ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

INVESTIGATION OF REGENERATIVE BRAKING EFFICIENCY IN DIFFERENT DRIVE CYCLES

M.Sc. THESIS

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Department of Mechanical Engineering

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

REJENERATİF FRENLEME VERİMLİLİĞİN FARKLI SÜRÜŞ ÇEVRİMLERİNDE İNCELENMESİ

YÜKSEK LİSANS TEZİ

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Berkay BARIN, a M.Sc. student of ITU Graduate School student ID 503201705 successfully defended the thesis entitled “INVESTIGATION OF REGENERATIVE BRAKING EFFICIENCY IN DIFFERENT DRIVE CYCLES”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To Mustafa Kemal Atatürk,

FOREWORD

In this thesis, regenerative braking efficiency is calculated and compared for various cycles in order to complete graduate program of ITU Automotive Programme.

Firstly, I would like to thank my thesis advisor Assoc. Prof. Dr. Osman Taha Şen for guiding me since very first day of the studying for this thesis.

Secondly, I would like to thank my father Halit Barın, my mother Mihriban Barın and my brother Hakan Barın for their motivational support.

Approximately 10 months of preparation period of this thesis, I lived in a hotel due to my profession. I had to study on evenings in the corner of various cafes without sleeping much. Finishing this thesis was not easy from a physical and mental point of view.

Sadly, I am closing my academic career with this study.

Last but not least, I would like to thank my dear girlfriend who shows me patience during thesis study. Occasionally, I was not be able to allocate time for her.

June 2023

Berkay BARIN
Automotive Engineer

TABLE OF CONTENTS

Page

ABBREVIATIONS

EV	**:** Electric Vehicle
ICE	**:** Internal Combustion Engine
SUV	**:** Sport Utility Vehicle
EB	**:** Electrical Brake
FB	**:** Frictional Brake
BBS	**:** Blending Braking System
ABS	**:** Anti-lock Braking Systems
OEM	**:** Original Equipment Manufacturer
NYCC	**:** New York City Cycle

SYMBOLS

a	**:** Acceleration of the test vehicle Capacitance
u_i	**:** Initial Value of Velocity
u_f	**:** Final Value of Velocity
t_i	**:** Initial Value of Time
t_f	**:** Final Value of Time
F_x	**:** Force on the tire
F_b	**:** Braking force
F_t	**:** Tractive force
F_B	**:** Required force to keep the vehicle at desired acceleration
F_{st}	**:** Grading resistance
F_r	**:** Rolling resistance
F_L	**:** Aerodynamic resistance
m	**:** Mass of the vehicle
λ	**:** Mass factor
G	**:** Final drive ratio
m_e	**:** Effective mass
g	**:** Gravitational acceleration
θ	**:** Slope angle of the road
f_r	**:** Rolling resistance coefficient
W	**:** Weight of the test vehicle
M_x	**:** Tire moment
M_m	**:** Motor moment
n_m	**:** Motor speed
x	**:** Distance
W_t	**:** Traction energy
W_b	**:** Braking energy
r_{bt}	**:** Braking to traction ratio

LIST OF TABLES

Page

LIST OF FIGURES

Page

INVESTIGATION OF REGENERATIVE BRAKING EFFICIENCY IN DIFFERENT DRIVE CYCLES

SUMMARY

As being an important fact, climate change threatens the world population and its impact has become crucial recently. Thus, the world is being prepared for a very fresh era: green energy and electrification era. The European Union proposes the EU7 emission regulation, which has lower limits compared to prior regulations; and net zero emission policies are already adopted by several governments throughout the world. These developments increase the importance of electric vehicles (EVs), which have already start to replace the conventional vehicles due to their zero tailpipe emissions. Furthermore, the high efficiency, quiet operation and improved performance characteristics of EVs make them more preferable, and the recent advancements in battery technology bring this preference to the fore. Though, EVs still have significant disadvantages such as limited driving range and long charging time. The concept of regenerative braking becomes crucial in increasing the battery state of charge, which improves the driving range and reduces the required charging duration. Thus, the optimization of the regenerative braking system operation becomes critical. The chief objective of this study is to investigate the utilization rate of regenerative braking in different drive cycles, which depends on braking rate and road conditions. Consequently, seven well-known different drive cycles are selected, which vary with distance, urban / highway scenario, traction per kilometres, etc. An E class sport utility battery electric vehicle is selected for modelling purposes and it is subjected to all drive cycles. The driving resistances are calculated and the instantaneous electric motor torque demand is obtained for all drive cycles. Furthermore, the total braking and traction force ratios are evaluated for all drive cycles. It is observed that the comparison of these drive cycles based on total braking and traction force values does not provide reasonable conclusions due to the variation of drive cycle range. Thus, results are compared by normalizing the traction and braking forces by the range of each drive cycle. Finally, a braking to traction ratio is determined for all drive cycles, and the tendency of regenerative braking utilization rate change is investigated. Based on the results, it is observed that the braking to traction ratio of the vehicle significantly reduces when the vehicle moves from urban to highway drive cycle. Furthermore, the utilization rate of the regenerative braking also drops down to %13 from %53, when the drive cycle transition from urban to highway occur. The low braking to traction ratio shows that the recovered energy begins to be insufficient in highway driving conditions, and enough energy cannot be provided for the charging of the battery pack. In addition, the test vehicle's weight has increased to its gross weight. Subsequently, results were reanalyzed in the view of weight change. Finally, it is observed that weight change has not a significant effect on utilization rate in city conditions, whereas it increases the efficiency around %6 in highway conditions.

REJENERATİF FRENLEME VERİMLİLİĞİNİN FARKLI SÜRÜŞ ÇEVRİMLERİNDE İNCELENMESİ

ÖZET

İklim değişikliğinin dünya nüfusunun üzerindeki etkisi son zamanlarda çok önemli hale geldi. Kamuoyu ve bilimsel gerçekler, devletler ve diğer otoriteleri iklim değişikliğine karşı sıkı düzenlemeler yapmaya zorluyor. Bu düzenlemelerin hedeflerinden biri de enerji verimini arttırmaktır. Enerji üretimi de iklim değişikliği üzerinde kritik bir rol oynuyor. Bu nedenle üretilen enerjinin tamamının efektif bir şekilde kullanılması hedefleniyor. Artan nüfus ve ekonomik büyüme ile birlikte gün geçtikçe artan enerji ihtiyacı, bu konuyu gün geçtikte daha kritik hale getiriyor. Gelişen bu şartlarla birlikte diğer sektörler gibi otomotiv sektörü de yeni bir döneme hazırlanıyor. Bu dönem emisyon standartlarının sıkılaştığı, elektrikli araçların öne çıkmaya başladığı yeşil enerji dönemi olarak nitelendirilebilir. Sektör, artık karbon ayak izini ve emisyon değerlerini arttıran geleneksel içten yanmalı motor taşıyan otomobillerin gün geçtikçe azaldığı bir döneme kendini hazırlıyor. Avrupa Birliği, önceki regülasyonlara kıyasla çok daha düşük sınırları olan EU7 emisyon regülasyonunu yayınladı. Ocak 2025 itibariyle devreye girecek olması planlanan bu regülasyon sayesinde net sıfır emisyon politikaları, dünya çapında birçok devlet tarafından devreye alınacak. Bu gelişmeler, geleneksel içten yanmalı motorlar karşısında, net sıfır emisyon sağlamaları nedeniyle elektrikli araçların önemini ve popülaritesini artırmaktadır. Ayrıca elektrik motorun yüksek verimliliği, sessiz çalışması ve geliştirilmiş performans özellikleri elektrikli araçların daha çok tercih edilmesine yol açıyor. Ek olarak batarya teknolojisindeki son gelişmeler de elektrikli araçların daha verimli ve uzun menzilli olmasını sağlıyor. Bütün bu olumlu özellikleriyle birlikte, elektrikli araçların hala sınırlı olan sürüş menzili ve uzun şarj süresi gibi kritik dezavantajları vardır.

Rejeneratif frenleme, elektrikli aracın yavaşlarken yaptığı iş sonucu açığa çıkan enerjiyi bataryaya geri kazandırır. Bu nedenle rejeneratif frenleme, bataryanın bir şarja ihtiyaç duymadan bir miktar doldurur. Bu durum da bataryanın gerekli şarj süresini ve doğal olarak şarja duyduğu ihtiyacı azaltır. Ayrıca rejeneratif frenleme sayesinde araç daha uzun süreler şarj olmaya gerek duymadan gidebileceği için araçların sürüş menzilini arttırır. Bu sebeplerden dolayı rejeneratif frenleme, elektrikli araçların dezavantajlarına potansiyel bir çözüm olabilir. Ek olarak geleneksel içten yanmalı araçların aksine fren ihtiyacının önemli bir kısmı rejeneratif frenlemeden karşılanabileceği için elektrikli araçlarda fren sistemi bakım maliyetleri azalır, mekanik frenler daha az yıpranır ve daha uzun ömürlü olur.

Bu çalışmanın temel amacı, farklı yol koşullarında rejeneratif frenleme performansının etkisinin nasıl değiştiğini incelemektir. Bunun için ilk etapta yüksek performanslı ve tam elektrikli bir spor araba seçildi. Bu araç, öncelikle yüksüz ağırlığı ile, şehiriçi, otoban ve hibrit olan yedi farklı çevrime tabi olarak koşturuldu. Bu çevrimler dünyaca bilinen ve farklı emisyon ve homogolasyon testlerinde kullanılan çevrimlerdir. İlk olarak aracın bu çevrimlerde hangi saniyede ne kadar km/h olması gerektiği ile

yavaşlama ve hızlanma değerleri m/s^2 cinsinden saptandı. Ardından, seyir esnasında araca etki eden kuvvetler hesaplandı. Bu kuvvetler hesaplanırken aracın eğimsiz bir yolda, rüzgarsız bir ortamda olduğu varsayıldı. Daha sonra bu kuvvetler ve araç hızı ile birlikte aracın o an tekerleklerde oluşturması gereken itki kuvveti hesaplandı. Bu itki kuvvetinin ardından motorun ne kadar moment iletmesi gerektiği hesaplandı. Motorun moment - devir grafiği ile talep edilen moment karşılaştırıldığında aracın bu momenti karşıladığı net olarak tespit edildi. Ardından aynı hesaplar frenleme kısmı için yapıldığında da motorun, jeneratör olarak çalıştığı rejeneratif frenleme kısmında da ihtiyaç duyduğu momentinin tamamının karşılandığı, aracın böylelikle mekanik frenleme sistemine seçilen çevrimlerde ihtiyaç duymadığı ortaya çıktı. Sonrasında aracın çekiş gücü ve frenleme gücü tüm çevrimler için ayrı ayrı hesaplandı. Ancak tüm çevrimlerin farklı mesafede olduğu için bulunan çekiş ve frenleme değerlerini direkt olarak kıyaslamak makul olmadı. Bu değerler, çevrimlerde katedilen kilometre değerlerine bölünerek (kJ/km) yedi çevrimde karşılaştırıldı. Ardından tüm çevrimler için frenleme esnasında ortaya çıkan güç, çekiş esnasında harcanna güce bölünerek frenleme / çekiş oranı bulundu. Bu oran rejeneratif frenlemeden kazanılacak potansiyel enerjiyle çekişe ne kadar katkıda bulunulacağının direkt göstergesidir. Diğer bir deyişle, frenleme / çekiş oranının bire yakın olması yüksek olması çekiş için gerekli enerjinin büyük kısmının rejeneratif frenlemeden karşılanabileceği anlamına gelir.

Bu kıyaslamalar sonucunda, araç hızının yüksek olduğu ve ivmelenme değişikliklerinin az olduğu otoyol çevrimlerinin şehiriçi çevrimlerine göre oldukça düşük rejeneratif frenleme değerlerine sahip olduğu görüldü. Kıyaslamanın daha anlaşılabilir olması amacıyla bir şehiriçi çevrimi olan NYCC (New York City Cycle) ile FTP75 Otoyol çevrimi ayrı olarak analiz edilip karşılaştırıldı.

Söz konusu iki çevrimin standart sapma değerleri hesaplandığında NYCC'deki sapmanın FTP75 Otoyol çevrimindeki standart sapmanın iki katından fazla olduğu görülmüştür. Bu da şehiriçindeki ivmelenme ve frenleme hareketlerinin otoyol çevrimine göre daha agresif olduğunu gösterir.

Daha sonraki analizlere göre, kilometre başına gelen çekiş enerjisinin FTP75 Otoyol çevriminde NYCC'ye göre yaklaşık iki kat daha az olduğu anlaşıldı. Kilometre başı frenleme enerjisinin ise NYCC'de FTP75 Otoyol çevrimine göre yaklaşık sekiz kat daha fazla olduğu görüldü. Sonuç olarak ivmelenmedeki yoğun değişiklikler sebebiyle şehiriçi çevrimde otoyol çevrimine göre hem frenlenme ve hem çekiş için yüksek enerjiler harcandı. Araç şehiriçi çevriminden otoyol çevrimine geçtiğinde aracın frenleme / çekiş oranının, bir diğer deyişle rejeneratif frenleme verimliliğinin önemli ölçüde azaldığı görülmektedir. Şehiriçinde % 53'e kadar çıkan frenleme / çekiş oranı araç otoyol çevrimindeyken % 13'e kadar düşüyor. Bu düşük frenleme / çekiş oranı, otoyol sürüş koşullarında geri kazanılan enerjinin çekiş için ihtiyaç duyulan enerjiyi sağlamak için yetersiz kalmaya başladığını ve bataryanın şarj edilmesi için yeterli enerjinin sağlanamadığını göstermektedir.

Diğer taraftan şehiriçi çevrimindeki yüksek frenleme / çekiş oranı rejeneratif frenlemenin veriminin yüksek olduğunu, şarj süresini ve şarj ihtiyacını gözle görülür bir şekilde azalttığını göstermektedir.

Bu çalışmalara ek olarak, test aracı daha önce yüksüz ağırlıkta test edildiği NYCC ve FTP75 Otoyol sürüş çevrimlerinde azami yüküne çıkartılarak tekrar test edildi ve kütlenin rejeneratif frenleme verimliliğine katkısı incelendi.

Ağırlık değişimi, şehiriçi şartlarında hem frenleme hen çekiş enerjisinde ağırlık değişimi (%26) kadar arttığı için frenleme / çekiş oranında bariz bir değişim

yaşanmadı. Ancak ağırlık değişimi otoyol koşullarında frenleme enerjisinin çekiş enerjisine göre daha yüksek etki gösterdi. Bu nedenle rejeneratif frenleme verimliliği yani frenleme / çekiş oranı %6 civarında arttı.

1. INTRODUCTION

Tailpipe emissions from vehicles are one of the most difficult and major problems in the world. The total number of vehicles is increasing day by day with the increasing population. Although emissions per car are decreasing, an increase can not be avoided.

Due to restrictive regulations such as the EU7, leading automobile companies are beginning to abandon conventional vehicles. They are starting to produce electric vehicles (EVs) with the goal of net zero emissions.

Finally, the number of electric vehicles is increasing more and more, while the number of conventional vehicles is decreasing.

Electric vehicles differ significantly from vehicles with internal combustion engines (ICE). They operate more quietly and efficiently. Besides, they can also recover some of the consumed energy by regenerative braking. The concept of regenerative braking can therefore help EVs to increase the limited range of electric vehicles so that the vehicle needs to be recharged less frequently.

Regenerative braking not only recovers energy, but also reduces wear on the pneumatic braking system by supplying brake force to the tires. Ultimately, the concept is very beneficial in terms of energy recovery, system wear and charge management.

1.1 Purpose of Thesis

Limited range and long charging duration are major disadvantage of electric vehicles. Regenerative braking is crucial for compensating these disadvantages of EV. This study investigated utilization rate of regenerative braking in different road conditions.Calculations have made based common drive cycles used in various automotive industry to simulate different speed and acceleration profile of different driving scenario. The goal is to explain impact of the speed and acceleration profiles over regenerative braking success.

1.2 Literature Review

1.2.1 Regenerative braking

First law of thermodynamics states that energy can neither be created nor destroyed, it can only be converted from one form of energy to another. Therefore, a decelerating vehicle's kinetic energy should be converted to other forms of energy. An ICE vehicle can only convert this energy into heat by its frictional brake system. However, an EV is able to convert this kinetic energy into electric as it can convert into heat. Regenerative braking is a technology used in hybrid and electric vehicles. It converts kinetic energy into electric energy. This can be accomplished by using electric motor as generator. Then, it can slow down the vehicle and generate electricity at the same time. This energy can be stored to use later. This process not only helps to recharge the battery but also reduces the amount of energy that would otherwise be lost as heat through the traditional braking system. That's why overall efficiency increases while emission and environmental harmful impact decreases. Regenerative braking reduces the demand of applying frictional brake so wear of the traditional brake system components decrease considerably. Regenerative braking is an energy-saving concept that helps to increase the overall energy efficiency of the vehicle. Although, it is commonly used in electric and hybrid vehicles, trains and elevators can utilize the regenerative braking.

