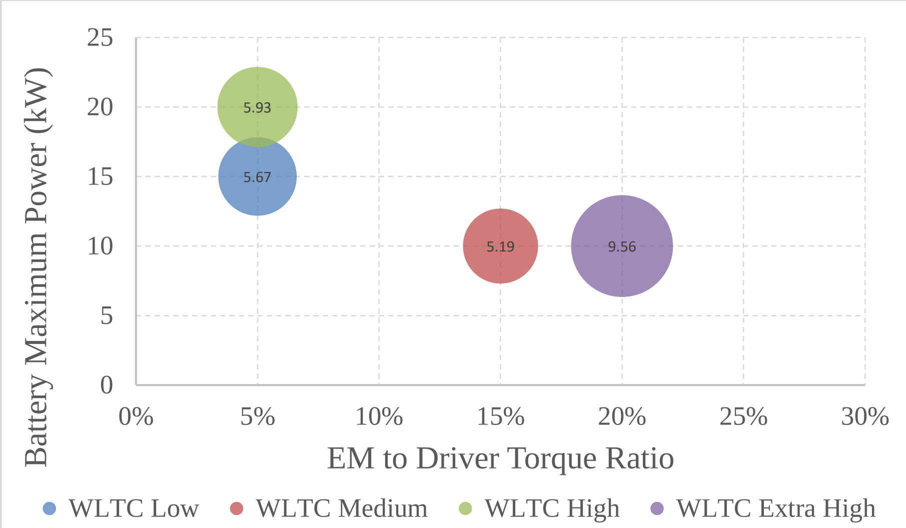

Figure 5.3 : Allocating pair of power split ratio and battery discharge power based on WLTC Class-3b velocity phases

Figure 5.4 compares ICEV4, the primary model of HEVP2, and the HEVP2 model with optimized drive control (EMS). In addition, four other simulation results are also depicted, with a fixed battery maximum discharge power and a fixed power split ratio for the entire WLTC Class-3b cycle. In Figure 5.4, P15R05 stands for battery maximum discharge power of 15kW (P15) and the power split ratio of 5% (R05). The same convention is valid for the other three bars starting with the letter P.

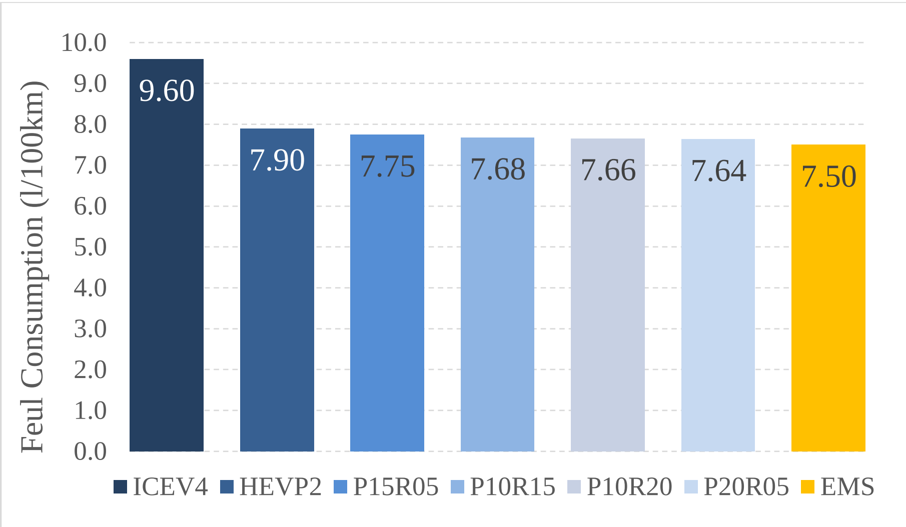

Figure 5.4 : Fuel consumption improvement in optimized HEVP2 model

As seen in the figure, the constant value for battery maximum discharge power and a fixed value for power split ratio (bars named P**R**) result in higher fuel consumption than the variable values of those parameters during the simulation. For each velocity phase of WLTC Class-3b or even in actual-world driving, the vehicle velocity and acceleration play a significant role in overall fuel consumption. Therefore, in actual driving, a precise allocation of battery discharge power and power split ratio to HEV powertrain based on vehicle velocity and acceleration will significantly improve the fuel economy. This conclusion will be the basis of the final part of this study, i.e., deciding about the vehicle's current hybrid mode and state based on the future traffic information.

