ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc. THESIS

Çağla DERİCİOĞLU

DESIGN AND IMPLEMENTATION OF ALGORITHMS FOR ONE PEDAL DRIVING IN ELECTRIC BUSES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 26/06/2018.

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Assoc. Prof. Dr. Mehmet U. CUMA	Prof. Dr. Mehmet TÜMAY	Asst. Prof. Dr. Mustafa SAVRUN
SUPERVISOR	MEMBER	MEMBER

This MSc Thesis is written at the Department of Institute of Natural and Applied Sciences of Çukurova University.
Registration Number:

Prof. Dr. Mustafa GÖK Director
Institute of Natural and Applied Sciences

ABSTRACT

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: Prof. Dr. Mehmet TÜMAY
: Asst.Prof. Dr. Mustafa Murat SAVRUN

Nowadays, interest in Electric Vehicles (EVs) is increasing day by day. Range problem of EVs decrease rapidly due to developing battery technologies however, the biggest problem of electric vehicles is still seen as range anxiety. The One Pedal Driving (OPD) which only accelerator pedal is enough to drive and stop the vehicle can overcome this anxiety problem and incease the ease of electric vehicle penetration. Regenerative braking has become standart for almost all electric vehicles but, the implementation of the system has always been a little different between manufacturers. In this study, OPD mode is developed for electric buses which has 100kW and higher electric motor and also it can be applied to other electric vehicles with minor changes on the algorithms. OPD would make it possible to use just the accelerator pedal to both speed up and slow down the vehicle. While electric vehicle is driving, the power is sended from vehicle's battery pack to wheels via electric motor. An inverter which turns battery's electrical power into correct form of power needed to generate desired traction torque is used. Basically, electrical energy is converted into kinetic energy. On the other hand, regenerative braking works by switching that process the other way around, turning the motor into generator to convert the wheel's kinetic energy back into electrical energy that can be stored in the battery. This process also slows the vehicle down since energy converted from kinetic energy to electrical energy. Adding such a new driving mode to electric vehicles can extend its range considerably. One of the most important purpose of this study is obtaining the accelerator pedal position correctly and accordingly implementing the required amount of positive/negative torque by the help of new algorithms. Another aim of this study is to correctly manage the vehicle traction torque without compromising the comfort of the passengers in the vehicle. Tests were conducted in accordance with the objectives of this study and the opinions of the drivers were obtained. As a result of tests, it has been observed that OPD mode provides more efficient, safer and much more comfortable driving compared to standard driving modes.

Key Words: One Pedal Driving, Electric Bus, Traction Torque Management

ÖZ

YÜKSEK LİSANS TEZİ

ELEKTRİKLİ OTOBÜSLERDE TEK PEDAL SÜRÜŞ İÇİN ALGORİTMALARIN GELİŞTİRİLMESİ VE UYGULANMASI

Çağla DERİCİOĞLU

ÇUKUROVA ÜNİVERSİTESİ FEN BİLİMLERİ ENSTİTÜSÜ
ELEKTRİK ELEKTRONİK MÜHENDİSLİĞİ ANABİLİM DALI

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: Yar. Doç. Dr. Mustafa Murat SAVRUN

Bugünlerde, Elektrikli Araçlara olan ilgi günden güne artmaktadır.Elektrikli araçların menzil problemi gelişen batarya teknolojileri ile hızla azalmaktadır ancak en büyük elektrikli araç sorunu hala menzil endişesi olarak görülmektedir. Aracın sürülmesi ve durdurulması için sadece gaz pedalının yeterli olduğu Tek Pedal Sürüş, bu endişe probleminin üstesinden gelebilir ve bu elektrikli araç penetrasyonunun kolaylaşmasına sebep olabilir. Rejeneratif frenleme hemen hemen tüm elektrikli araçlar için standart hale gelmiştir ancak sistemin uygulanması her zaman üreticiler arasında farklı olmuştur.Bu çalışmada 100kW ve daha büyük elektrik motoruna sahip elektrikli otobüsler için Tek Pedal Sürüş modu geliştirilmiş olup, algoritmalarda yapılacak olan küçük değişikliklerle diğer elektrikli araçlara da uygulanabilmektedir. Tek Pedal Sürüş sadece gaz pedalı kullanarak aracı hem hızlandırmayı hem de yavaşlatmayı mümkün kılar. Elektrikliaraç sürülürken, batarya paketlerindeki güç bir elektrik motoru ile tekerleklere aktarılır. İstenen çekiş torkunu üretmek için, bataryadaki elektrik gücünü doğru güç formuna dönüştüren bir evirici kullanılır. Temel olarak, elektrik enerjisi kinetik enerjiye dönüştürülür. Bunun yanı sıra, rejenaratif frenleme, bu işlemi başka şekilde değiştirerek, tekerleğin kinetik enerjisini bataryalarda depolanabilen elektrik enerjisine dönüştürmek için, motoru jeneratöre çevirerek çalışır. Bu süreç aynı zamanda, elektrik enerjisi kinetik enerjiye dönüştürüldüğü için aracı yavaşlatır. Elektrikli araçlara böyle bir sürüş modu eklemek, araçların menzilini önemli ölçüde uzatacaktır. Bu çalışmanın en önemli amaçlarından biri de, yeni geliştirilen algoritmaların yardımıyla gaz pedalı pozisyonun doğru bir şekilde elde edilmesi ve buna bağlı olarak gerekli miktarda pozitif/negatif tork uygulamaktır. Bu çalışmanın diğer bir amacı ise, araçtaki yolcuların konforundan ödün vermeden araç çekiş torkunu doğru bir şekilde yönetmektir. Testler, bu çalışmanın amaçlarına uygun olarak geliştirilmiş ve testler sonrasında sürücülerin yorumları alınmıştır. Testler sonucunda, Tek Pedal Sürüş modunun standart sürüş modlarına göre daha verimli, daha güvenli ve çok daha konforlu bir sürüş sağladığı gözlemlenmiştir.