In 1886, history of regenerative braking systems are initiated by American inventor Frank J, Sprague, whose the owner of Electric Railway - Motor Company. He designed a regenerative braking system which motors work as a generator during braking. Generator created current and sent it back to supply line as wheels of locomotive are turned [1]. After this invention, researches are mostly focused on locomotive industry [2]. Locomotives at Baku-Tiblis-Batumi railway systems are one of the common early examples of regenerative braking systems utilization [3]. Then, regenerative braking appeared first time in an American EV concept Amitron in 1967. Amitron was first vehicle to utilize regeneration in automotive industry [1]. At the same year with introduction of Amitron, Electric Fuel Propulsion Inc. released an EV called MARS II, predecessor of MARS I. To maximize the recuperation, regenerative braking systems intervened as soon as driver released the accelerator pedal. MARS II was able to brake the vehicle from 48 kph to 0 about 152 meters without using frictional

brakes[4]. Eventually, Toyota Prius had major contribution for commercialization of regenerative braking systems into the sector in recent years [3].

Energy storage system is the main component of RBS because all recuperated energy is aimed to return it. Energy storage systems can be classified such as battery, superconducting magnetic, flywheel and spring-based energy storage systems.

However, the most common one in automotive industry is battery energy storage systems [1]. Batteries can differ in the sense of substance: Lead–Acid,Ni–Cd, Ni–Zn, Ni– MH, Na–S, NaNiCl2 and Li-ion. Specific power density, specific energy density, energy efficiency, cycle lifetime and cost are the main parameters for selecting the substance. In Figure 1.1, an overview is given for various battery technologies in terms of specific power and energy. In the Figure, SuperCap is supercapacitor, Pb is lead, Li-ion is lithium-ion, NiCd is nickel–cadmium, NiMH is nickel–metal hydride and NaNiCl2 is sodium–nickel chloride. ZEBRA: Zero Emission Battery Research Activities. It is foreseen that Li-ion batteries to dominance the market. Additionally, super-capacitors can be used with them for high power functions such as boosting and regenerative braking [5].

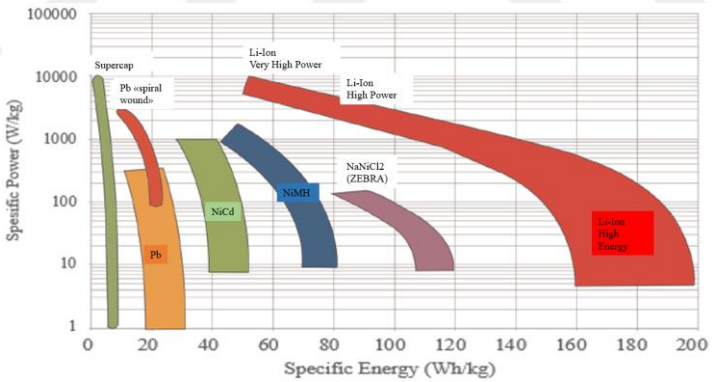

Figure 1.1 : Overview of various battery technologies [5].

In order to understand regenerative braking, strategies of braking should also be introduced. Braking force distribution between the axles and torque distribution between the frictional brake (FB) and electrical brake (EB) affect the regenerative braking capability. Blended braking system (BBS) is the system which FB and EB utilized jointly to supply desired braking torque. In this system, EB and FB can supply the desired torque either separately or together depends on the braking mode [6]. In case of gradual braking mode, the vehicle decelerates slightly. For instance, it can occur just before the traffic lights or crosswalk. It would be achieved with minimal

contribution of FB, hence regenerative energy can be optimized by EB [6]. On the other side, in case of urgent braking, short braking distance and rapid deceleration are required. Hence, FB is fully used without considering regeneration. Overall EB force can not meet this rapid braking requirement due to overheating and state of charge (SOC) saturation.

In urgent braking case, deceleration may reach very high values so that traction loss between tire and road surface may occur. The vehicle slides or drift out of control. This phenomena called skid. There is a system to avoid skid in modern vehicles : ABS (anti-lock braking systems). There are speed sensors located in each tires to detect slip. These sensors sense skid, then they decrease and increase braking torque to prevent steering loss. ABSs are usually based on EB because their aim is not regenerating energy [6]. Hence, ABS and SOC are key parameters in braking algorithm shown in Figure 1.2.

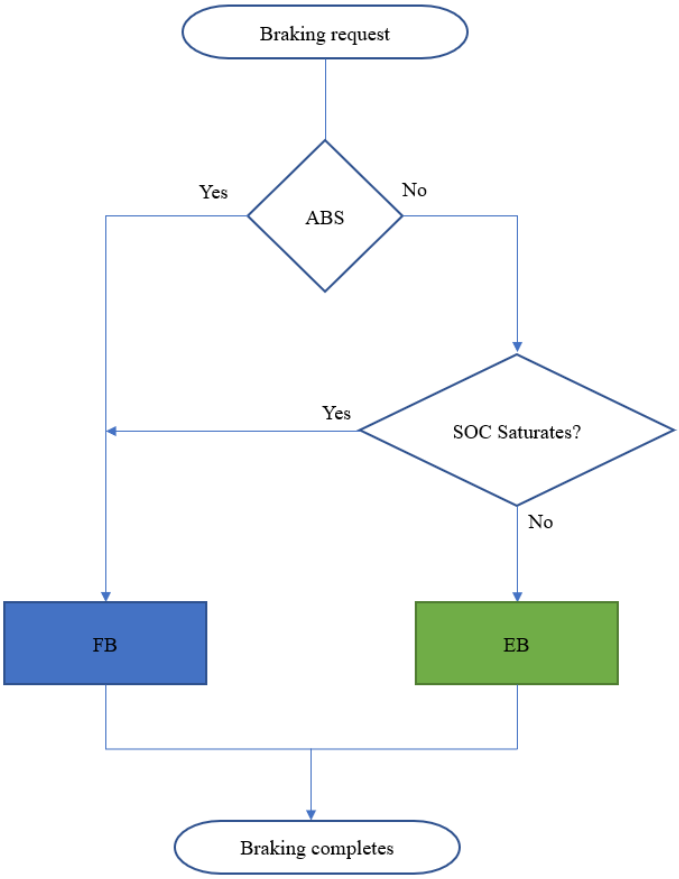

Figure 1.2 : Braking algorithm [6].

The algorithm decides to allocate between FB and EB in case of braking. Firstly, the algorithm checks if ABS intervention necessity in case of braking request. If ABS needs to be active, then FB supplies all of the necessary braking force.

Secondly, the algorithm checks saturation of SOC. If SOC saturates, FB supplies all of the force again. However, if SOC does not saturate, then EB supplies all of the braking force. This algorithm ensures regeneration optimization and safe stopping distance. It is also important to note that regenerative braking efficiency decreases dramatically in low battery voltage situations, as the resistance in the battery increases greatly [6]. Additionally, in case of SOC is greater than 90 percent, charging should be avoided as a safety issue. In conclusion, the optimum interval for regenerative braking is between 10 and 90 percent of the battery [7]. One of the factors which influencing regenerative braking efficiency is ability to charge. According to [8], charge power of battery is linearly proportional to regenerated energy. The relation can be obtained in Figure 1.3.

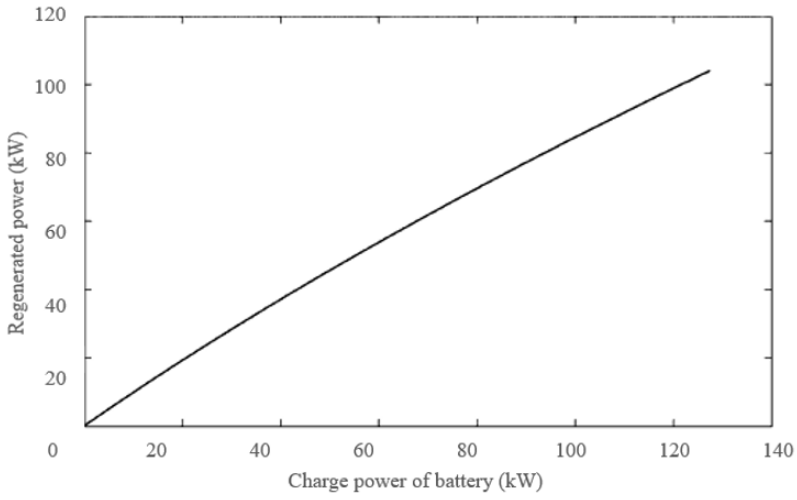

Figure 1.3 : Relationship between charge power and regenerated power of the battery [8].

While considering brake system strategies, one should analyze how to distribute the total force between the axles. It would be more efficient to utilize regenerative braking on front wheels because they consume approximately %65 of braking energy [9]. Based on this fact, there are three braking control strategies: series braking with optimal feel, series braking with optimal energy recovery, and parallel braking. Main aim in series braking with optimal feel is to ensure minimum braking distance and optimized driver feeling. In case of desired deceleration value is less than 0.2g, only

EB force is supplied. On the other hand, in case of desired deceleration is bigger than 0.2g the braking forces on front and rear axles are executed in conjunction with EB and FB in order to follow ideal brake force distribution curve [9]. If the vehicle's brake system is designed so that the distribution takes place above the ideal curve, rear wheels tend to lock first. In a similar way, the front wheels tend to lock before rear wheels if the distribution takes place below the curve. It is less undesired if front wheels locked first [10]. Series braking with optimal energy recovery's main aim is to gain as much as possible energy. In this strategy, EB is utilized prior. If demanded deceleration value is achievable with only EB, then EB is applied [9].

1.2.2 Drive cycles

Original equipment manufacturers (OEMs) need to test their prototype due to different reasons such as emission and power consumption measurements. However, testing them in a real world is not always easy and cheap solution. Hence, OEMs utilizes standardized drive cycles. They are set of data points containing vehicle speed and time. Additionally, it contains gear ratio in case of vehicle with manual transmission installed. Here are a few of the most common drive cycles: FTP75 test cycle is a transient test cycle for passenger and light duty cars. It contains both urban and highway scenario seperately. WLTC is a chassis dynamo-meter cycle for emission measurements in light duty vehicles. NYCC is a low speed city cycle. Japan 10-15 Mode is an urban test cycle for fuel consumption and emission certification [11].

1.3 Thesis Outline

After an introduction is made, rest of the thesis is planned as following: In chapter 2, used methodology in this study has been explained, the test vehicle and drive cycles features has shared. In chapter 3, results has been given in graph as outcome of followed methodology. In chapter 4, the final chapter, findings and contribution of this study has discussed. Additionally, the reader is given recommendations for future research of regenerative braking efficiency factors.

2. METHODOLOGY

The methodology used in this study included the analysis of regenerative braking efficiency in various cycles with a test vehicle. The test vehicle was subjected to seven various cycles. These cycles demonstrated different road conditions: urban, highway and mixed. Calculations were performed using Microsoft Excel, which allowed for accurate calculation and comparison of regenerative braking efficiency in each cycle. Overall, the methodology used in this study aimed to provide a comprehensive and accurate analysis of regenerative braking efficiency in different cycles, using same test vehicle for each cycle. Microsoft Excel is used to perform the calculations.

2.1 Test Vehicle Specifications

An E class sport utility battery EV is selected as a test vehicle. Detailed features are given in Table 2.1. The vehicle is powered by 250 kW electric motor. The features of the motor and battery are given at Table 2.2. Additionally, the motor's torque – speed graph is shown at Figure 2.1. Maximum and minimum (negative) motor moment at corresponding motor speed can be found on motor torque - speed characteristics.

Table 2.1 : Vehicle specifications.

	Test Vehicle
Length (mm)	4915
Height (mm)	1619
Width (mm)	1937
Curb Weight (kg)	2510
Gross Weight (kg)	3170
Drag Coefficient	0.29
Frontal Area (m^2)	2.65
Tire Diameter (mm)	0.316
Final Drive Ratio	9.2
Traction	4WD

2.2 Drive Cycles

The test vehicle executed seven various drive cycles to understand road condition effect over regenerative braking efficiency. To make a clear comparison, NYCC (New York City Cycle) and FTP 75 Highway are selected.

These drive cycles' vehicle speed- time graphs are shown in Results section. Graphs of the rest of five drive cycles are shown in Appendix section.

Table 2.2 : Motor and battery specifications.

	Motor - Battery
Number of motors	2
Motor type	Induction- asynchronous
Net Power (kW)	250
Net car power to weight ratio (watt/kg)	99.6
Max Net Torque (Nm)	664
Max motor speed (rpm)	9000
Battery Type	Lithium-Ion
Battery energy capacity (kWh)	95
Net battery energy capacity (kWh)	85

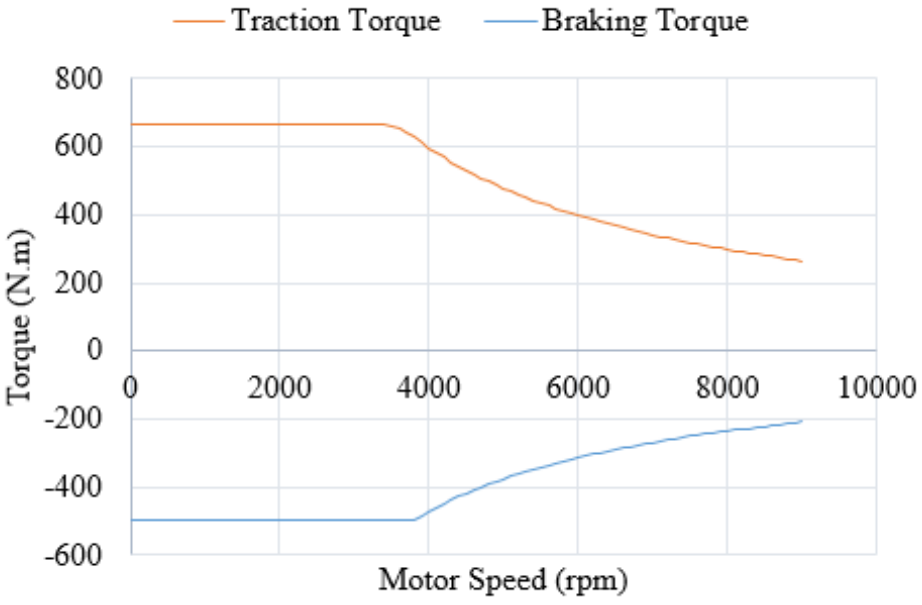

Figure 2.1 : Torque - speed characteristics of the motor.

2.3 Formulations

In this section, formulations were explained in depth.

2.3.1 Acceleration

Firstly, acceleration values were determined by conventional definition of acceleration which can be shown in equation 2.1.

$$a = \frac{du}{dt} = \frac{u_f - u_i}{t_f - t_i} \tag{2.1}$$

Acceleration value is shown as a, u_i and u_f are initial and final velocity whereas t_i and t_f are initial and final time value, respectively. It should be noted that lateral acceleration is not considered in this study that's why velocity refers to longitudinal velocity directly.

To give reader a good idea for braking intensity, the acceleration value is divided into gravity which assumed to be constant and 9.81 m/s^2.

If a is negative it means the vehicle is decelerating.

2.3.2 Force calculation

To calculate the force on the tire F_x , writing equation of motion along the longitudinal direction is necessary. This equation can be written as below:

$$F_x = F_B + F_{st} + F_r + F_L \tag{2.2}$$

In where F_B is the required force to keep the vehicle at desired acceleration, F_{st} is the grading resistance, F_r is the rolling resistance, F_L is the aerodynamic resistance.

In equation 2.3, F_B is written as below:

$$F_B = ma \tag{2.3}$$

In equation 2.3 , m represents mass of vehicle. However, since F_x should include rotational and non-rotational parts of the vehicle, effective mass of the vehicle m_e should take it into account.

$$m_e = m\lambda \tag{2.4}$$

Then, the mass factor λ can be obtained in following empirical equation taken from [12] :

$$\lambda = 1 + 0.04 + 0.0025G^2 \quad (2.5)$$

In equation 2.5, G represents final drive ratio of the vehicle. Hence, equation 2.3 should be transformed such as:

$$F_B = m_e a \quad (2.6)$$

In equation 2.7, Fst can be shown as:

$$F_{st} = mgsin\theta \quad (2.7)$$

where θ is slope angle of the road and zero in this study because the test vehicle is assumed to travel along a road without slope. Hence, F_{st} is zero as well.

F_r can be expressed as:

$$F_r = f_r W cos\theta \quad (2.8)$$

where W is weight of the test vehicle and f_r is the rolling resistance coefficient. The f_r is assumed constant for simplification and selected a proper value based on vehicle type and road condition [13].

The F_L can be expressed as:

$$F_L = 0.5\rho A c_x (u + u_w)^2 \quad (2.9)$$

where ρ is air density, A is frontal area of the vehicle, c_x is the drag coefficient and u_w is wind speed. Since wind speed is unpredictable in real life, it would be wise to ignore it for simplification. Hence, the equation (2.9) becomes:

$$F_L = 0.5\rho A c_x u^2 \quad (2.10)$$

Lastly, if F_x is negative it means the vehicle is subjected to the braking force F_b . If F_x is positive it means the vehicle is subjected to the tractive force F_t .