5.3. Energy Management Strategy in Traffic

Depending on the knowledge of the future traffic information, velocity, and altitude, the energy management strategies are classified by causal and non-causal controllers. In causal EMS, the future traffic information is not known to the controller; in contrast, in non-causal controllers, the detailed knowledge of the velocity and altitude of the future road is known, which makes this strategy mostly applicable in regulatory vehicle test situations, or vehicles driving through a predefined route, like public transportation vehicles. (Guzzella & Sciarretta, 2013)

Also, based on applying optimal control theory, there is another classification of EMS. Optimal strategies, which are still increasingly researched, are derived from the optimal control theory. Heuristic EMS relies on state-of-the-art techniques and knowledge, primarily used in series production vehicles or prototypes. (Guzzella & Sciarretta, 2013)

This study, however, considers a rule-based heuristic approach based on instantaneous acceleration and velocity of the vehicle and the future traffic information. The outcomes of the investigations discussed in earlier sections are employed to develop an efficient EMS for the HEVP2 model. Hence, the following requirements must be satisfied at any time:

i. Deciding current hybrid mode based on future traffic information
ii. Operating ICE at the most efficient points
iii. Battery charge and discharge based on predefined SOC level

In (Langari & Won, 2005), sixteen parameters have been studied, affecting vehicle fuel consumption. In the current study, extensive simulations are implemented to find the most affecting parameters, followed by some other simulations to find the decision-making thresholds of those crucial parameters, which are:

i. Instantaneous vehicle acceleration
ii. Average acceleration of future traffic
iii. ICE angular speed
iv. Driver demanded torque
v. ICE optimum torque
vi. Torque at the gearbox input shaft
vii. Vehicle velocity
viii. Battery SOC.

A flowchart is created to elaborate the constructed decision-making process for selecting the current hybrid mode of the vehicle (Figure 5.5). When the vehicle is in motion, the controller evaluates its instantaneous acceleration and velocity. Suppose the vehicle is either accelerating or cruising at constant velocity. In that case, the future traffic acceleration during a 60 seconds horizon is considered to know if congestion is ahead or not. If the future information confirms the traffic congestion, then in certain engine operation speed and driver demanded torque, the batteries will be charged to save energy in the battery to be used during congested future traffic.

In addition, velocity optimization is recommended for the driver to drive with optimum acceleration or constant velocity. In contrast, if the future traffic is not congested, based on certain engine operation speed and driver demanded torque, eDrive, eLPM, or eBoost are allowed. Furthermore, suppose the vehicle's current velocity is above 15 m/s, and the vehicle is in a constant velocity state while the future traffic is not congested. In this case, eLPM is allowed by the controller based on specific driver torque demand and SOC level.

HEVP2 model is simulated in a sustainable charge WLTC Class-3b cycle, considering the constructed rule-based EMS controller. In this step, velocity optimization is still not implemented only to observe the effectiveness of the EMS controller. At the end of the simulation, the overall fuel consumption has fallen to 7.3 L/100 km (Figure 5.6) while maintaining the battery SOC at 80%. Compared with ICEV4, the result reveals a 24% fuel saving of the HEVP2 model with an EMS controller that considers the future traffic situation for deciding on the current hybrid mode.