Anahtar Kelimeler: Tek Pedal Sürüş, Elektrikli Otobüs, Çekiş Torku Yönetimi

EXTENDED SUMMARY

Electric vehicles have a different place in the developing transportation technologies than others. While hybrid vehicles were the first to create excitement in the transport sector, the interest in electric vehicles was higher than in hybrid vehicles. For these reasons, electric vehicles are more environmentally friendly and do not emit CO2 because of improved battery technology, they have more economical accessibility than diesel fueled vehicles and options to increase driver comfort. Along with this, the range anxiety concerns emerged with the spread of electric vehicles. Drivers have begun to worry about how far they will go and stay on the road with their charge rate on electric vehicles. Almost all electric vehicles are equipped with regenerative braking to provide increase range and to save some of the energy consumed back into the battery.

Regenerative braking uses the motor as a generator when the road conditions are favorable and charges the batteries by reversing the direction of the current. But despite the energy recovery procedure, the biggest obstacle in front of the penetration of electric vehicles is still concerns with range anxiety. To overcome this concern, it has become important to carry out One Pedal Driving operations in order to increase the regenerative braking up to the maximum level and at the same time to increase the safety and comfort of the driver. Single pedal travel enables the functions of the gas pedal and brake pedals to be combined in a single pedal, allowing the driver to drive the vehicle with only this pedal. To perform single pedal travel, the accelerator pedal is selected and the brake pedal is also available for emergency situations. In this mode of operation, the pedal features an accelerator pedal, combined with both acceleration and deceleration functions.

In fact, different investigations have been made on the modes of operation involving combined featured pedals, but the most ergonomic solution is found by Dr. Sven Gustafsson. He began his work on one pedal driving in 1994 and after

a number of tests, one pedal driving was performed in 2002. Almost all of the single pedals driving exercises at the moment are based on his design.

On the basis of one pedal driving, the functions of the accelerator pedal and the brake pedal are integrated on a single pedal. Since the pedals are not interchanged, the driver reacts much quicker and the stopping distance is shortened during sudden stops. The lack of pedal travel also removes the possibility of the driver mixing the accelerator pedal with the brake pedal in an emergency situation. In addition to this, the driver, who switches between continuous accelerator and brake pedals in stop-and-go traffic, needs to spend a lot of effort, but there is little effort and no fatigue as there is no need to switch between pedals in one pedal driving mode. Since there is no brake pedal used except for emergencies, the brake losses have been completely removed. Thus, the recovery rate during driving on electric vehicles has increased considerably and increases in the range have been observed by numerous tests. The greatest contribution of this technology is to increase the driving comfort in electric vehicles and to remove the range anxiety.

This thesis describes how a one pedal driving mode developed and applied to the electric busses with 100kW and larger electric motors. As a test vehicle, electric bus with a length of 12 meters, 150kW motor power and a torque of 2700 Nm were selected. One of the reasons for applying this driving mode to electric busses is that this driving mode has not been applied to electric busses before. No study has been found about the development of new driving modes for electric buses in the literature. Moreover, no research has been found, especially regarding one pedal driving mode. This research contributed to the literature.

Technical details of this driving mode includes dıfferent stages , firstly it is important to take the accelerator pedal’s position correctly, because traction torque is controlled according to the position of the accelerator pedal in order to provide one pedal driving mode. In this study, the pedal position is calculated as a percentage by the software developed in the test environment to read the pedal position correctly. Further studies; with newly developed algorithms specific to one pedal driving positive or negative traction torque is transmitted to the motor driver according to the pedal position to ensure an one pedal driving mode without problems. The last part is; the required brake value to fully stop the vehicle is calculated using the algorithms executed for one pedal mode.

In one pedal driving mode, the accelerator pedal is actually used for three different functions. The acceleration is the first function. When the accelerator pedal position ratio reaches 45%, the vehicle is starting to accelerate. When the driver presses the accelerator pedal more and more, the vehicle continue to accelerate in the same direction. The second function of the driving sequence is called coasting. When the accelerator pedal pressing ratio is between 45% and 55%, the vehicle will move freely at the gained speed. Acceleration continues even as accelerator pedal position increases above 55%. When the accelerator pedal position falls below 45%; the vehicle starts to decelerate and the braking function of the one pedal driving mode is engaged. Since the brake pedal is not used during one pedal driving mode, the response rate is much higher than the standard driving mode.

The accelerator pedal position is obtained as percentage on test bench and the traction torque and braking requests for different functions are determined by the new developed software. After these studies, tests are conducted on urban traffic and a special test road. In these tests, one pedal driving mode and standard driving mode are compared under the same road conditions. In all done tests, it was concluded that the energy recovery rate during one pedal driving mode was much higher and the net consumption was significantly less. In addition, tests have been conducted with three different drivers, which have never been tried, tested several times, and tested for longer than the other drivers, and it is discussed how the energy recovery rate affected from the adaptation level of drivers to this new driving mode. As a result of these tests, the driver who has tried the one pedal driving mode for a longer period of time has achieved the maximum energy recovery.

As a result, when all the software development studies and the different tests are completed and also the opinions of the drivers are received, it is clearly seen that the one pedal driving mode reduce the net energy consumption and thus extend the range considerably and reduce the driver's anxiety about range. This result has been a feature that increases the ease of use of electric vehicles. In addition, the absence of pedal changeover during one pedal driving that allows less effort than standard driving for drivers in stop-and-go traffic. One of the most important consequence is that the one pedal driving mode shortens the reaction time of drivers and provides a much safer driving experience.