2.3.3 Motor speed calculation

Demanded motor speed n_m can be expressed via its relationship with vehicle speed:

$$n_m = \frac{60}{2\pi}\frac{u}{r}G \quad (2.11)$$

where r is tire radius of the vehicle.

2.3.4 Moment calculation

Demanded tire moment M_x can be expressed as:

$$M_x = F_X r \tag{2.12}$$

Demanded motor moment M_m can be expressed as:

$$M_m = M_X / G \tag{2.13}$$

2.3.5 Energy calculation

Braking energy W_b can be expressed as:

$$W_b = F_b x \tag{2.14}$$

where x is distance travelled on the corresponding second. The distance can be expressed as:

$$x = udt \tag{2.15}$$

Traction energy W_t can be expressed as:

$$W_t = F_t x \tag{2.16}$$

Finally, braking / traction ratio is founded by diving braking energy to traction energy:

$$r_{bt} = W_b / W_t \tag{2.17}$$

3. RESULTS

The test vehicle is ran for seven various drive cycles. In Table 3.1, main features of each drive cycle are shown. In first part of this section, only two of these cycles, NYCC and FTP75 Highway, are displayed in order to enhance comparison quality. The vehicle ran the cycles in its curb weight. Subsequently, in latter part of the section, graphs where weight of the vehicle has increased to its gross weight are displayed. Rest of the cycles can be viewed in Appendix section. These cycles are performed with curb weight of the vehicle. All graphs shown in this study are obtained via MS Excel.

3.1 Speed Profile

3.1.1 Vehicle speed profile

Vehicle speed profile of NYCC and FTP75 Highway are shown in Figure 3.1 and 3.2 respectively.

These graphs show the reader that NYCC is a cycle aimed to demonstrate city conditions whereas FTP75 Highway is an expressway.

Table 3.1 : Drive cycle features.

	Distance (m)	Duration (s)	Average speed (m/s)	Max speed (m/s)
City II	6210	867	7.16	1533
FTP75 Highway	16494	765	21.56	26.75
WLTC	23266	1800	12.92	36.47
FTP75 Urban	17677	1877	9.47	25.33
ECER15	10932	1220	8.96	33.33
NYCC	1899	598	3.17	12.39
Japan1015	4165	660	6.31	19.44

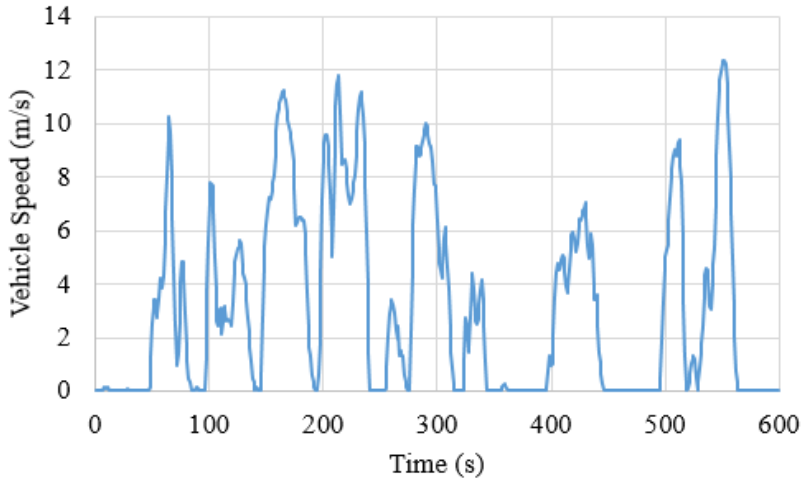

Figure 3.1 : NYCC vehicle speed profile.

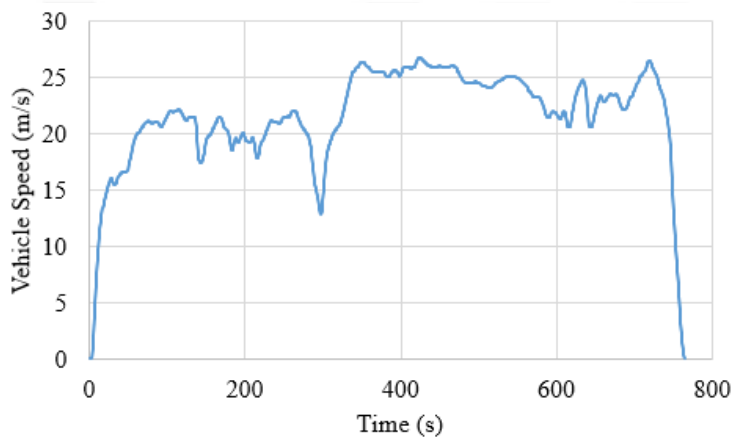

Figure 3.2 : FTP75 Highway vehicle speed profile.

3.1.2 Motor speed profile

Similarly to vehicle speed profile, motor speed profile of NYCC and FTP75 Highway are shown in Figure 3.3 and 3.4 respectively.

3.2 Acceleration Profile

Acceleration profile of NYCC and FTP75 Highway are shown in Figure 3.5 and 3.6 respectively. These graphs show the reader that there are lots of speed change in NYCC due to classical city conditions. In contrast, acceleration change occurs rarely in FTP75 Highway cycle. Additionally, standard deviation of NYCC is more than twice as big as FTP75 Highway: 0.67 and 0.30 respectively.

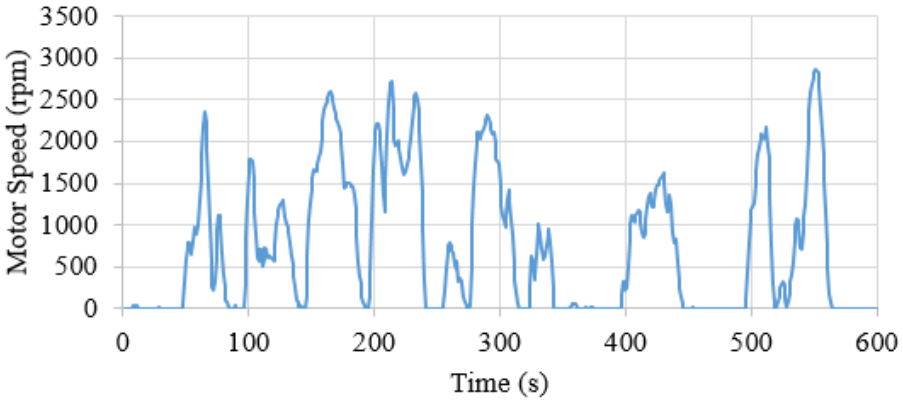

Figure 3.3 : NYCC motor speed profile.

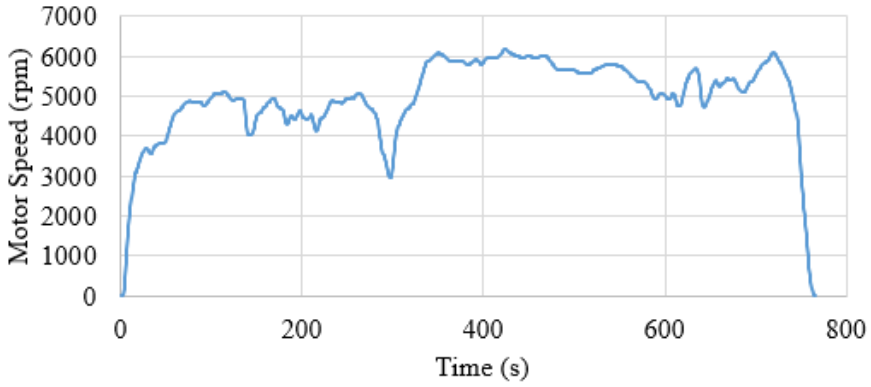

Figure 3.4 : FTP75 Highway motor speed profile.

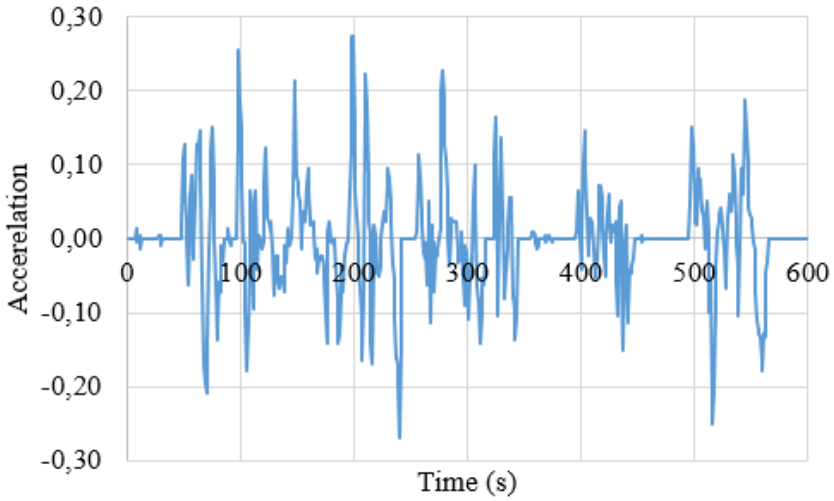

Figure 3.5 : NYCC acceleration profile.

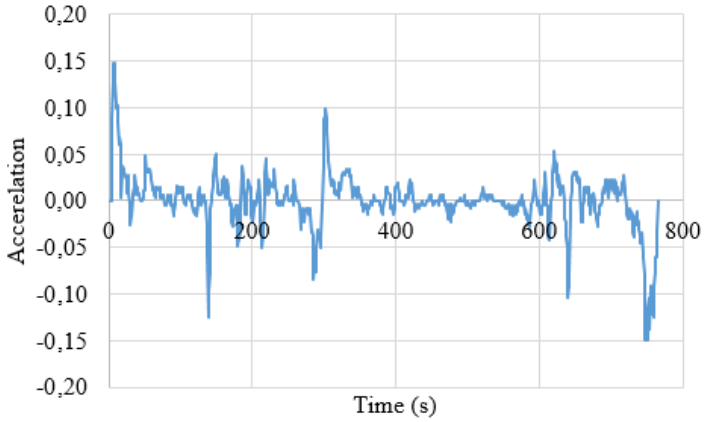

Figure 3.6 : FTP75 Highway acceleration profile.

3.3 Moment Profile

3.3.1 Tire moment

Tire moment profile of NYCC and FTP75 Highway are shown in Figure 3.7 and 3.8 respectively. These graphs show the reader demanded moment on the tire for each cycle.

3.3.2 Motor moment

Motor moment profile of NYCC and FTP75 Highway are shown in Figure 3.9 and 3.10 respectively. These graphs show the reader demanded motor moment for each cycle.

In Figure 3.11 and 3.12, motor sufficiency for traction and generator sufficiency for braking can be seen for the cycles.

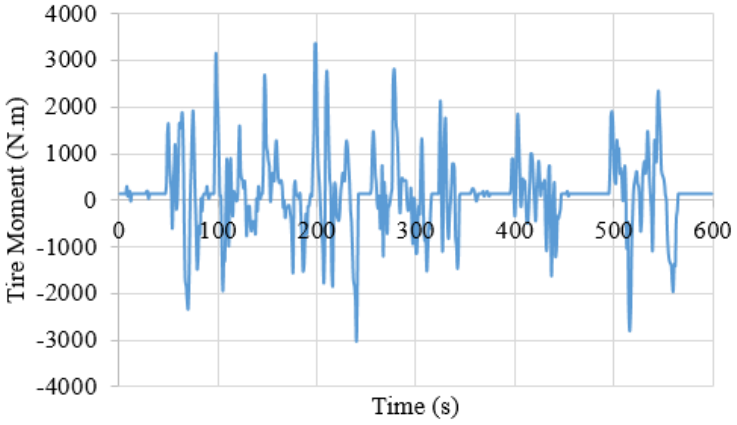

Figure 3.7 : NYCC tire moment profile.

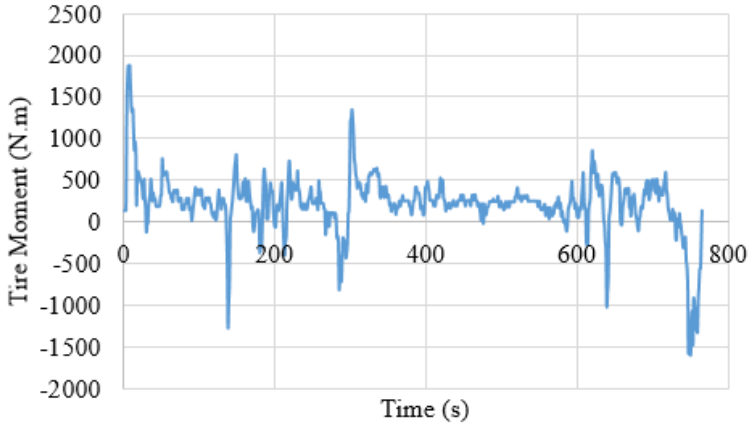

Figure 3.8 : FTP75 Highway tire moment profile.

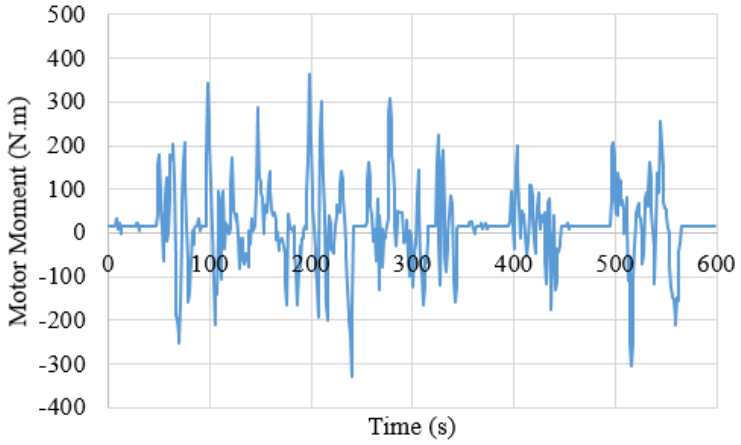

Figure 3.9 : NYCC motor moment profile.

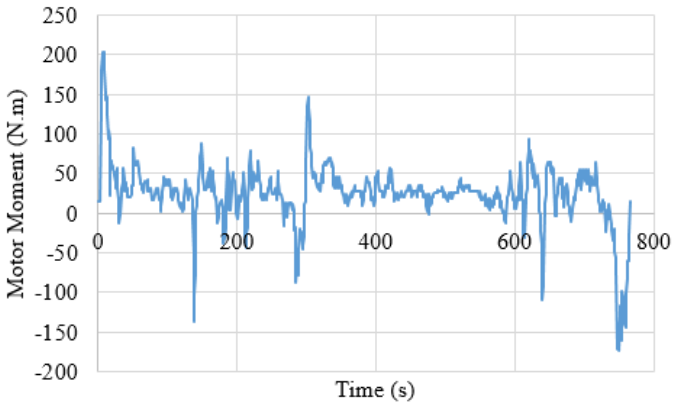

Figure 3.10 : FTP75 Highway motor moment profile.

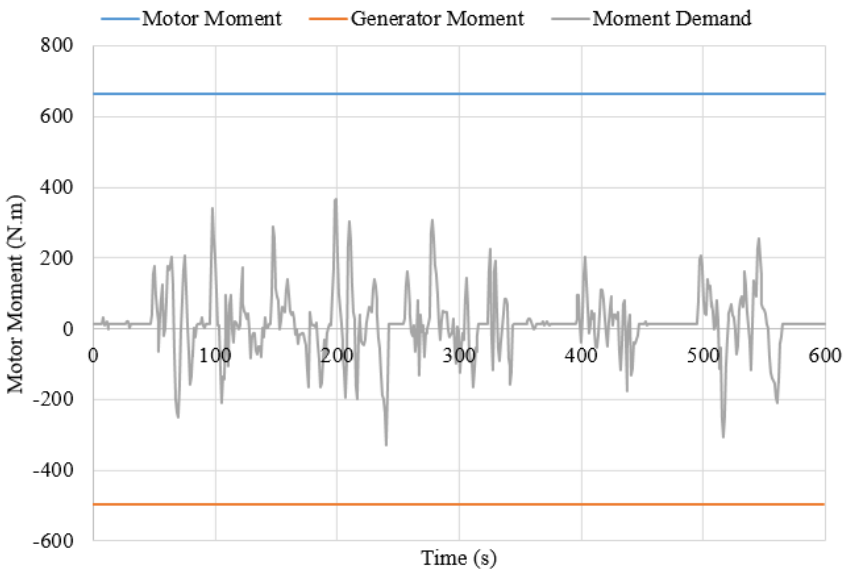

Figure 3.11 : NYCC demanded and maximum motor moment comparison.

3.4 Energy

3.4.1 Braking and traction energy

Total energy consumed by traction and potential recoverable energy by braking are given for NYCC and FTP75 Highway which shown in Figure 3.13 and 3.14 respectively.