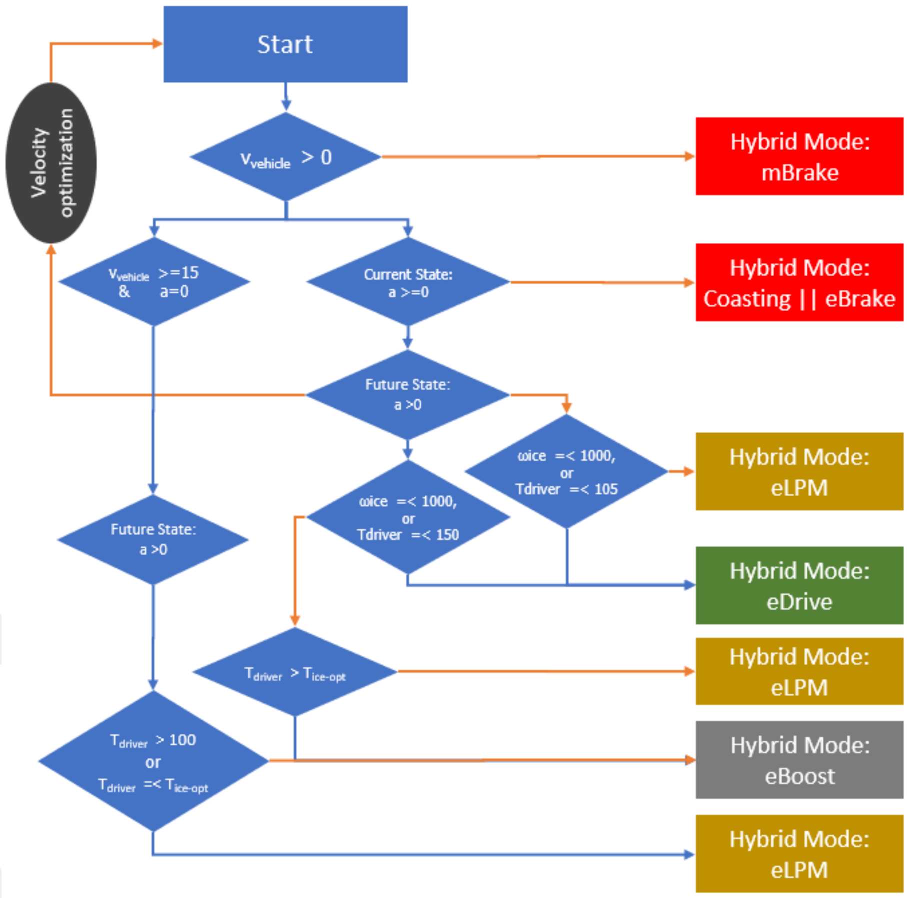

Figure 5.5 : Current hybrid mode decision procedure based on future traffic information

As mentioned, velocity optimization is implemented when congestion is detected in future traffic, meaning that the current velocity and acceleration are much more than the future velocity. The results are recommended to the driver, advising for a smooth driving to avoid unnecessary fuel consumption.

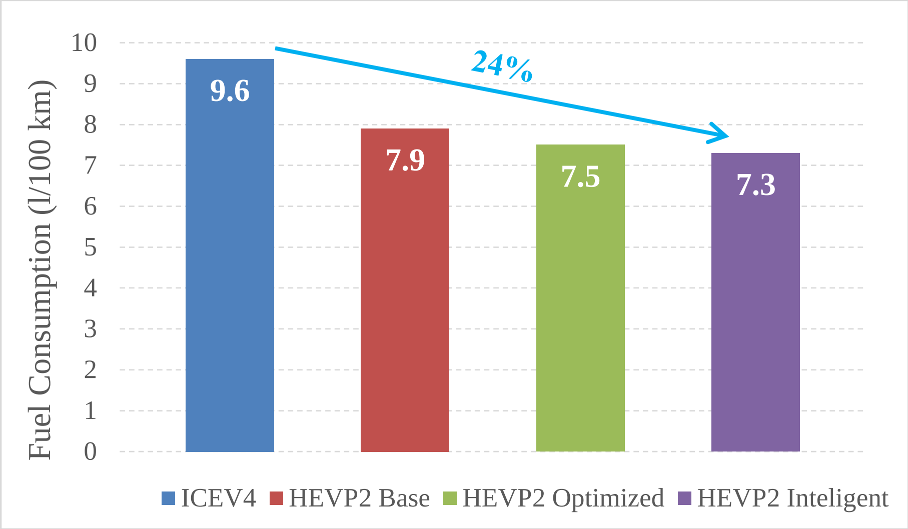

Figure 5.6 : HEVP2 model fuel economy improvement

In this study, the city traffic information of the road ahead is collected at a distance corresponding to a 60 seconds horizon using ITS, V2I, and V2V communication. Suppose the acceleration during the entire prediction horizon is negative or fluctuating rapidly. This shows congestion ahead of the vehicle. The future velocity information during the sampling horizon is optimized by Savitzky-Golay smoothening function (Niedźwiecki & Ciołek, 2019) with a polynomial fitting with the order of three and an observatory frame size of 60 seconds. This function is known as the Least Square Smoothing Filter (LSS). Applying this function is to smooth the rough and fast-changing velocity of future traffic while closely tracking the future velocity's signal and accounting for the transient effects.