GENİŞLETİLMİŞ ÖZET

Elektrikli araçlar, gelişen ulaşım teknolojilerinin arasında diğerlerinden farklı bir yer tutmaktadır. Hibrid araçlar ulaşım sektöründe ilk olarak heyecan yaratsa da, elektrikli araçlara olan ilgi hibrid araçlardan daha yüksek olmuştur. Bunun sebepleri arasında, elektrikli araçların daha çevreci olup, CO_2 salınımı yapmamaları, gelişen batarya teknolojisi sayesinde dizel yakıtlı araçlara göre çok daha ekonomik bir ulaşım sağlamaları ve sürücü konforunu artırmaya yönelik opsiyonlar içermeleridir. Bunun yanı sıra, elektrikli araçların yaygınlaşması ile birlikte menzil endişesi kavramı ortaya çıkmıştır. Sürücüler, elektrikli araçlarındaki şarj oranı ile ne kadar gidecekleri ve yolda kalıp kalmayacakları hakkında endişe duymaya başlamışlardır. Neredeyse tüm elektrikli araçlarda menzil artırımı sağlamak ve harcanan enerjinin bir kısmını bataryalara geri depolayabilmek adına rejeneratif frenleme yapılmaktadır.

Rejeneratif frenleme, yol şartlarının uygun olduğu durumlarda, motoru jeneratör olarak kullanmakta ve akımın yönünü ters çevirerek bataryaları şarj etmektedir. Fakat bu enerji gerikazanım prosedürüne rağmen, elektrikli araçların penetrasyonunun önündeki en büyük engel hala menzil endişesidir. Bu noktadan yola çıkılarak, rejeneratif frenlemenin maksimum düzeye çıkarılması ve aynı zamanda sürücünün güvenlik ve konforunun artırılması için Tek Pedal Sürüş (One Pedal Driving) çalışmalarının yapılması önem kazanmıştır. Tek Pedal sürüş, gaz pedalı ile fren pedallarının fonksiyonlarını tek bir pedalda birleştirip, sürücünün sadece bu pedalla aracını sürebilmesini mümkün kılmaktadır. Tek pedal sürüşü gerçekleştirmek için, gaz pedalı seçilmiş olup, fren pedalı da acil durumlar için kullanılabilir halde bırakılmıştır. Bu sürüş modunda gaz pedalı, hem hızlanma hem de yavaşlama fonksiyonlarının kombine edildiği bir pedal özelliği taşımaktadır.

Aslında, kombine özellikli pedalları içeren sürüş modları üzerine farklı araştırmalar yapılmıştır fakat bu konudaki en ergonomik çözüm Sven Gustafsson tarafından bulunmuştur.

Sven Gustafsson, tek pedalla sürüşü gerçekleştirme çalışmalarına 1994'de başlamıştır. 2002 yılında ise; sayısız testlerden sonra tek pedal sürüş gerçekleştirilmiştir. Şu anda yapılan tek pedal sürüş çalışmalarının hemen hemen hepsi onun dizaynına dayanmaktadır.

Tek pedal sürüşün temelinde gaz pedalı ile fren pedalı fonksiyonlarının tek bir pedalda birleştirilmesi bulunmaktadır. Pedallar arası geçiş yapılmadığından, sürücü çok daha çabuk tepki vermekte ve ani duruşlardaki durma mesafesi kısalmaktadır. Pedal geçişinin olmaması, sürücünün acil bir durumda gaz pedalı ile fren pedalını karıştırması ihtimalini de ortadan kaldırmaktadır. Ayrıca dur-kalk trafikte sürekli gaz ve fren pedalları arasında geçiş yapan sürücünün fazla efor harcaması gerekmektedir fakat tek pedal sürüş modunda pedallar arası geçişe gerek duyulmadığından az efor sarfedilmekte ve yorgunluk oluşmamaktadır. Acil durumlar dışında fren pedalı kullanılmadığı için, fren kayıpları tamamen ortadan kaldırılmıştır. Böylece, elektrikli araçlarda sürüş esnasındaki geri kazanım oranı oldukça artmış ve menzilde artışlar gözlemlenmiştir. Bu teknolojinin en büyük katkıları, elektrikli araçlardaki sürüş konforunun artırılması ve menzil endişesinin ortadan kaldırılmasıdır.

Bu tezde, tek pedal sürüş modunun geliştirilmesi ile 100kW ve daha büyük motorlara sahip elektrikli otobüslere uygulanması konu edilmiştir. Test aracı olarak 12 metre uzunluğunda 150kW motora ve 2700Nm torka sahip elektrikli otobüsler seçilmiştir. Bu sürüş modunun elektrikli otobüslere uygulanma sebeplerinden biri bu sürüş modunun elektrikli otobüslere daha önce uygulanmamış olmasıdır. Yapılan literatür çalışmasında elektrikli otobüsler için yeni sürüş modlarının geliştirilmesi ile ilgili kaynak bulunamamıştır. Üstelik, özellikle tek pedal sürüş modu ile ilgili de herhangi bir araştırmaya rastlanmamıştır. Bu araştırma ile literatüre katkıda bulunulmuştur.

Elektrikli otobüslerin seçilme nedenlerinden biri de şehir içi kullanımda tercih edilen elektrikli otobüslerin rotalarının her gün aynı olması böylece yol şartlarının (eğim, yükseklik vb.) değişiklik göstermemesi sebebiyle; standart sürüş modu ile tek pedal sürüş modunu karşılaştırmanın daha doğru sonuçlar vermesidir. Ayrıca, elektrikli otobüslere böyle bir sürüş modu eklemek, daha problemsiz ve güvenli bir sürüş sağlayıp, sürücülerin de konforunu artıracağından bu otobüslerin kullanımını artırıp tercih sebebi olmasını sağlayabilmektedir.

Bu sürüş modunun teknik detaylarına bakıldığında, gaz pedalı pozisyonunun yüzde olarak elde edilmesi önemli yer tutmaktadır. Çünkü tek pedal sürüşün sağlanması için gaz pedalı pozisyonuna bakılarak çekiş torkunun yönetilmesi gerekmektedir. Bu tez çalışmasında, öncelikle kurulan test masasında gaz pedalı pozisyonu, geliştirilen yazılım sayesinde yüzde olarak hesaplanmıştır. Daha sonraki çalışmalar ise; elde edilen gaz pedalı pozisyonuna göre tek pedal sürüşe özgü yeni geliştirilen algoritmalar yardımıyla, pozitif veya negatif çekiş torkunun motor sürücüsüne iletilip, tek pedal sürüş modunun sorunsuz bir şekilde sağlanması olmuştur. En son kısım ise; aracın tamamen durması için gerekli fren değerinin yine tek pedal sürüş için yürütülen algoritmalar yardımıyla hesaplanmasını içermektedir.