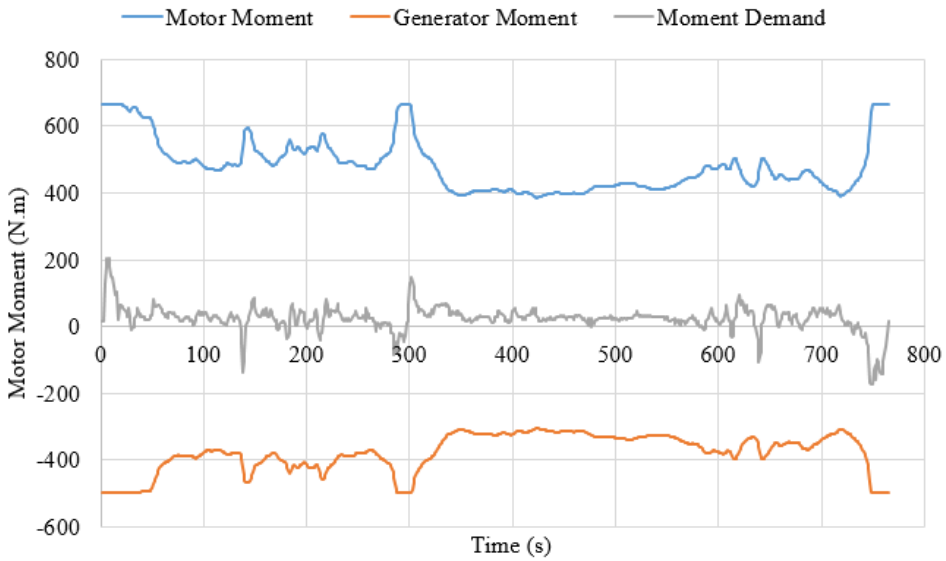

Figure 3.12 : FTP75 Highway demanded and maximum motor moment comparison.

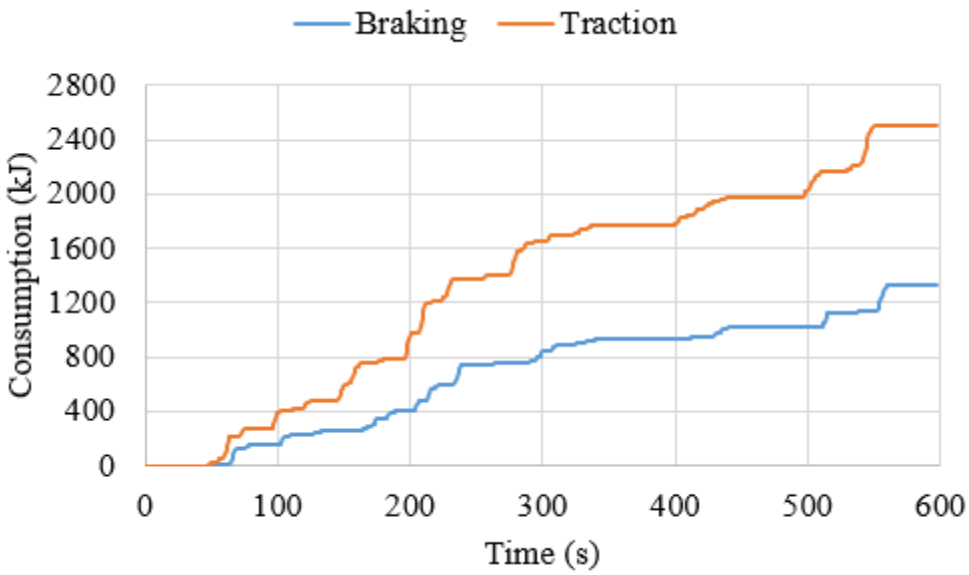

Figure 3.13 : NYCC traction and braking energy.

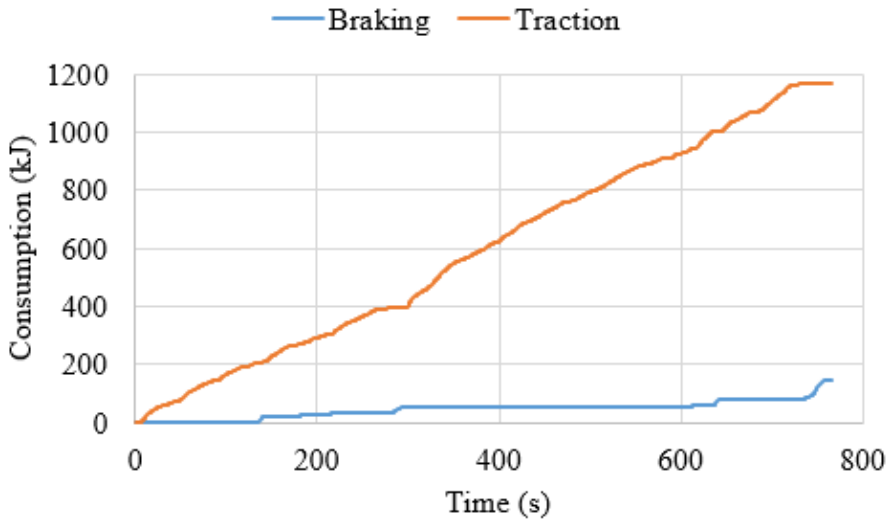

Figure 3.14 : FTP75 Highway traction and braking energy.

3.4.2 Braking to traction ratio

Braking to traction ratio are given for NYCC and FTP75 Highway which shown in Figure 3.15 and 3.16 respectively.

3.5 Gross Weight Results

Since vehicle speed, motor speed and acceleration values depend on the cycles, it is not necessary to repeat these graph because they are identical with curb weight graphs.

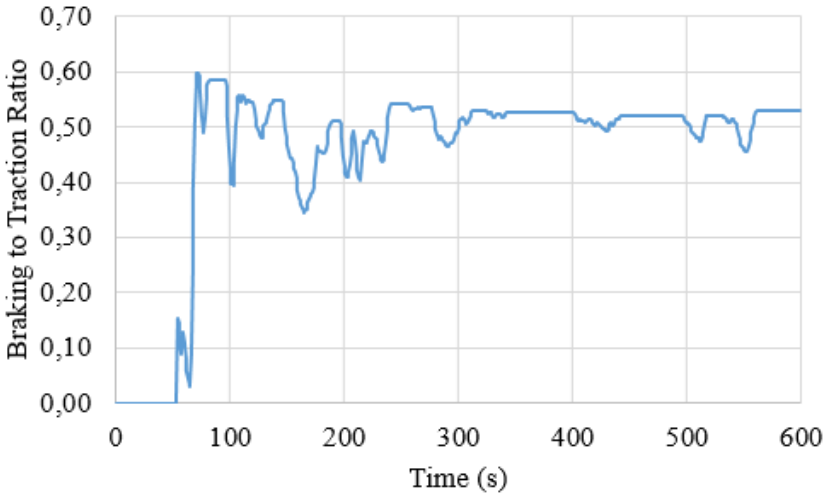

Figure 3.15 : NYCC braking to traction ratio.

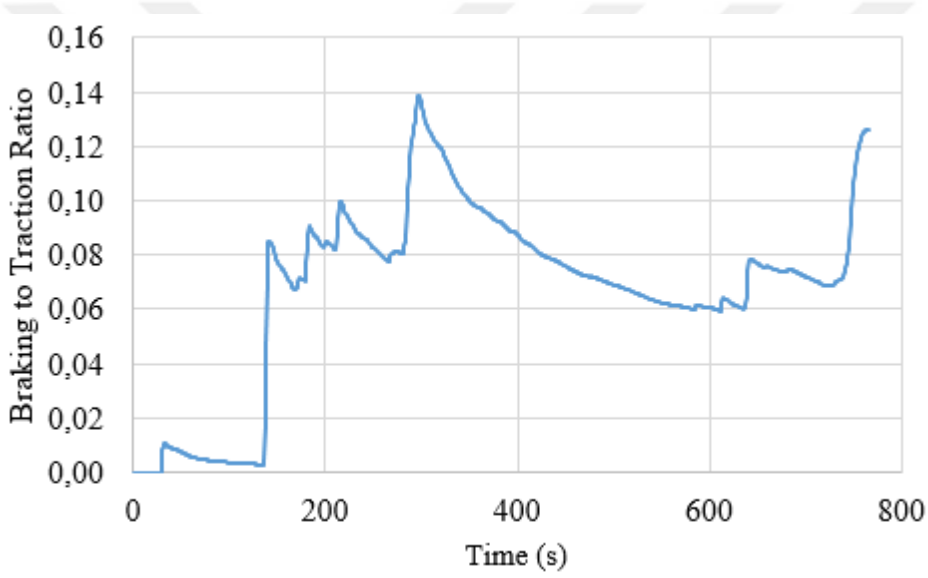

Figure 3.16 : FTP75 Highway braking to traction ratio.

Tire moment profiles of the cycles with gross weight vehicle are shown in Figure 3.17 and 3.18 respectively. Motor moment profile of NYCC and FTP75 Highway for gross weight are shown in Figure 3.19 and 3.20 respectively. These graphs show the reader demanded motor moment for each cycle.

In Figure 3.21 and 3.22, motor sufficiency for traction and generator sufficiency for braking can be seen for the cycles.

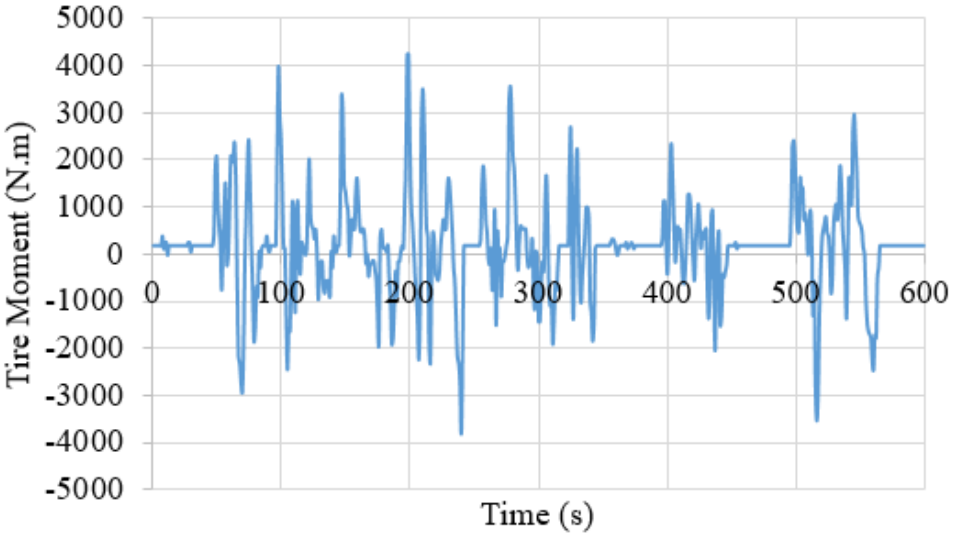

Figure 3.17 : NYCC tire moment profile for gross weight.

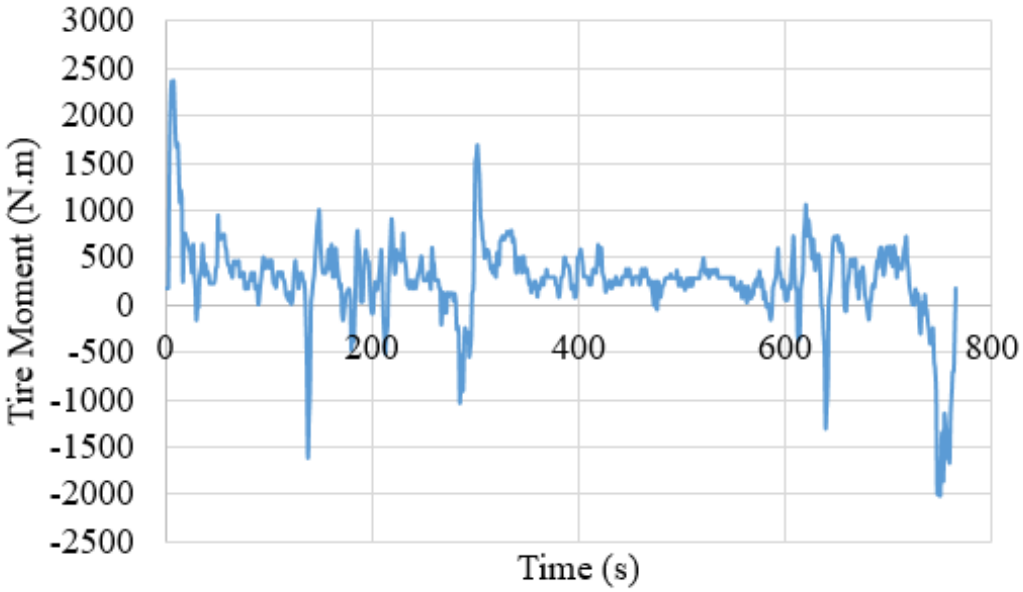

Figure 3.18 : FTP75 Highway tire moment profile for gross weight.

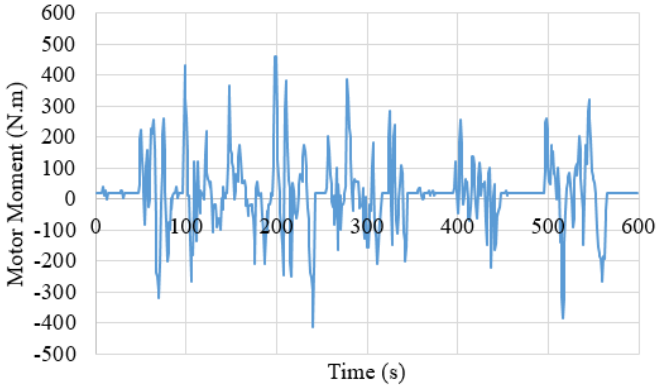

Figure 3.19 : NYCC motor moment profile for gross weight.

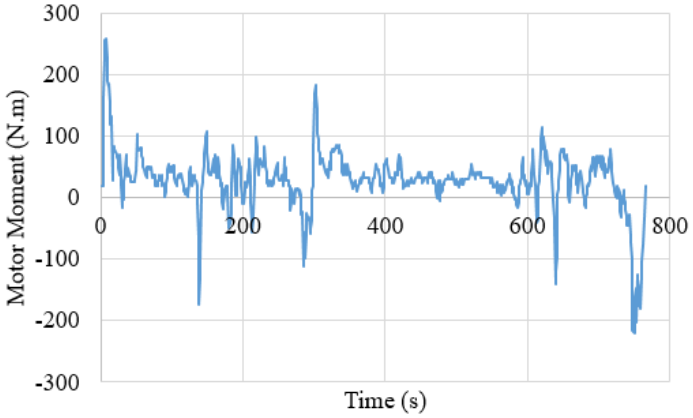

Figure 3.20 : FTP75 Highway motor moment profile for gross weight.

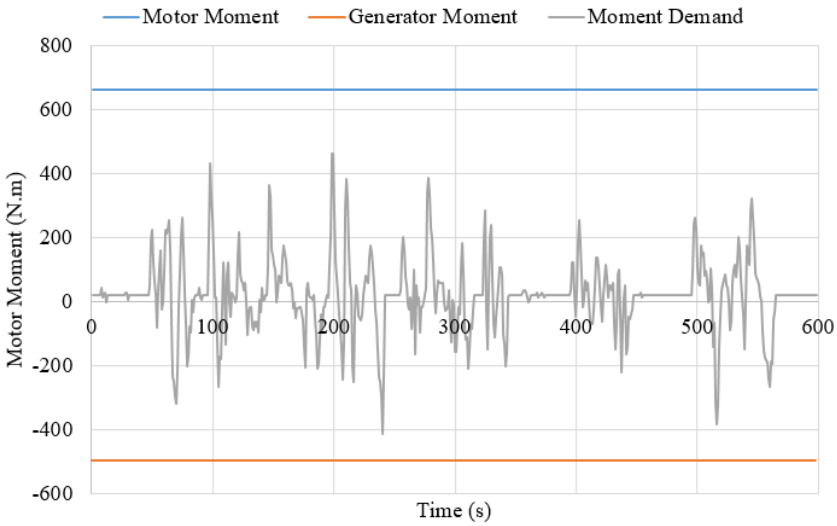

Figure 3.21 : NYCC demanded and maximum motor moment comparison for gross weight.

Total energy consumed by traction and potential recoverable energy by braking are given for NYCC and FTP75 Highway with gross weight which shown in Figure 3.23 and 3.24 respectively.

3.5.1 Braking to traction ratio

Braking to traction ratio are given for NYCC and FTP75 Highway with gross weight which shown in Figure 3.25 and 3.26 respectively.