This study used the WLTC Class-3b profile as future traffic velocity information. The future velocity optimization controller processes it in advance and generates the velocity profile for being used in the simulation of the HEVP2 model. This part of the study is implemented in ©MATLAB R2021b, and the output is transferred to the ©AVL Cruise Simulation tool. It is assumed that each minimum velocity of the WLTC Class-3b profile is a physical velocity obstacle, which should also be treated in the optimized velocity profile. Figure 5.7 shows the optimized velocity using Savitzky-Golay smoothening function in MATLAB. It is essential to mention that the traveled distance in WLTC Class-3b standard profile is 23.3 km. However, it is 22.3 km when the vehicle follows the velocity profile optimized by Savitzky-Golay smoothening function. It means that the vehicle travels only one km distance less than when there is no application of velocity optimization.

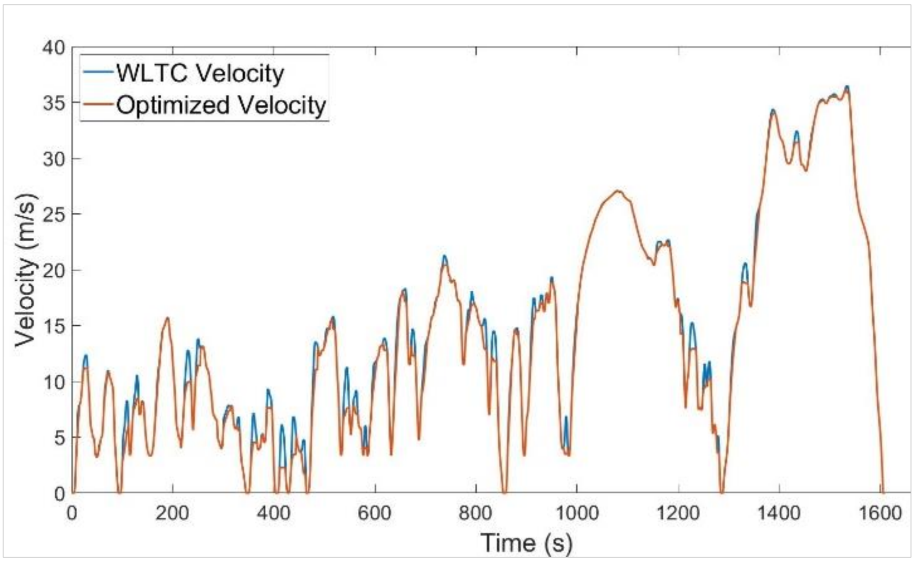

Figure 5.7 : Future velocity optimization based on WLTC Class-3b

Similar to earlier simulations, the latest version of the HEVP2 model is simulated through the sustainable charge constraint. The overall fuel consumption is further improved and results in 7.04 L/100 km, corresponding to an additional 3.6% improvement in fuel economy compared to the latest model of HEVP2 and a 26.7% improvement compared to the ICEV4 model.

Figure 5.8 shows the development of fuel economy improvement, from the base conventional vehicle model, ICEV4, to the HEVP2 Final model with incorporated intelligent EMS deciding about the current hybrid mode based on the future traffic information integrated with the implementation of a velocity optimization function to generate an efficient velocity trajectory.