Tek pedal sürüş modunda, gaz pedalı aslında üç farklı fonksiyon için kullanılmaktadır. Bunlardan ilki hızlanma fonsiyonudur. Gaz pedalı basılma oranı %45'e varınca, araç hızlanmaya başlamaktadır. Sürücünün gaz pedalına daha çok basması ile araç aynı oranda hızlanmaktadır. İkinci fonksiyon ise serbest hareket ya da serbest salınım olarak adlandırılan sürüş sekansıdır. Gaz pedalı basılma oranı %45 ile 55% arasında iken araç kazanılmış hızla serbest hareket eder. Gaz pedalı posizsyonu %55'in üzerine çıktığında da hızlanma devam etmektedir. Gaz pedalı pozisyonu %45'in altına düştüğünde ise; araç yavaşlamaya başlar ve tek pedal sürüş modunun frenleme fonksiyonu devreye girer. Bu sırada fren pedalı kullanılmadığı için gerikazanım oranı standart sürüş moduna oranla çok daha yüksek olmaktadır.

Gaz pedalı poziyonu test masasında yüzde olarak elde edilmiş ve yeni geliştirilen yazılım sayesinde gaz pedalının gerçekleştirdiği farklı fonksiyonlardaki çekiş torku ve frenleme istekleri belirlenmiştir.Bu çalışmalar sonrasında ise şehiriçi trafikte ve özel bir test yolunda testler yapılmaya başlanmıştır. Bu testlerde aynı yol şartlarında tek pedal sürüş modu ve standart sürüş modu karşılaştırılmıştır. Yapılan tüm testlerde, tek pedal sürüş modu esnasındaki gerikazanım oranının çok daha yüksek olduğu ve net tüketimin de belirgin şekilde daha az olduğu sonucuna varılmıştır. Ayrıca, tek pedal sürüş modunu daha önce hiç denememiş, birkaç kez denemiş ve diğer sürücülere nazaran daha uzun süre denemiş olan üç farklı sürücü ile testler yapılmış ve sürücülerin bu yeni sürüş moduna alışma durumlarının gerikazanım oranını nasıl etkilediği tartışılmıştır. Bu testler sonucunda en fazla gerikazanım oranını, daha uzun süre tek pedal sürüş modunu denemiş olan sürücü elde etmiştir.

Sonuç olarak, yapılan tüm yazılım geliştirme çalışmaları ve değişik testler tamamlandığında, aynı zamanda sürücülerin de görüşleri alındığında; tek pedal sürüş modunun net enerji tüketimini azaltarak menzili uzattığı ve sürücülerdeki menzil endişesini büyük ölçüde azalttığı açıkca görülmüştür. Bu sonuç elektrikli araçlarının kullanım kolaylığını artıran bir özellik olmuştur. Ayrıca standart sürüş modundaki yoğun pedal geçişlerinin tek pedal sürüşte olmaması, dur-kalk trafikte sürücülerin daha az efor sarfetmesine olanak sağlamıştır. En önemli sonuçlardan biri de, tek pedal sürüşün sürücülerin reaksiyon süresini kısaltıp çok daha güvenli bir sürüş sağlaması olmuştur.

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CONTENTS **PAGE**

LIST OF TABLES **PAGE**

LIST OF FIGURES **PAGE**

LIST OF ABBREVIATONS

3D	: Three Dimensional
AC	: Alternating Current
BLDC	: Brushless Direct Current
BMS	: Battery Management System
CA	: Controller Application
CAN	: Controller Area Network
CATIA	: Computer Aided Three Dimensional Interactive Application
CPS	: Combined Pedal Solution
DC	: Direct Current
DTC	: Direct Torque Control
ECU	: Electronic Control Unit
EKF	: Extended Kalman Filter
EPA	: U.S. Environmetal Protection Agency
EV	: Electric Vehicle
GPS	: Global Positioning System
ICAN	: Instrumentation CAN
IGBT	: Insulated Gate Bipolar Transistor
IM	: Induction Motor
I/O	: Input / Output
IPMSM	: Interior Permanent Magnet Synchronous Motor
KCAN	: Karosserie CAN
KIBES	: Key to on Board Electronic System
kWh	: kiloWatthour
MCAN	: Multiplexer CAN
NHTSA	: National Highway Traffic Safety Administration
OPD	: One Pedal Driving
PCAN	: Powertrain CAN
PDU	: Protocol Data Unit

PGN	: Parameter Group Number
PLC	: Programmable Logic Controller
PM	: Permanent Magnet
PMSM	: Permanent Magnet Synchronous Motor
PR	: Parallel Regenerative
SAE	: Society of Automotive Engineers
SNRA	: Swedish National Road Administrative
SOC	: State of Charge
SPN	: Suspect Parameter Number
SPS	: Split Pedal Solution
SR	: Switched Reluctance
TC1	: Transmission Control 1
TSC1	: Torque Speed Control 1
U.S.	: United States
V	: Voltage
XBR	: External Brake Request
XCAN	: Extended CAN

1. INTRODUCTION

1.1 Background and Research Motivation

The transportation and automotive sectors are among the most effected sectors after the Paris Declaration on Electromobility on Climate Change (Climate Initiatives Platform, 2015). In recent years, electric vehicles and technological developments have experienced tremendous improvements because as government, investor and automotive manufacturers have increased their interest about electric vehicles. At the same time, the fuel economy rules, which are getting harder day by day in the U.S., China and Europe, are predicted to lead to a significant growth in the electric vehicle sector (EPA and NHTSA).

The electric vehicle industry which is very new has some specific problems such as low range. For this reason, it is very important to develop algorithms and driving modes to increase the Electric Vehicle (EV) range. Therefore, new and comfortable driving options for electric vehicles continue to be developed.