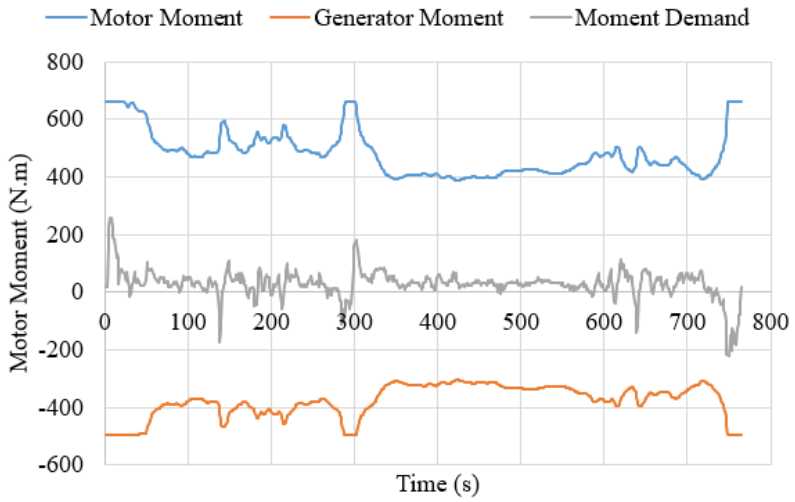

Figure 3.22 : FTP75 Highway demanded and maximum motor moment comparison for gross weight.

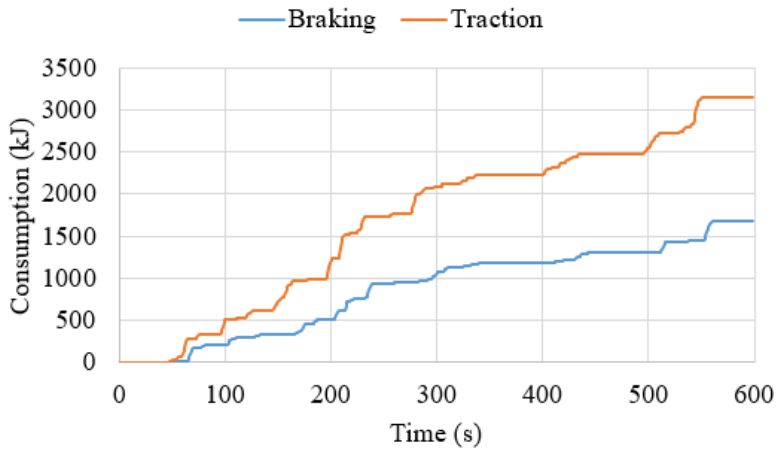

Figure 3.23 : NYCC traction and braking energy for gross weight.

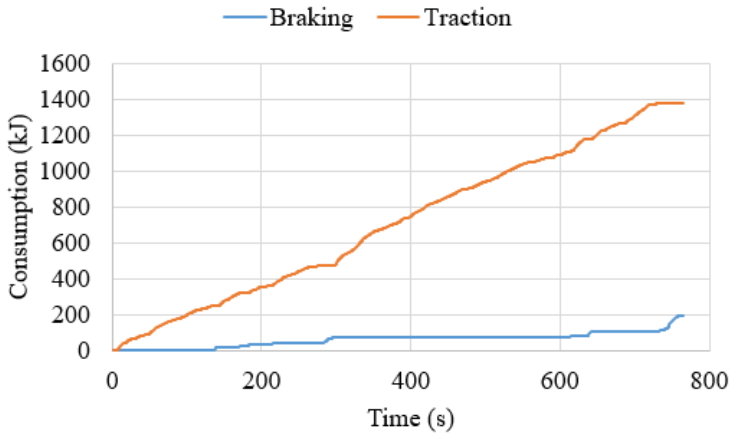

Figure 3.24 : FTP75 Highway traction and braking energy for gross weight.

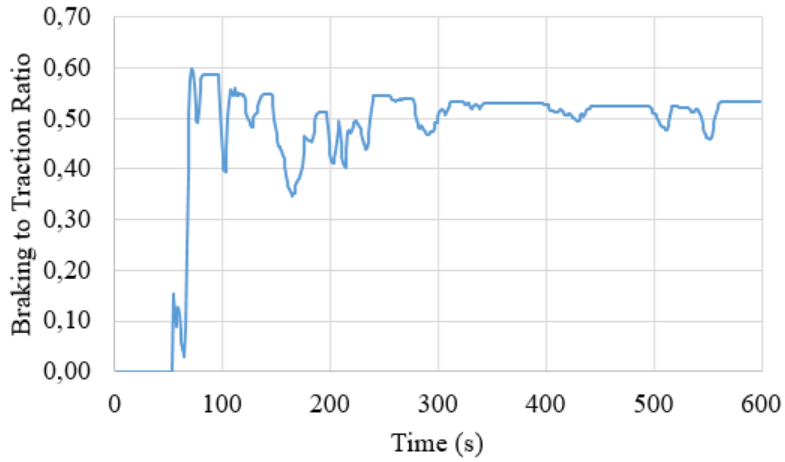

Figure 3.25 : NYCC braking to traction ratio for gross weight.

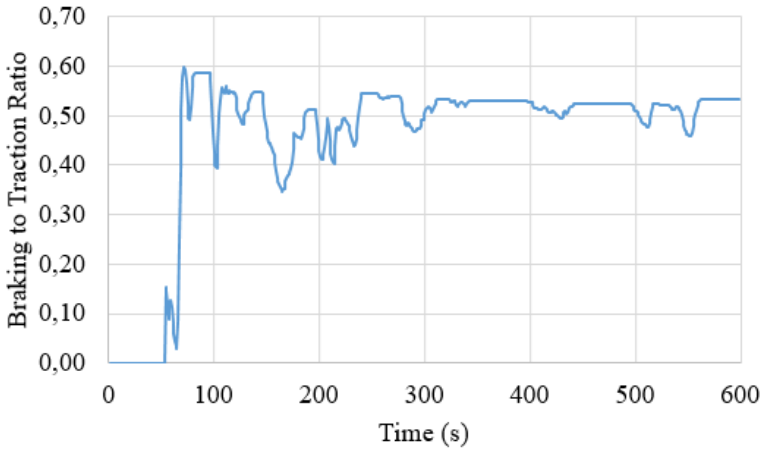

Figure 3.26 : FTP75 Highway braking to traction ratio for gross weight.

4. CONCLUSION AND RECOMMENDATIONS

Within the scope of this study, regenerative braking power and its efficiency compared to traction power were calculated on various common cycles. These cycles consisted urban, highway and mixed conditions. In these cycles, very high acceleration which enables ABS activation is not reached. Road slope and battery conditions were not taken into account. Vehicle weight was its curb weight.

Firstly, velocities taken from cycles are used to obtain acceleration and corresponding motor speed. Then, required tire force and moment are calculated based on vehicle specifications such as frontal area and tire diameter. Afterwards, moment demanded from motor is calculated according to tire moment. Finally, maximum and demanded moment corresponding to motor speed are compared. It is seen that the motor can compensate the braking force by regenerative braking only.

Secondly, braking and traction energy are calculated by instantaneous force and distance covered at each seconds. Then all braking and traction energy are summed separately. Afterwards, braking to traction ratio is obtained. Inherently, every cycles used in this study have different distance values. It can be seen that in Table 4.1 with their braking and traction consumption. It is clear that, making comparison between the cycles is not very reasonable due to different travelled distance.

Table 4.1 : Cycle comparison in terms of energy consumption.

	Distance (km)	Braking (kJ)	Traction (kJ)
City II	6.2	2324	5461
FTP75 Highway	16.5	1468	11666
WLTC	23.3	6818	21110
FTP75 Urban	17.7	6288	16155
ECER15	10.9	2854	9098
NYCC	1.9	1328	2507
Japan1015	4.2	1581	3643

For the sake of comparison quality, their braking and traction values were divided by travelled distance. It can be seen that in Table 4.2 with corresponding braking to traction ratios. Then, it is wise to comparison the cycle in consumed energy per km

and ratio. It is obtained that braking and traction consumption energy values are higher in city conditions than highway conditions. For instance, the vehicle consumed 353.88 kJ/km for braking and 909.24 kJ/km for traction in FTP75 Urban cycle whereas it consumed 88.98 for braking and 707.32 kJ/km for traction in FTP75 Highway cycle.

Table 4.2 : Cycle comparison in terms of energy consumption per kilometer.

	Braking per km (kJ/km)	Traction per km (kJ/km)	Braking to Traction Ratio
City II	374	879	0.43
FTP75 Highway	88.98	707.32	0.13
WLTC	293.02	907.32	0.32
FTP75 Urban	353.88	909.24	0.39
ECER15	261.09	832.29	0.31
NYCC	698.99	1320.08	0.53
Japan1015	379.5	874.7	0.43

Lastly, it was determined that braking to traction ratio varies according to the cycle. The ratio varied between 0.13 and 0.53 in chosen cycles. This variance can be explained by cycle condition. City cycles had higher braking to traction ratio than highway cycles due to frequent acceleration changes. These changes increase the force required on the tires, F_x , and causes braking and traction per km values to increase. To give reader a better understanding, NYCC and FTP75 Highway cycles are selected and compared. NYCC has braking to traction more than as twice as FTP75 Highway: 0.53 to 0.13. In other words, the test vehicle has ability to gain more energy back to battery in NYCC compared to FTP75 Highway. This support the idea that it is more frequent for motor to work as a generator in city conditions. Utilizing this braking energy for traction leads to more distance covered with same charging duration. On the other hand, highway condition are not very useful for regenerative braking. Acceleration changes are not often, the test vehicle brakes and accelerates rarely. This fact increases charging demand because SOC decrease can not be compromised. In addition to that comparison, the vehicle's weight has increased to gross weight and tests are executed in NYCC and FTP75 Highway cycles again. The comparison can be seen in Table 4.3. Braking and traction energy have increased approximately as equal as weight has increased, about %26 in city conditions. Hence, braking / traction ratio did not change significantly. However, in highway conditions, braking energy increased by %32 whereas traction energy increased by only %18. This increase in

energy values made the braking / traction ratio higher roundabout %12. In other words, weight increase effects braking energy more than traction energy in highway conditions. Then, regenerative braking efficiency becomes higher. It is also crucial to note that motor and generator characteristics was still able to meet demanded moment from tire with gross weight regardless of whether it's positive or not. Regenerative braking can fully supply all of the braking energy in both city and highway conditions.

For further study, it may be recommended to include the condition which ABS is intervened because cycle used in this study exclude regular driving scenarios. Any high deceleration rates do not occur which makes tires lock up and enables ABS. Another recommendation for further study is to include slope scenarios. In this study, the measurements are executed on flat surface. The slope is also expected to influence the overall regenerative braking ratio. As a last recommendation, driver behavior can be simulated. This is one of the factors influencing braking to traction ratio as well.

Table 4.3 : Cycle comparison in terms of energy consumption per kilometer.

	NYCC		FTP75 Highway	
	Curb Weight	Gross Weight	Curb Weight	Gross Weight
Braking (kJ)	1327.56	1681.33	1467.63	1938.12
Traction (kJ)	2507.18	3156.92	11666.23	13748.49
Braking per km (kJ/km)	698.99	885.26	88.98	117.51
Traction per km (kJ/km)	1320.08	1662.18	707.32	833.56
Braking/Traction ratio	0.53	0.53	0.13	0.14

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APPENDICES

APPENDIX A: Motor and Vehicle Speed Profiles of the Cycles
APPENDIX B: Acceleration Profiles of the Cycles
APPENDIX C: Tire and Motor Moment Profiles of the Cycles
APPENDIX D: Energy Consumption Profiles of the Cycles
APPENDIX E: Braking to Traction Ratios of the Cyclesaps

APPENDIX A

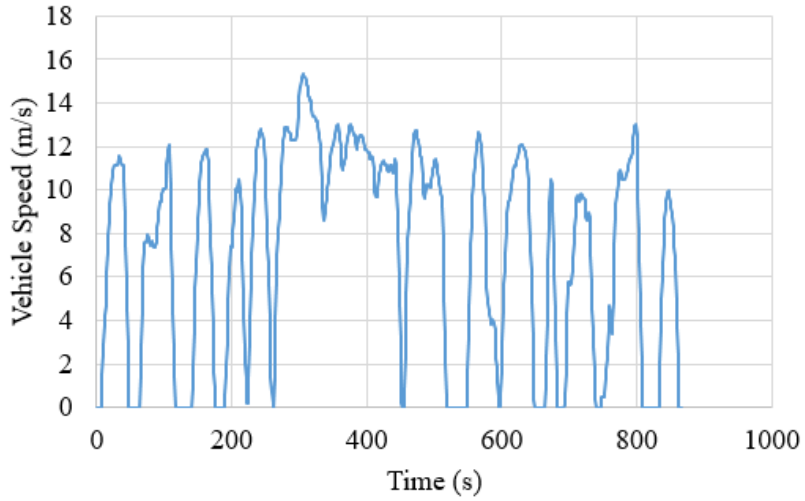


Figure A.1 : Vehicle speed profile of City II.

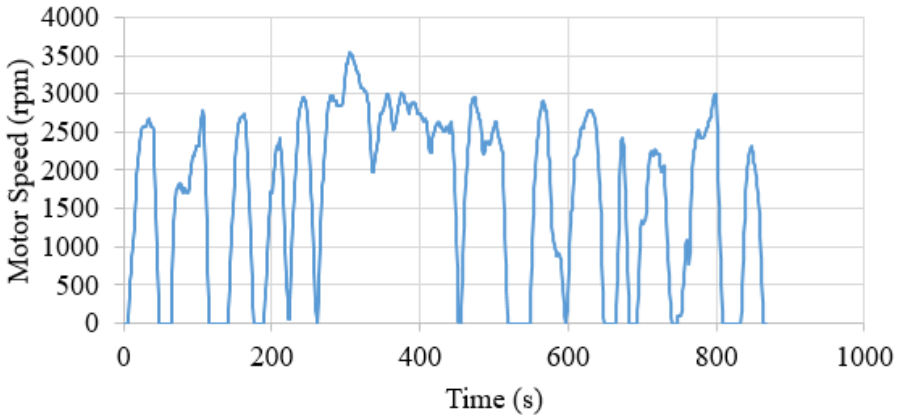


Figure A.2 : Motor speed profile of City II.

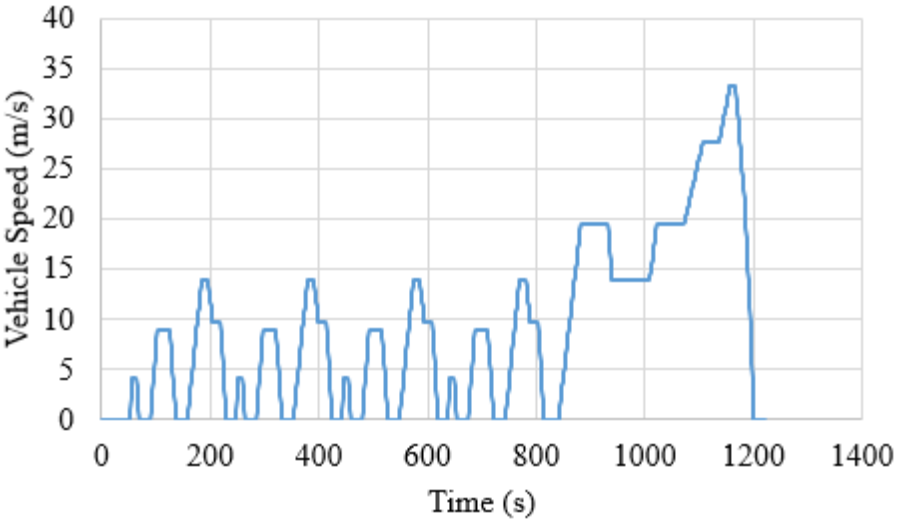
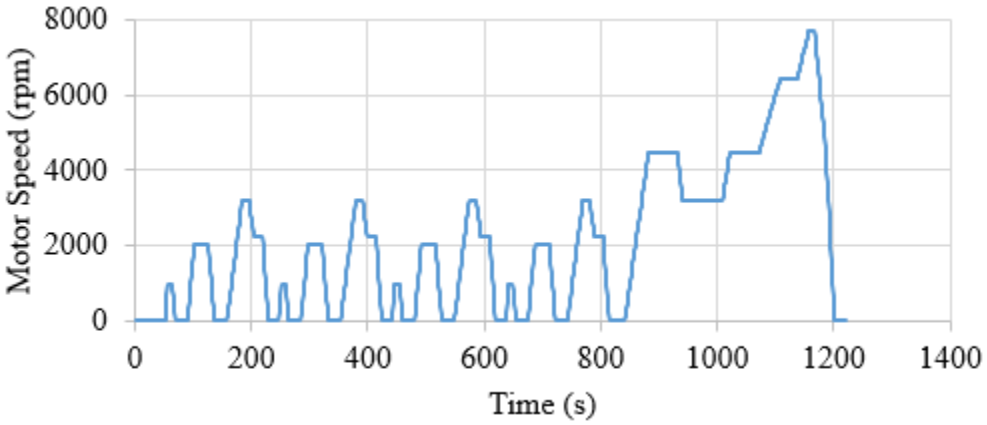


Figure A.3 : Vehicle speed profile of ECER15.