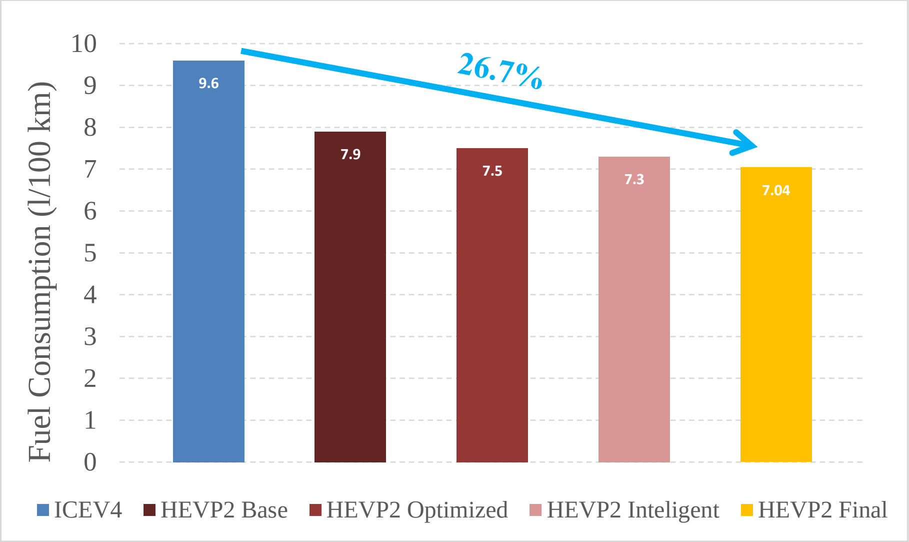

Figure 5.8 : Fuel consumption reduction from ICEV4 model to HEVP2 Final

6. CONCLUSION

This study uses the AVL Cruise Simulation tool to design and simulate an LCV model with a conventional four-cylinder ICE powertrain, ICEV4. Then, the same software tool is used to simulate P2 and P4 parallel hybrid models, HEVP2 and HEVP4, of the exact vehicle with the downsized three-cylinder engine. The fuel-saving of the HEVP2 model is 17.7% compared to the ICEV4 powertrain. In contrast, the HEVP4 model reduces fuel consumption by 15.6%. The simulations are performed in the WLTC Class-3b test cycle. It is concluded that even with a straightforward hybridization of an LCV Mercedes Benz Sprinter with a DOH of 50%, there is considerable potential for fuel economy improvement. For this specific vehicle type, the HEVP2 hybrid configuration is recommended.

In addition, by applying the variable power-split ratio and variable battery maximum discharge power, an additional 5.1% reduction in fuel consumption is feasible. This achievement supports the conclusion that designing the hybrid powertrain with a variable power-split ratio matched with an adequate battery discharge power based on specific vehicle velocity and acceleration has considerable potential for fuel economy improvement.

Moreover, an intelligent energy management system is developed by considering the future traffic information in a 60-second horizon using the WLTC Class-3b test cycle. An algorithm is designed to distinguish the future traffic congestion and command the HEV controller to operate the powertrain in an efficient hybrid mode and ensure enough battery charge is available for upcoming congestion when the vehicle should run on electric mode. The simulation outcomes present an additional 2.7% reduction in fuel consumption, resulting in an overall fuel saving of 24% compared to ICEV4. Therefore, based on this finding, it can be concluded that operating the HEV while considering the future traffic conditions for selecting the current hybrid mode and maintaining enough battery power for future congestion plays a considerable role in the energy management of HEVs.

The final part of this study considers the application of the Savitzky-Golay smoothening function with a polynomial fitting of order three and an observation horizon with the size of 60 seconds. When the intelligent energy management system detects either congestion or highly fluctuating velocities in future traffic, the function creates an optimized velocity trajectory using future velocity data to avoid unnecessary acceleration and deceleration to save energy. This method could enhance the fuel economy by an additional 3.6% compared to the previous design and 26.7% compared to the ICE4. With that being said, concluding on the effectiveness of incorporating an intelligent energy management strategy based on the evaluation of future traffic data into the controller of the HEV powertrain is inevitable.

In connection with the entire study and the obtained results, the author's conclusions can be summarized as follows:

i. Based on the market share and daily traveled distance of LCVs, their hybridization is essential in improving fuel economy and cutting CO_2 emissions.
ii. For specific velocity and acceleration, applying a specific power split ratio paired with an adequate battery discharge power is encouraged to improve the fuel economy of HEVs.
iii. Processing future traffic data via V2V, V2I, ITS, and GPS communication enables selecting the most efficient hybrid mode, maintaining battery charge for future use, and determining optimum velocity trajectory; therefore, efficient energy consumption can be realized. This is important for LCVs with high daily travel distances exposed to different traffic patterns.

Though substantial results are achieved in this study, it is recommended to conduct extensive research on the following subjects:

i. In the current study, the power split ratio and battery maximum discharge power is investigated based on four velocity phases of WLTC Class-3b. Therefore, machine learning (ML) techniques to train the HEV controller for a more precise variable power split ratio paired with a specific battery discharge power in minimal velocity domains can enhance the HEV powertrain's controller efficiency. The procedure is recommended to take into account other velocity profiles. The final calibration of the controller can be realized in a real-driving test to validate the functionality and effectiveness of the solution.

ii. Optimization of the velocity trajectory, particularly for LCVs with high daily traveled distance, needed to be studied more. Optimization through a combination of dynamic programming (DP) and machine learning tools from data science engineering to minimize energy consumption without sacrificing travel time can further enhance the HEV controller. Savitzky-Golay smoothening function can be used; however, DP and ML can facilitate choosing the most efficient horizon size for data collection of the future traffic and the polynomial order of the function for smoothening the velocity trajectory based on different velocities and accelerations. Other velocity profiles are recommended to be evaluated along with a real-driving test for validation.

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RESUME

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