In addition to the advances in electric vehicles, another innovation that provides drivers with more comfortable driving is autonomous vehicle technology. It allows driverless travel with the help of various sensors, lidar and cameras. The safety and reliability of an autonomous vehicle depends on the compatibility of many sensor systems, such as camera, radar, lidar and GPS devices. These equipments can be used for accelerating, braking, decelerating, etc. The layout of these equipments can be seen in Figure 1.1 in below:

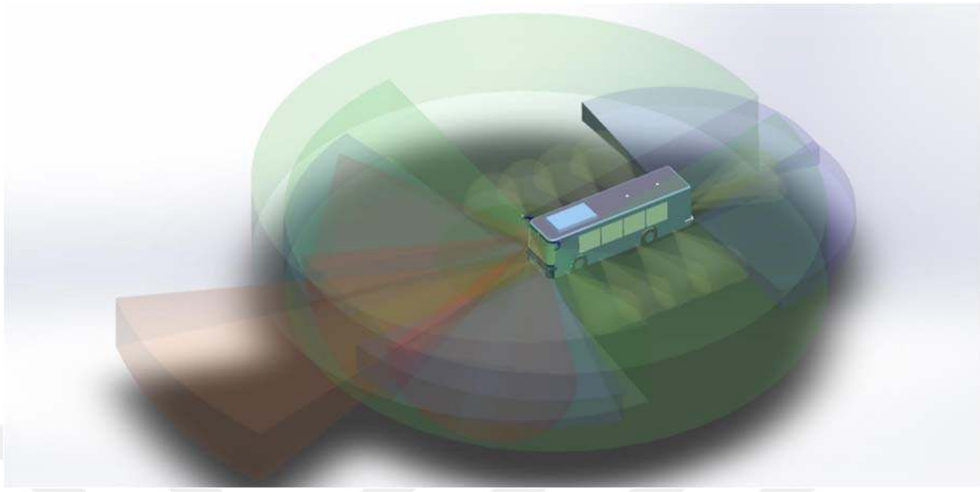


Figure 1.1. The lay out of several sensors on an autonomous vehicle

Nowadays, the pioneers of automotive sector are developing and testing their autonomous vehicles for future use. The advantages of autonomous vehicles are very attractive for many sectors, so improvements to the technology that will be will be faster each day. The autonomous vehicles can present more comfotable driving via reducing driver effort and decreasing unsafe accelerating and decelerating operations.

Despite the rapid development of autonomous vehicles, new methods are being developed to improve comfort and reduce the range problem when the vehicle is used by the driver. The other focus point to present more comfortable, safer and efficient travelling options to driver is implementing **One Pedal Driving** or **Combined Pedal Driving**. In this driving mode, functions of accelerator and brake pedals are combined in one pedal. Although there is a brake pedal for emergency situations, only acceleration pedal is used in this system and it can provide both accelerating and braking functions. The success of One Pedal Driving is measured by coming to full stop without using the brake pedal.

Actually, the accelerator pedal is used for three different modes in one pedal driving mode:

1. Accelerate
2. Coast
3. Brake Energy Recuperation

One pedal driving mode requires highly sensitive traction torque management for these three modes. The most important part of implementing one pedal driving is applying positive and negative torque to the wheels with respect to the acceleration pedal position. Different pedal position intervals must be determined for three modes. Basically, when the pedal position percentage is increasing, the determined positive torque is applied to wheels so the vehicle begins to accelerate. Oppositely, if the pedal position percentage is decreasing, the determined negative torque is applied to wheels and the vehicle slow downs.

In case of changing pedal position during 50%±5%, vehicle stays in coasting mode and rolls freely for maximum energy efficiency. In coasting mode, the electric vehicle gets more chance to recuperate the energy via regenerative braking and increase its range. So, coasting mode must be managed very effectively for electric vehicles to overcome range problem.

The conventional pedal structure has some drawbacks. First of all, it takes long time to braking in an emergency situation. According to scientific researches, it takes at least 0.2 seconds to move the foot from one pedal to the other and at 90 kilometres per hour this adds five meters to vehicle's stopping distance (New Scientist, 2002).

Another problem with separate pedals is that the risk of using wrong pedal is very likely. Use of wrong pedal may cause unintended acceleration and also it causes an accident immediately after using misapplication of pedals. Also, the friction brake is used frequently in vehicle which has conventional driving mode so, this situation affects negatively the energy efficiency. The energy efficiency is a vital issue in an electric vehicle because the vehicle range calculations substantially depends on available energy of batteries.

Up to now, a few studies have been implement about combined pedal structure to overcome with the aforementioned drawbacks of pedals but the most ergonomics and technologic solution came from Swedish inventor Sven Gustafsson. Current OPD studies depends on design of him. Rickard Nillson who tested out Gustafsson's pedal for the Swedish National Road Administration (SNRA) said that this combined pedal solution provides more natural driving to drivers. Also, Rickard Nillson commented that one pedal driving may make more safer the whole traffic (New Scientist, 2002).

The possible advantages of one pedal driving are belows:

- improving energy efficiency of electric vehicle
- increasing vehicle range
- increasing driver's comfort
- eliminate movement of the foot between accelerator and brake pedal
- decreasing risk of pedal misapplication
- reducing reaction time for emergency situations

1.2 Scope of Thesis

In this study, the algorithms are developed for an electric bus in order to implement one pedal driving. An electric bus requires more power and traction torque than an electric car therefore, the developed algorithms within this study are dedicated to electric buses which has 100 kW and higher electric motors.

In order to develop special algorithms for electric buses, the acceleration pedal position is read from directly acceleration pedals' signal outputs without entering any controller. According to the accelerator pedal position, the required traction torque value is sended to the wheels with the help of Motor Drive. Actually, this operation is controlled by Motor Electronic Control Unit (Motor ECU) in standard driving mode but in this study, override control mode is active for engaging the one pedal driving mode by Vehicle Controller. So, the whole traction torque operations are managed by developed algorithms within this study. Also, the regenerative energy recuperation improvement and fault diagnosis are developed with new one pedal driving algorithms. In order to constitute these algorithms, a Programmable Logic Controller (PLC) based software is used. Besides, the algorithms are tested in a specially prepared test bench for being sure about safe driving before applying to electric bus.