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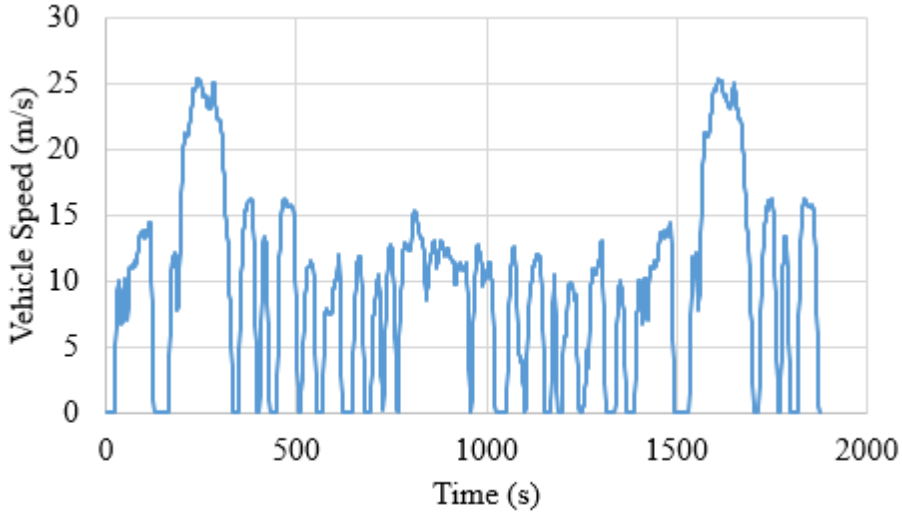

Figure A.5 : Vehicle speed profile of FTP75 Urban.

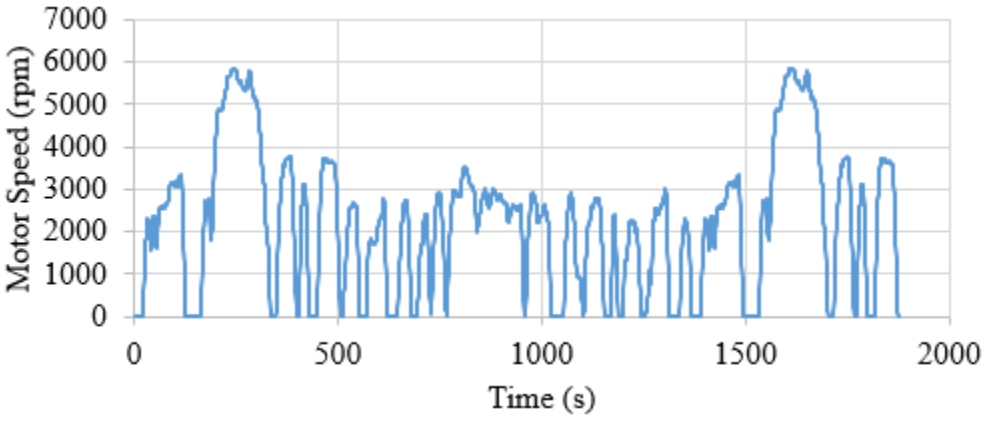

Figure A.6 : Motor speed profile of FTP75 Urban.

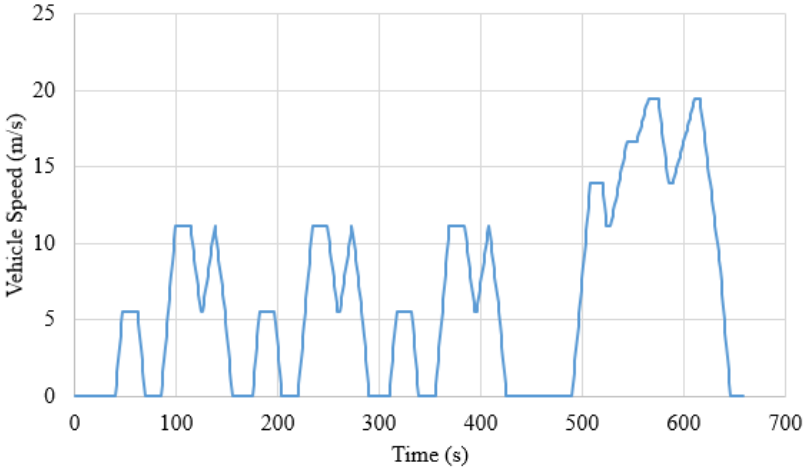

Figure A.7 : Vehicle speed profile of Japan 10-15.

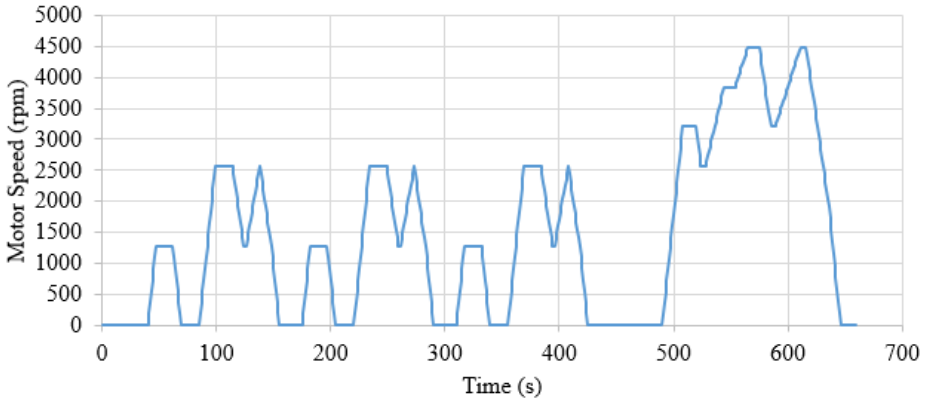

Figure A.8 : Motor speed profile of Japan 10-15.

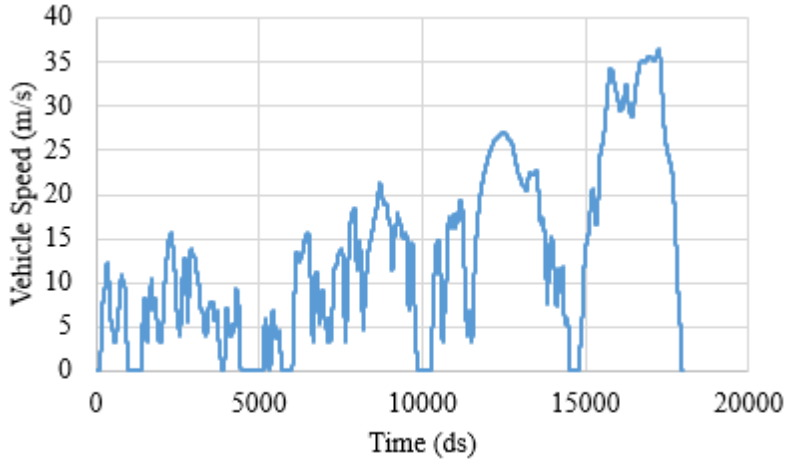

Figure A.9 : Vehicle speed profile of WLTC.

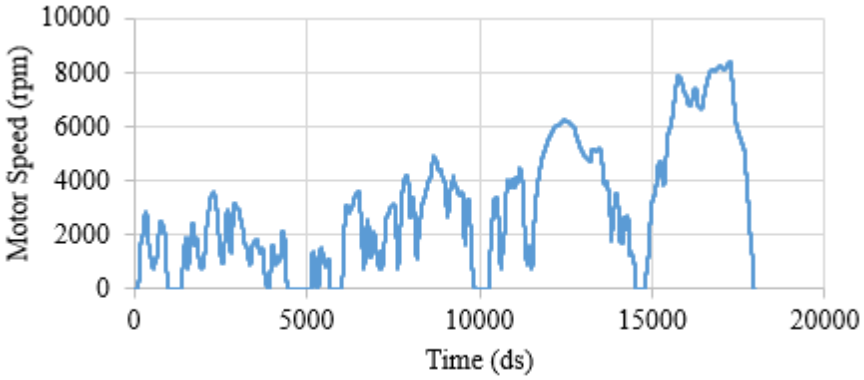

Figure A.10 : Motor speed profile of WLTC.

APPENDIX B

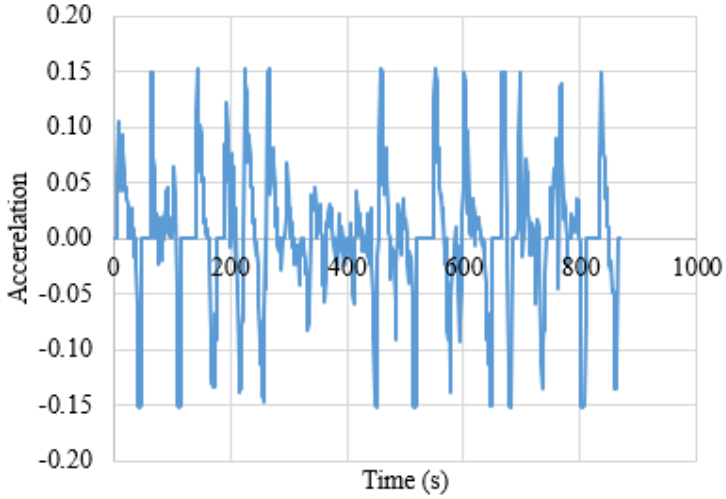

Figure B.1 : Acceleration profile of City II.

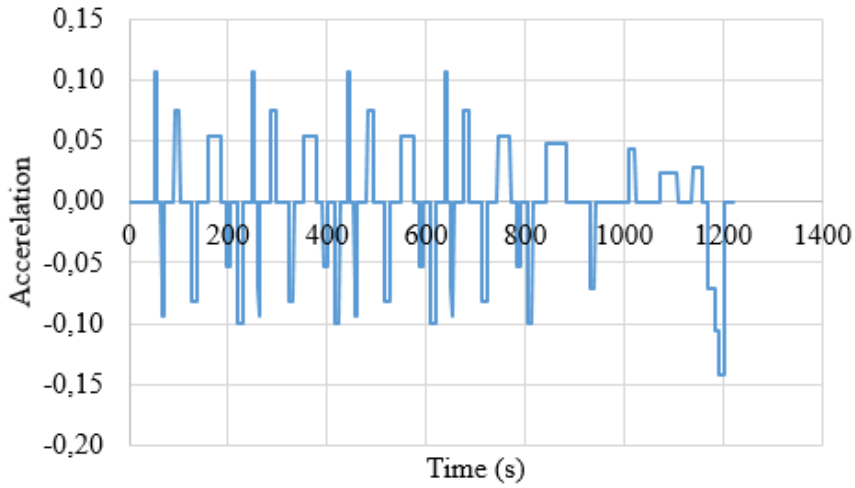

Figure B.2 : Acceleration profile of ECER15.

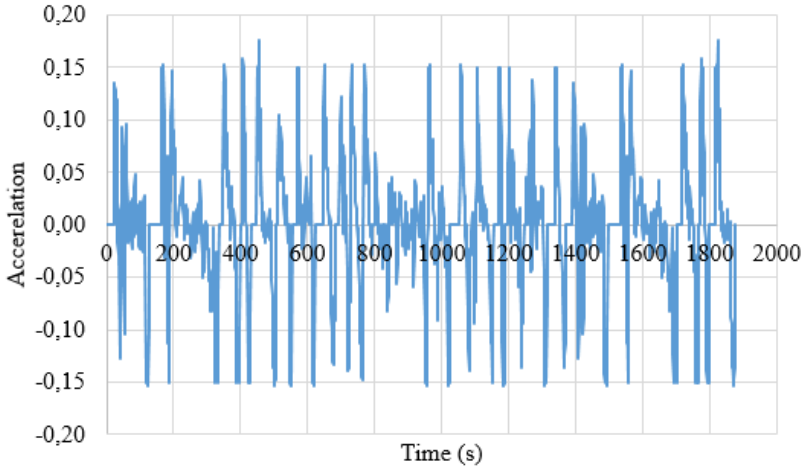

Figure B.3 : Acceleration profile of FTP75 Urban.

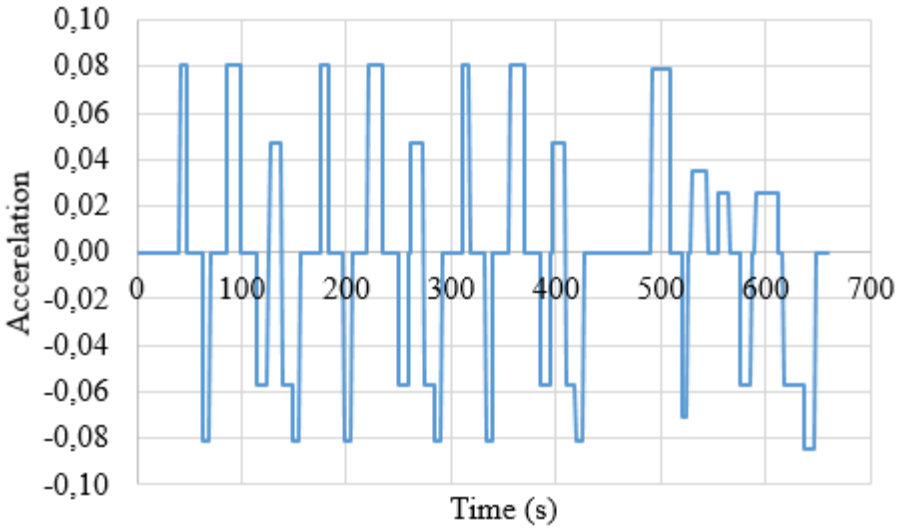

Figure B.4 : Acceleration profile of Japan 10-15.

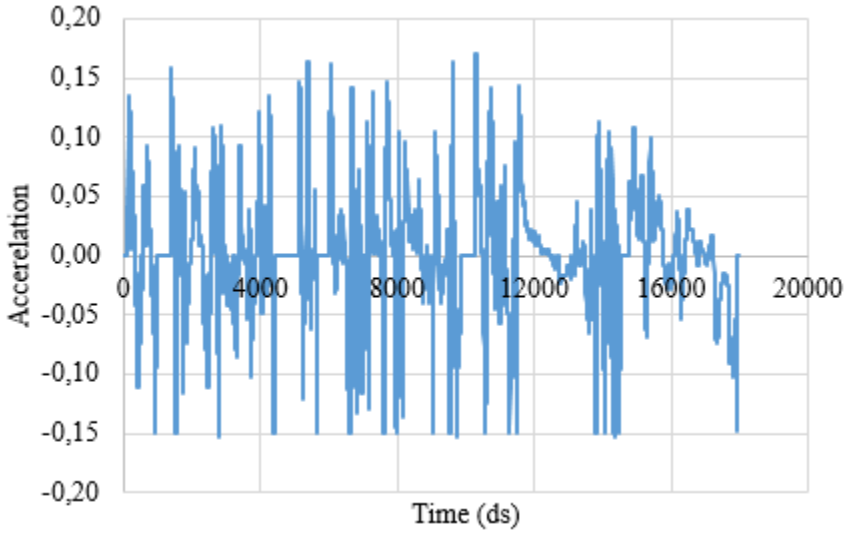

Figure B.5 : Acceleration profile of WLTC.

APPENDIX C

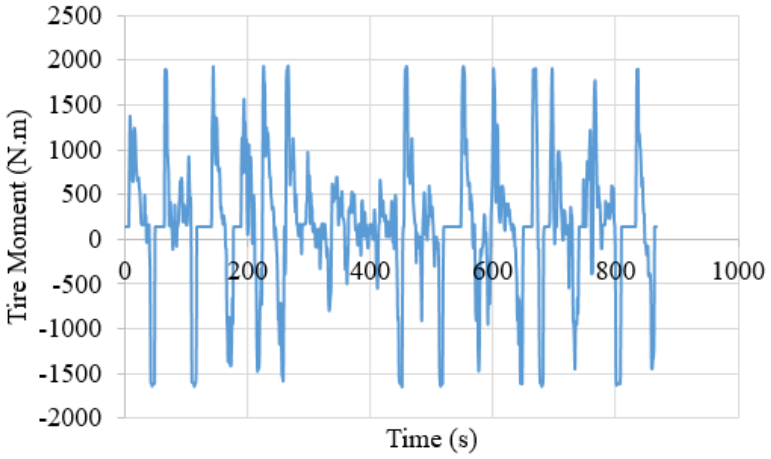

Figure C.1 : Tire moment profile of City II.

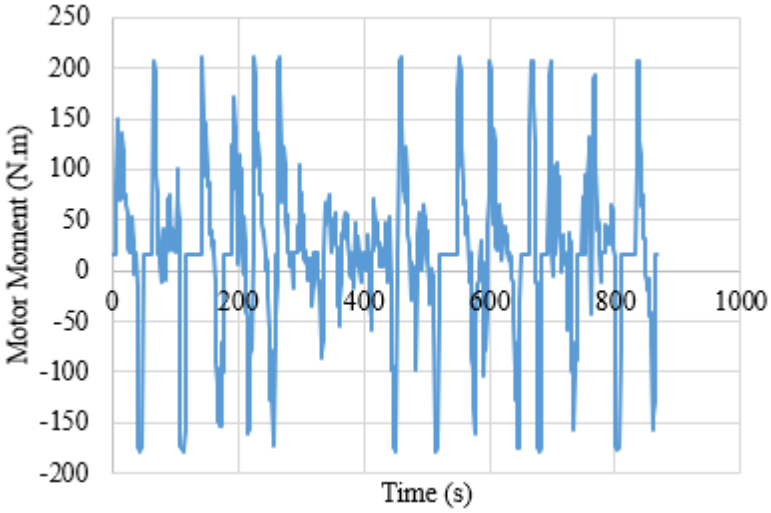

Figure C.2 : Motor moment profile of City II.