The aims of this thesis are developing algorithms in order to control of the electric vehicle's motor indirectly and integrating this algorithms for implementing one pedal driving in an electric bus. The designed algorithms make it possible to manage traction torque process and estimation of torque value for consecutive situations.

In briefly, this thesis discusses the design and development of one pedal driving algorithms and application to these algorithms into an electric bus. One pedal driving mode is improved for presenting more comfortable driving options to electric vehicle drivers. Also, this driving mode can provide more efficient driving because it mostly allow for regenerative energy recovery during driving. It can contribute the spreading of electric vehicles by present new driving mode option. Finally, the developed algorithms and gained experiences about traction torque management can be used for Autonomous Vehicle technology in near future.

1.3. Outline of the Thesis

In first chapter, the general definitions about electric vehicles and one pedal driving mode are presented. In addition, comparison of conventional and one pedal driving technology and their progress are introduced.

In the second chapter, firstly the literature review of the torque control methods in electric vehicle are presented. Secondly, the literature review for one pedal driving technology is presented and finally the differences of this study in contrast to literature are presented in detail.

In third chapter, powertrain system of an electric bus is presented. Also, the communication structure of powertrain is introduced.

The fourth chapter presents experimental results for the one pedal driving method. In this chapter firstly test road conditions are defined. Afterwards, the speed and altitude profiles are demonstrated via a tracking application. Finally, the energy consumption comparison tables are demonstrated with the help of the test results.

In the fifth chapter, the conclusions of the thesis are given and the future work studies are discussed.

2. LITERATURE REVIEW

The one pedal driving technology consist of dedicated subjects such as obtaining the accelerator pedal positions correctly, management of traction torque according to accelerator pedal position and also implemention of this technology to electric buses. The related previous studies about these subjects has been explained below.

In recent years, with the increase of using electric vehicles, the torque control and management issues have become more critical for energy efficiency. One pedal driving mode is composed of many specific torque subjects such as torque control methods, traction torque management, reading accelerator pedal position percentage, traction torque formulation and developing algorithms for torque management. Also, there are varios studies about torque management issues that is available in literature. In following subsections, the literature review summary will be explained.

Jinfang, Lifang, Chenglin, Zunzhi and Xiaowei (2012) have studied coordinated control of motor regenerative torques defined by accelerator and brake pedals of an electric vehicle. They have thought that the accelerator pedal has the dual function of defining driving torque and regenerative braking torque. Therefore, they propose the relationship between accelerator pedal and motor torque in their study. Also, they determined the conditions for motor output regenerative braking torque defined by the accelerator pedal as in Equation 1:

$$\frac{\mathrm{dAccPed}}{\mathrm{dt}} < 0 \text{ and } AccPed < \mathrm{A1}$$
$$\text{or } \frac{\mathrm{dAccPed}}{\mathrm{dt}} > 0 \text{ and } AccPed < \mathrm{A2} \qquad \text{(Eq.1)}$$

where *AccPed* is the accelerator pedal opening, A1 and A2 are threshold values of accelerator pedal, A1<A2 (Jinfang et. al., 2012).

They depicted the definiton of motor torque as shown in below Figure 2.1:

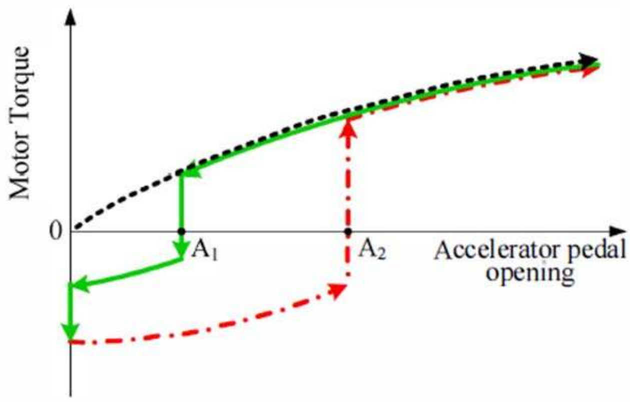


Figure 2.1. Definition of motor torque (Jinfang et. al., 2012).

Also, they proposed two kinds of braking mode for a front-axle-driven electric vehicle. They have developed fuzzy logic controllers for these modes and carried out simulations for revealing the relationship between accelerator pedal and motor driving torque. They gathered the results of their simulations in a table which is given in Table 2.1:

Table 2.1. Results of mode simulation in terms of regenerative efficiency (Jinfang et. al., 2012)

Mode	**Braking Distance (m)**	**Energy (kJ)**				**Energy recovery efficiency (%)**
		Recove-rable kinetic	**Air resistance**	**Rolling resistance**	**Recovery braking energy**	
0	30.96	89.745	0.40	3.71	32.559	38.02
I	29.19	89.745	1.26	3.50	37.374	43.98
II	24.12	89.745	0.88	2.89	57.369	66.73

In this part, the limited availability of studies about One Pedal Driving will be introduced. The reason of rareness of studies about One Pedal Driving depends on improvement rate of electric vehicles, driver's attitude towards to electric vehicle and new pedal solutions. In the forthcoming days, there will be more researches and studies about this topic undoubtedly. This study may contribute to literature about implementing new driving mode to electric buses.

2.1 Previous Studies About One Pedal&Combined Pedal Solutions

The most two detailed studies about One Pedal Driving (OPD) is revealed by Boekel, Besselink, Nijmeijer from Eindhoven University of Technology in 2015.

In first inspected article, they considered the design and realization process of OPD algorithm from various aspects for implementing to an electric vehicle. First of all, they have tested the available electric vehicles which are popular in Netherlands in order to form an opinion about driver control of regenerative braking and coasting. They used these information which are obtained from tests to define a list of design requirements for the OPD design.

They have divided into five groups the OPD design process

1. General Requirements
2. Inverter Settings for OPD
3. OPD Accelerator Pedal Mapping
4. Vehicle Accelerator Map
5. Controller Enhancement

In first section, they have listed the limitations and requirements for their vehicle to apply the One Pedal Driving algorithms. In second section, they have emphasized the importance of setting acceleration and deceleration parameters.

In other following sections, they have investigated that One Pedal Driving is all about applying a positive or negative torque to the wheels with respect to the accelerator pedal position.

They also worked about the formulations for upper and lower boundaries for different driving sequences such as coasting, regenerative braking and acceleration and they have draw a graphic to demonstrate the longitudinal acceleration as a function of the accelerator pedal position and vehicle velocity. The depicted accelerator pedal map graphic is given in Figure 2.3:

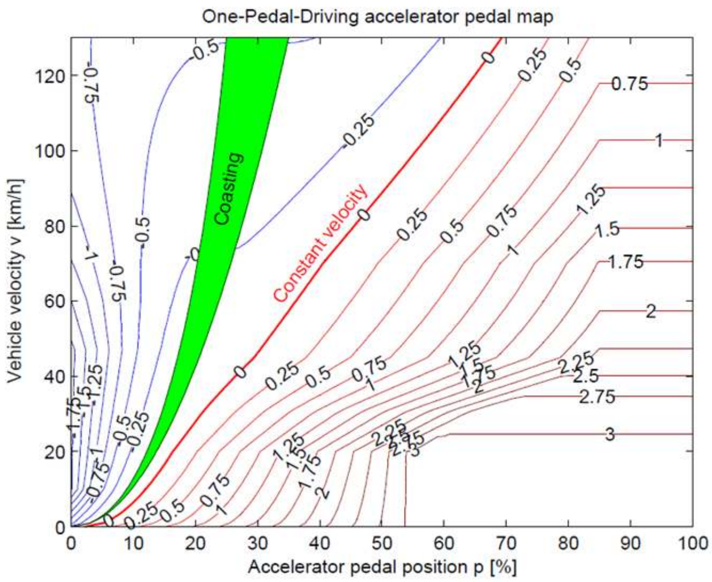
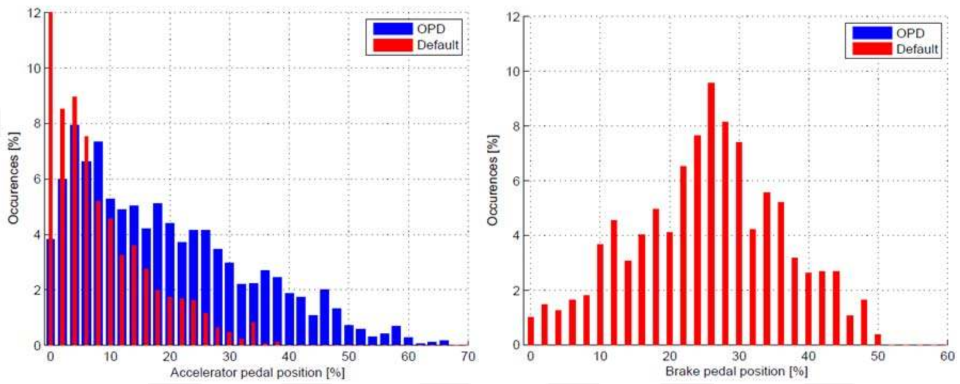


Figure 2.2. Accelerator Pedal Map (Boekel et al., 2015)

Various aspects of the OPD algorithm can be observed: an area where coasting is possible, the maximum possible deceleration increases at lower forward velocities when the accelerator pedal is fully released, the pedal does not have to be applied 100% to achieve maximum acceleration. The line describing zero longitudinal acceleration (ax = 0 m/s^2) is important as it corresponds to driving with constant forward velocity. It appears that for this condition the relation between accelerator pedal position and vehicle velocity is almost linear (Boekel et al., 2015).

In last section of their article, they compared the energy usage and pedal usage comfort via some tests with various drivers. The histograms of the accelerator and brake pedal position for the default regenerative braking strategy are given in following Figure 2.4:



(b)

Figure 2.3. Histograms of the (a) accelerator pedal position brake pedal position (Boekel et. al, 2015)

They deduced these below informations from their tests:

- OPD can make energy consumption reduction
- People can adapt very quickly to OPD
- The attitude of drivers towards to OPD is positive
- Efficiency of the vehicle has improved slightly

The improving of energy efficiency of the vehicle is one of the most remarkable results of One Pedal Driving. In many studies, the efficiency effects of OPD were discussed. One of these articles is reviewed for this study. The focus point is_energy efficiency gains of an One Pedal Driving algorithm for EVs (Wang et. al.,2015).

Also, driving speed optimization is worked with using two different driving styles; one of them is called as "constant speed driving" and the other one is called as "optimal speed driving". The researchers have thought that for the constant speed driving, the vehicle accelerates to a constant speed, then it maintains this speed and finally decelerates to standstill at the destination and for the optimal speed driving, the driving speed is optimized to achieve the minimum energy consumption for the trip. To obtain the minimized energy consumption, they optimized the acceleration profile and used the MATLAB function FMINCON (Wang et. al., 2015).

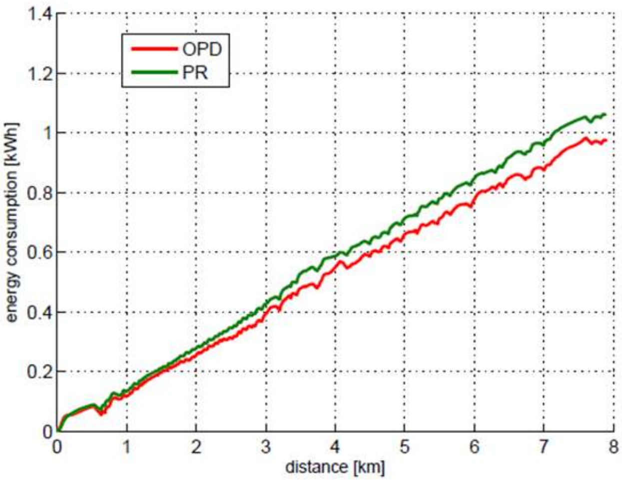
They have showed the results of comparison between the constant speed and optimal speed driving in a table. In comparison table, some abbreviations are used for parameters. These abbreviations can be summed up like this : C is city road; R is rural road; H is highway; s is driving distance; t_d is driving time; Vm is the average driving speed; Ec is the energy consumption of constant speed driving; Eop is the energy consumption of optimal driving; Cp is the percentage of coasting in optimal speed driving; ΔE is the energy saving of optimal driving compared to constant speed driving.