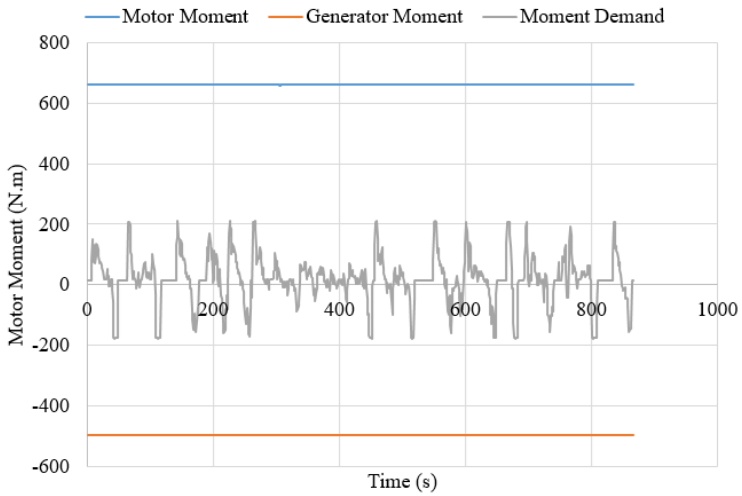

Figure C.3 : Demanded and maximum motor moment comparison of City II.

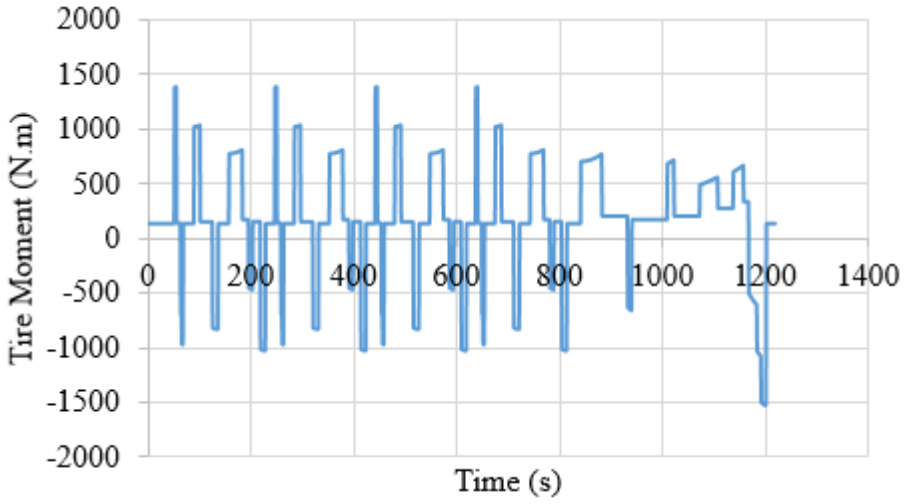

Figure C.4 : Tire moment profile of ECER15.

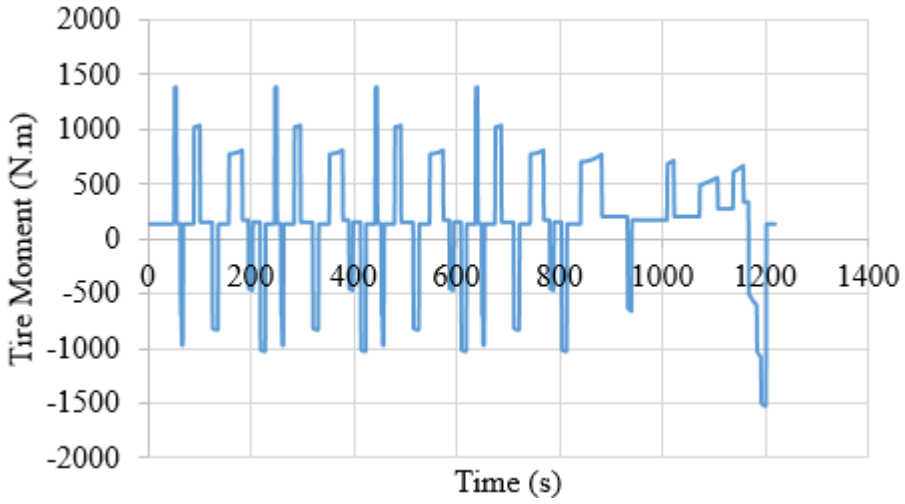

Figure C.5 : Motor moment profile of ECER15.

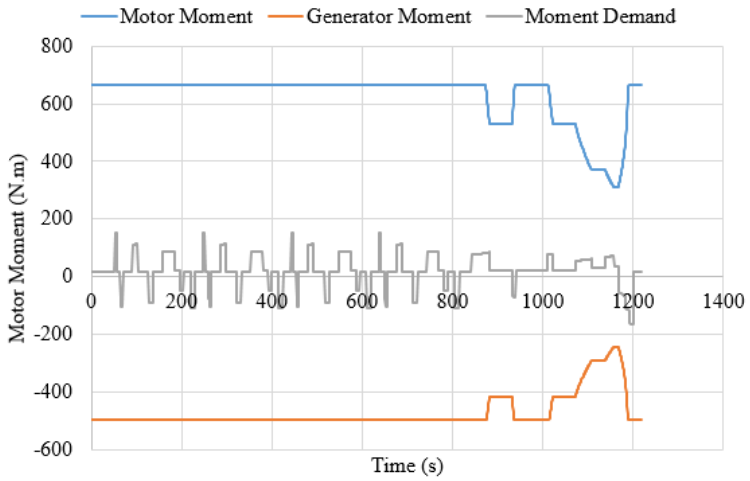

Figure C.6 : Demanded and maximum motor moment comparison of ECER15.

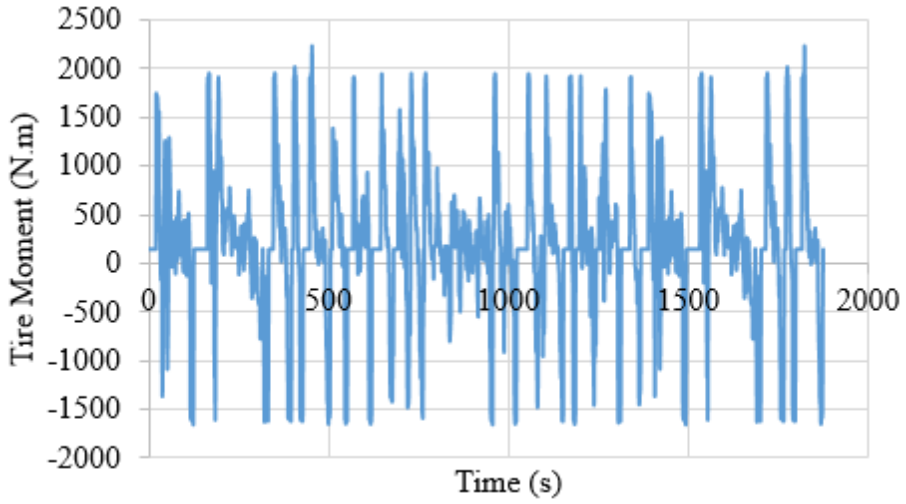

Figure C.7 : Tire moment profile of FTP75 Urban.

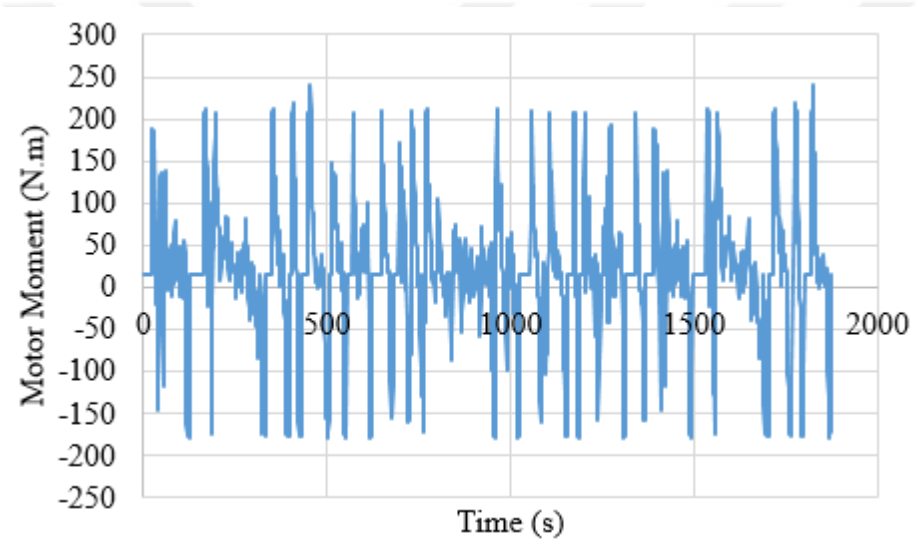

Figure C.8 : Motor moment profile of FTP75 Urban.

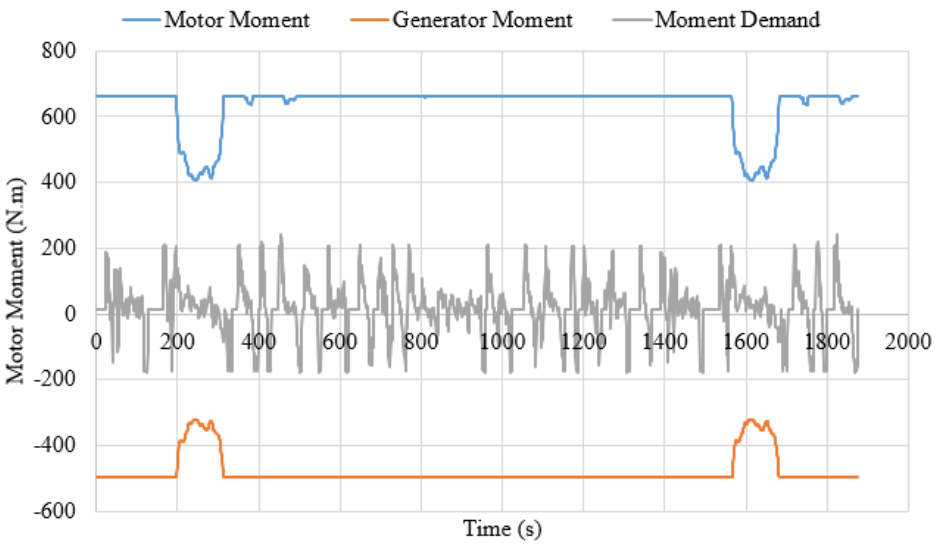

Figure C.9 : Demanded and maximum motor moment comparison of FTP75 Urban.

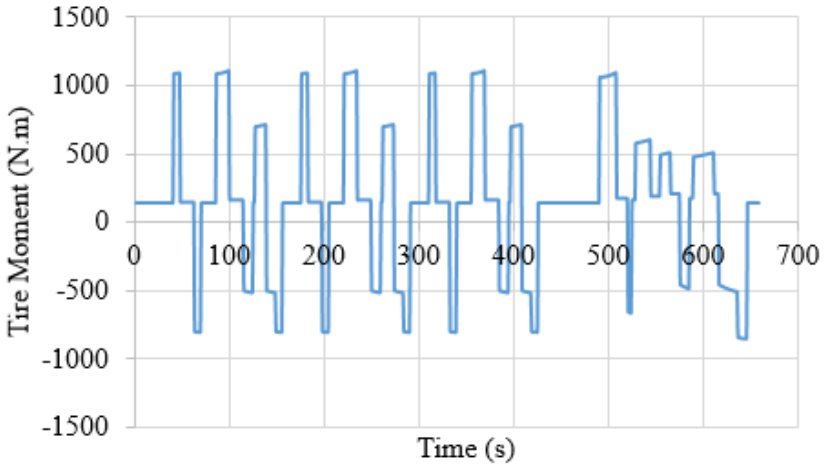

Figure C.10 : Tire moment profile of Japan 10-15.

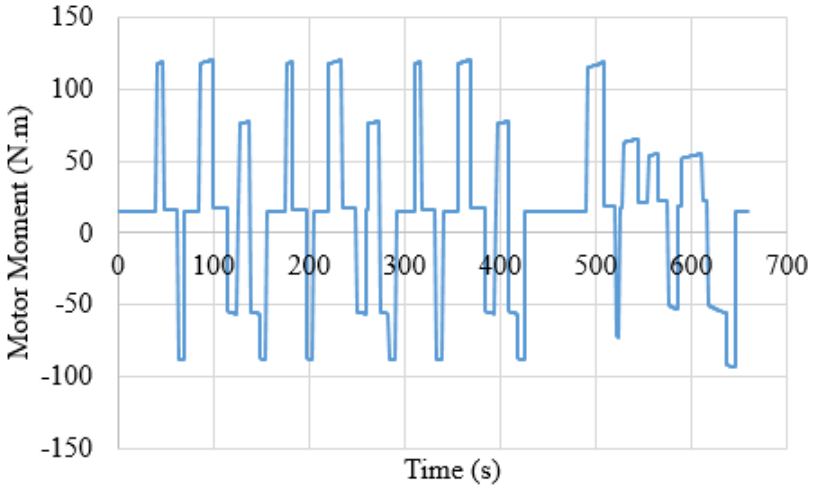

Figure C.11 : Motor moment profile of Japan 10-15.

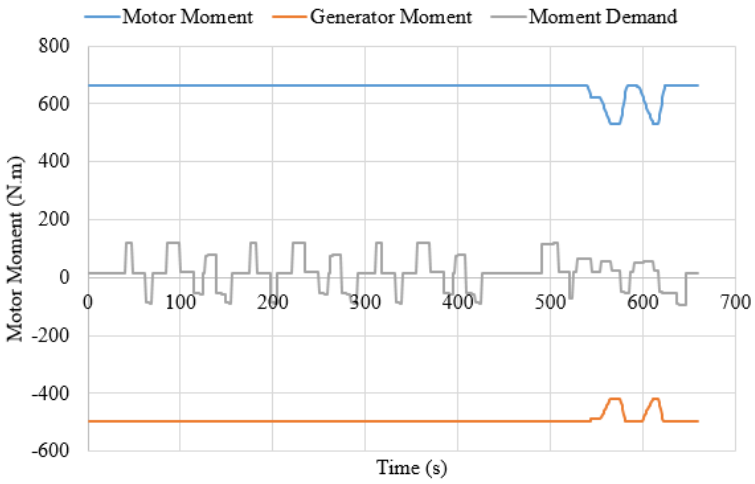

Figure C.12 : Demanded and maximum motor moment comparison of Japan 10-15.

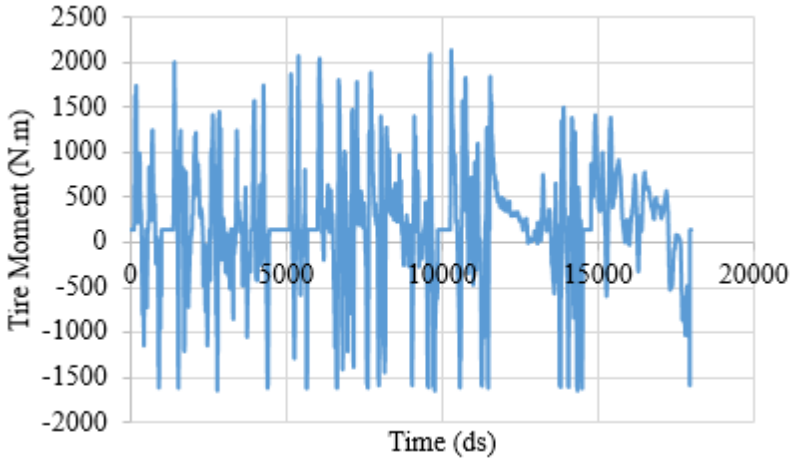

Figure C.13 : Tire moment profile of WLTC.

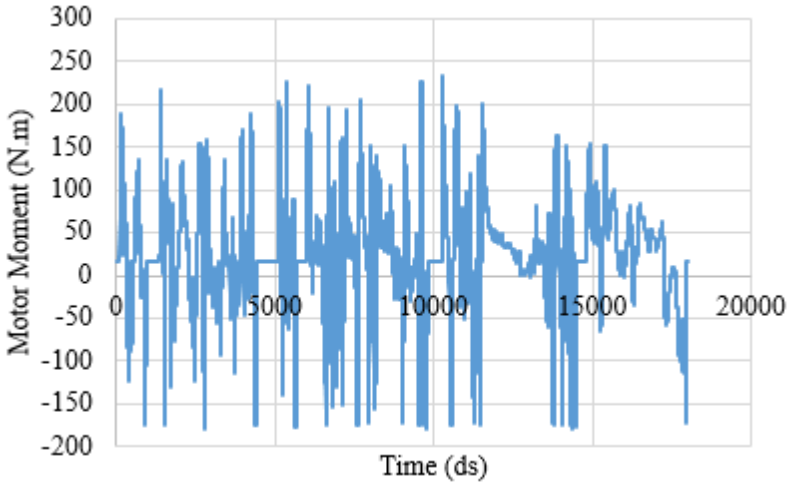

Figure C.14 : Motor moment profile of WLTC.

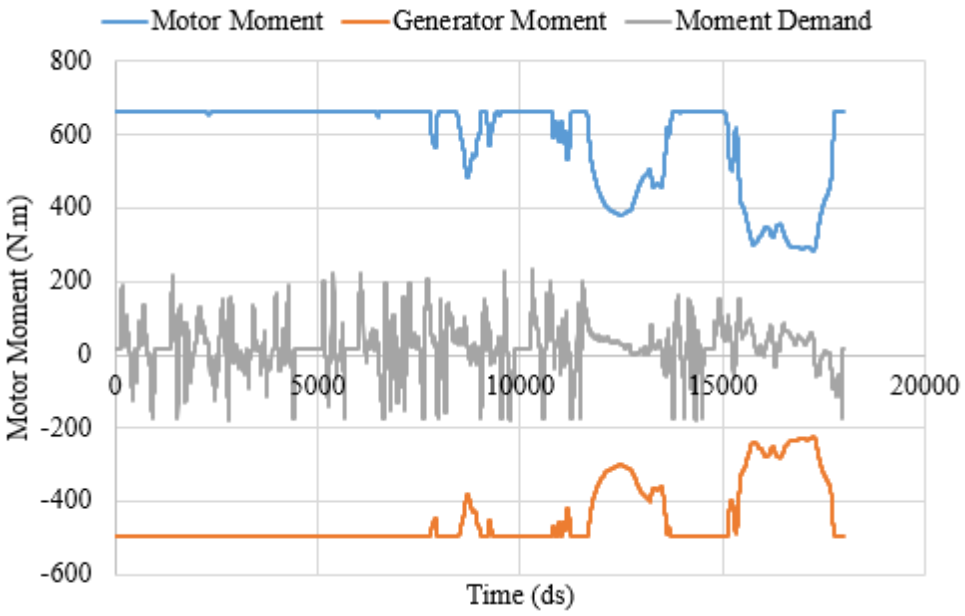

Figure C.15 : Demanded and maximum motor moment comparison of WLTC.

APPENDIX D

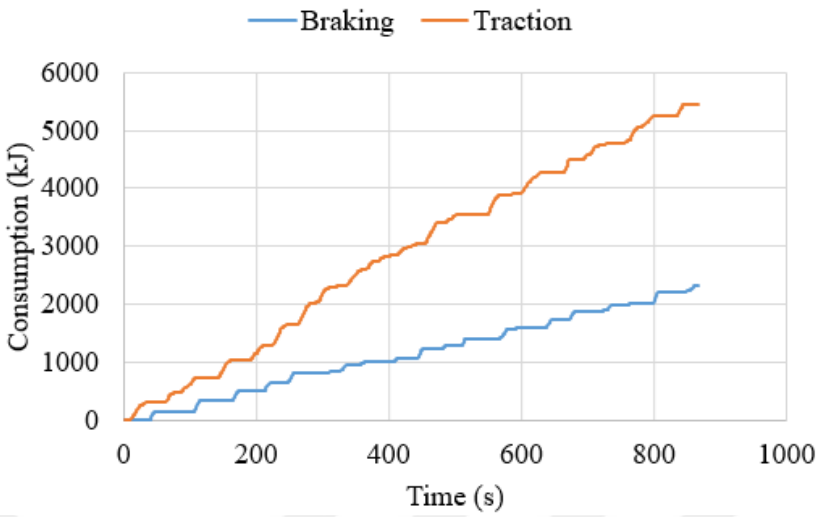

Figure D.1 : Traction and braking energy of City II.

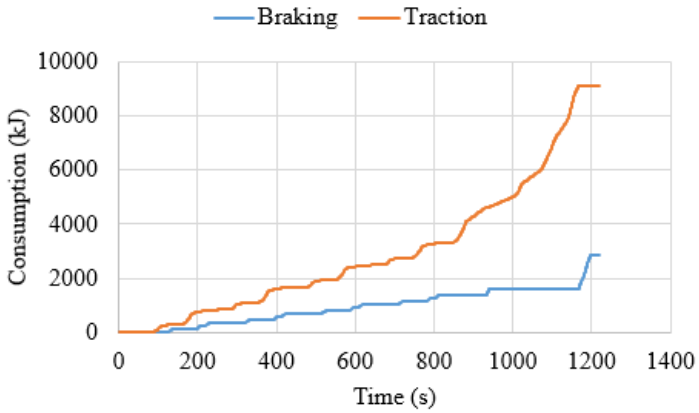

Figure D.2 : Traction and braking energy of ECER15.

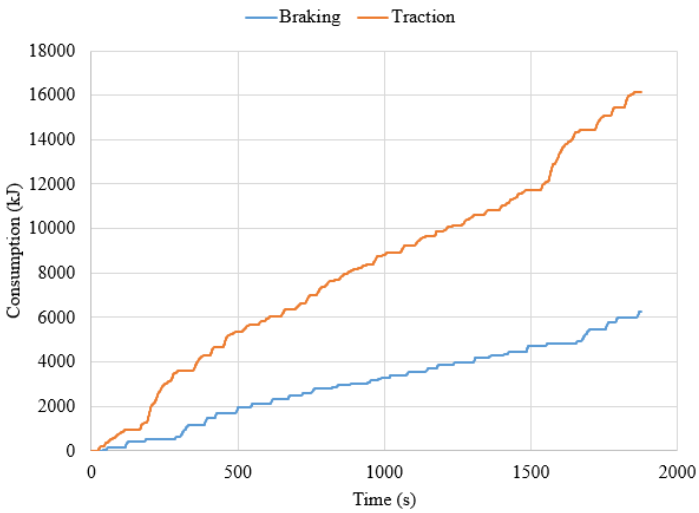

Figure D.3 : Traction and braking energy of FTP75 Urban.

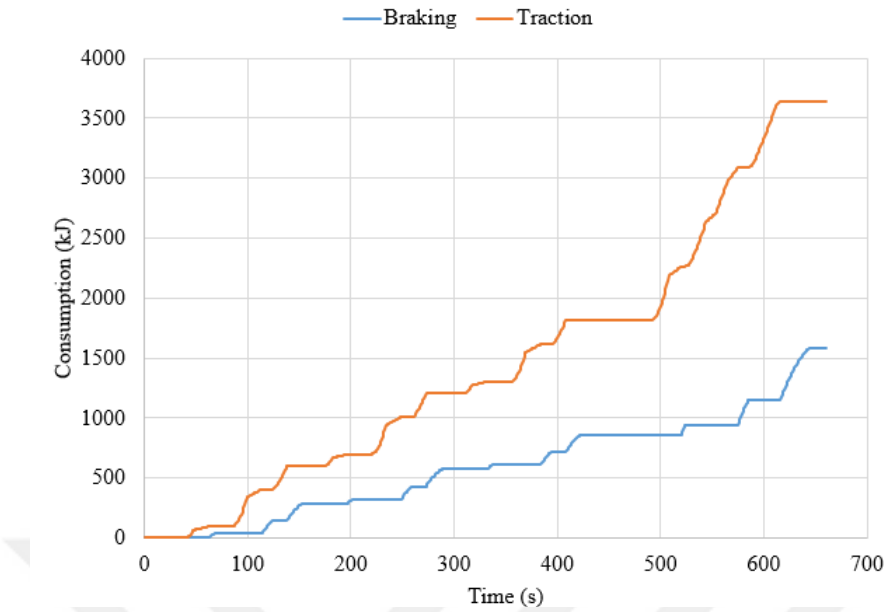

Figure D.4 : Traction and braking energy of Japan 10-15.

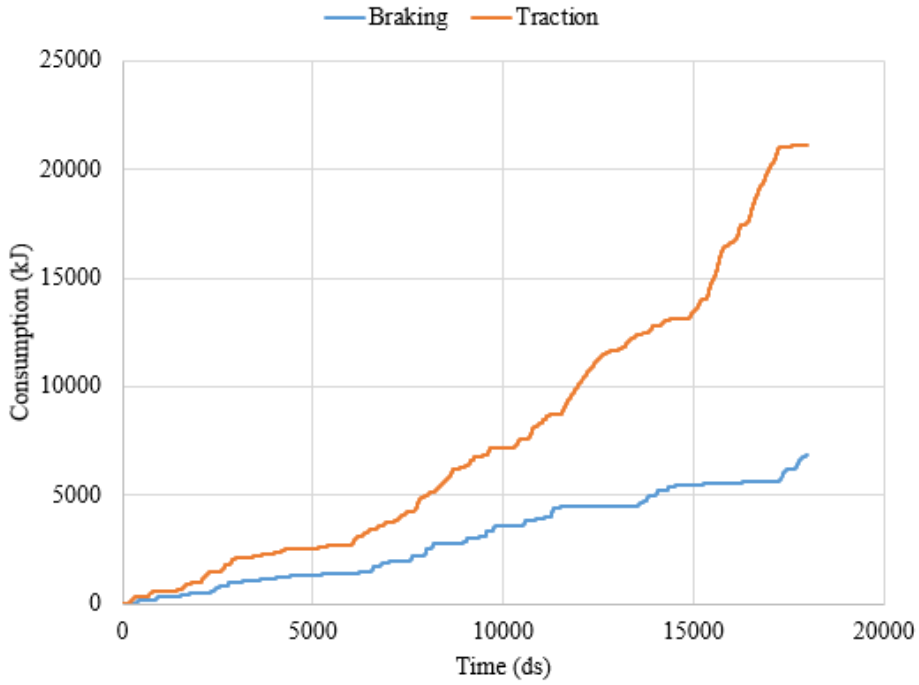

Figure D.5 : Traction and braking energy of WTLC.

APPENDIX E

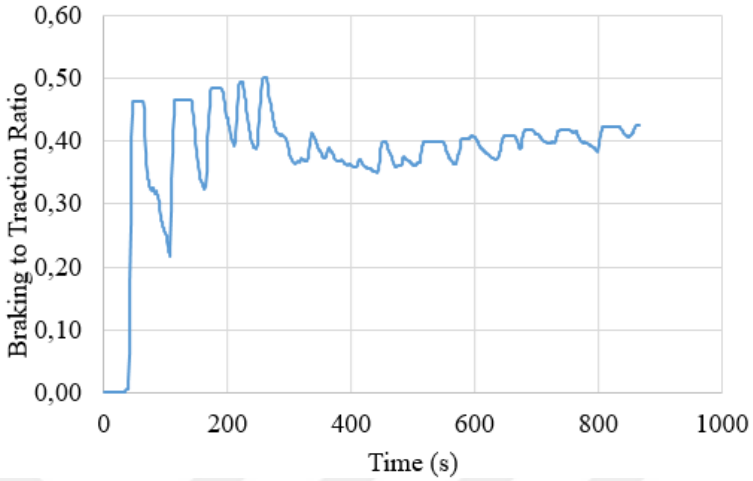

Figure E.1 : Braking to traction ratio of City II.

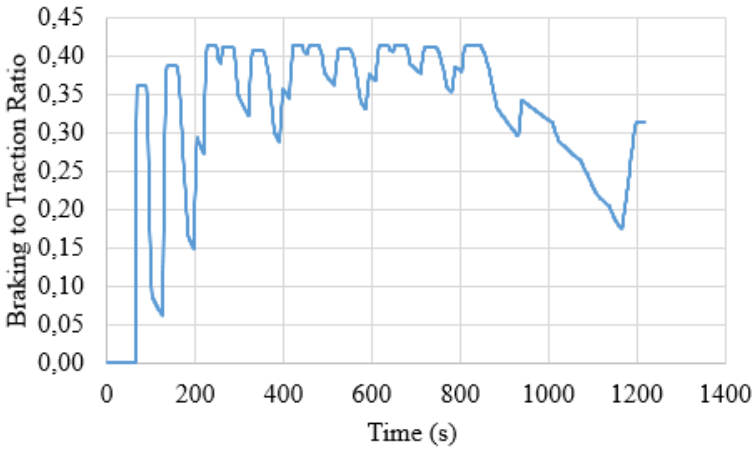

Figure E.2 : Braking to traction ratio of ECER15.

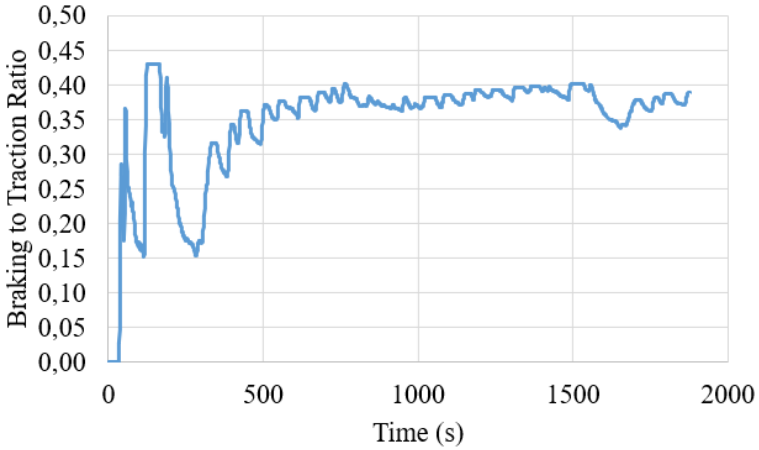

Figure E.3 : Braking to traction ratio of FTP75 Urban.

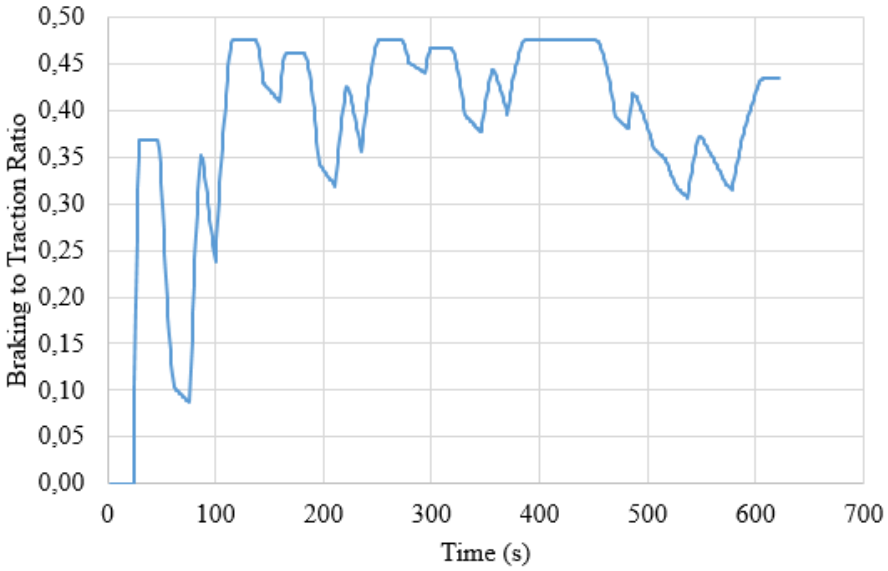

Figure E.4 : Braking to traction ratio of Japan 10-15.

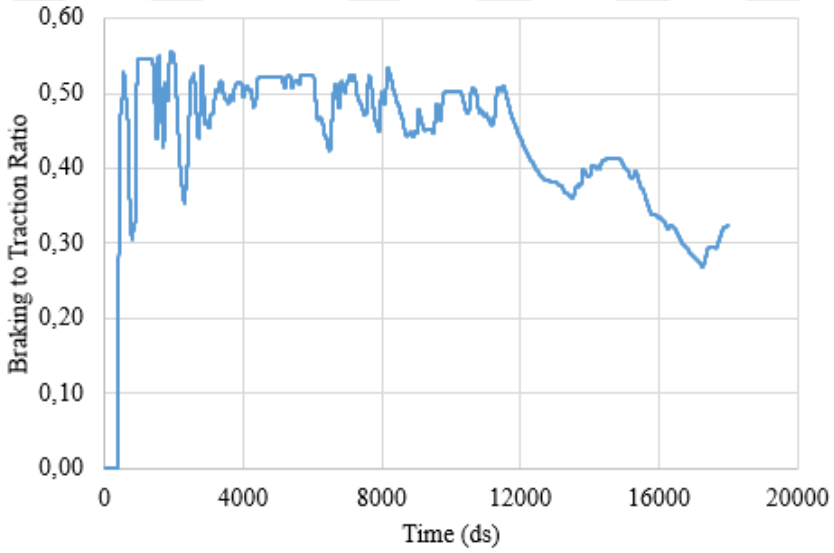

Figure E.5 : Braking to traction ratio of WTLC.

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