Table 2.2. Comparison between the constant speed driving and optimal speed driving (Wang et. al., 2015)

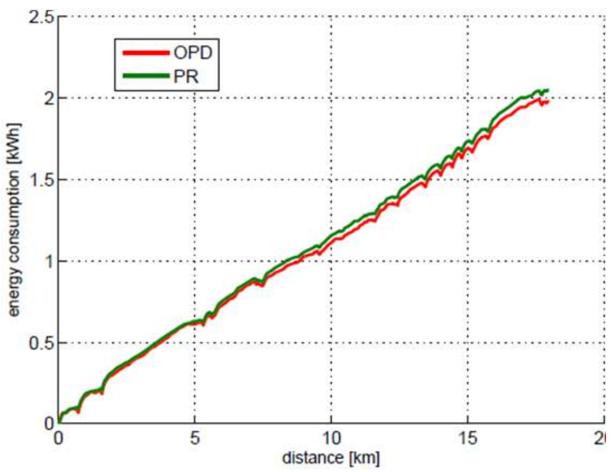
	s [km]	**t_d [s]**	**Vm [km/h]**	**Ec [Wh]**	**optimal**		**ΔE [%]**
					Eop [Wh]	**Cp [%]**	
C	0.1	14	25	19	17	10.0	10.7
	0.2	21	34	30	27	12.4	11.0
	0.3	31	35	39	34	19.4	12.4
	0.5	50	36	54	48	28.8	11.6
R	1.0	69	52	110	101	22.6	8.2
	1.5	103	52	151	141	20.0	6.4
	2.0	130	55	198	188	18.5	4.9
H	5.0	185	97	698	683	5.8	2.2
	10.0	359	100	1349	1333	3.3	1.2
	20.0	712	101	2626	2608	1.7	0.7

In addition the driving speed optimization works, they investigated the regenerative braking control strategies. They implemented two regenerative braking control strategies in the their test vehicle, a parallel regenerative braking control strategy (PR) and a one pedal driving control strategy (OPD).

They analyzed the accelerator pedal maps of these two algorithms and compared the energy efficiency of them based on measurements and simulations.



(a)



(b)

Figure 2.4. Energy consumption in (a) city driving (b) rural driving (Wang et. al., 2015)

Their comparison results showed that the efficiency of the OPD algorithm is better than the PR algorithm. The other comparison of authors demonstrates that the battery output power of the OPD algorithm and the PR algorithm are almost the same for traction, but the OPD algorithm can recuperate more energy during braking and 93% of the regenerative energy measured at battery output can be used again for propulsion. What strikes is their simulation result that the OPD algorithm can save up to 2% to 9% energy compared to the PR algorithm based on the same driving speed in city and rural driving (Wang et. al., 2015).

Another significant research about combined pedal solutions made by Marcus Schmitz, Christian Maag, Monika Jagiellowicz and Michael Hanig who are from Wuerzbug Institute for Traffic Sciences. Their article about combined pedal solutions was published in Intelligent Transport Systems journal in 2013. The purpose of their study can be divided into two parts.

They analyzed firstly the acceptance and energy efficiency of different recuperation settings and secondly they compared two different pedal solutions, namely **split pedal solution (SPS)** and the **combined pedal solution (CPS)** with regard to drivers' opinion. The configuration of combined pedal solution and split pedal solution is given in Figure 2.5:

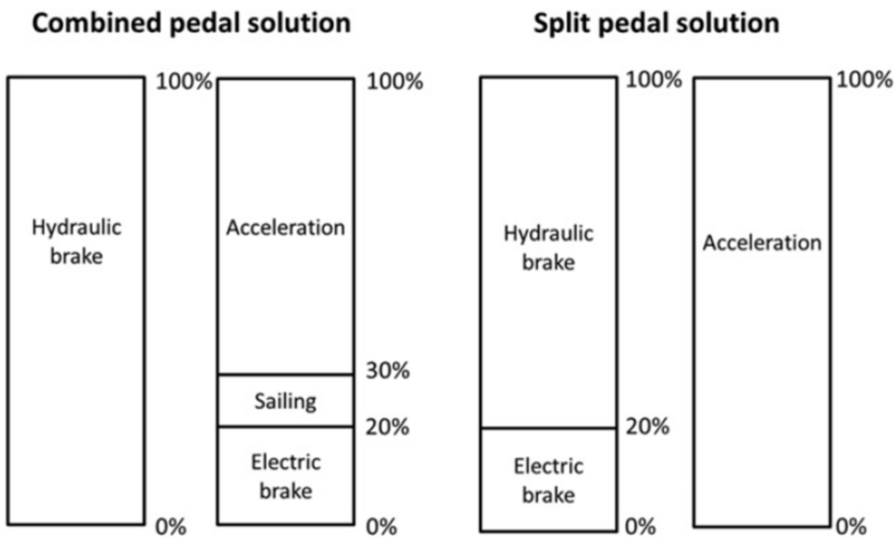


Figure 2.5. Configuration of brake pressure and accelerator pedal way for the CPS (left) and SPS (right) – (Schmitz et. al., 2013)

Basically, they have thought that the drivers can use the regenerative brake force to decelerate their electric vehicle similar to the drag torque of a conventional combustion engine with the help of integration the electric brake into the accelerator pedal. They focused on comparison of two different pedal solutions, namely SPS and CPS.

The urban and rural test drives are carried out by different drivers for comparison the pedal solutions in terms of mean frequency of hydraulic brake usage, percentage of sailing time, spended and recuperated energy per pedal solutions. The result of test drives in urban areas is depicted as graphics in Figure 2.7:

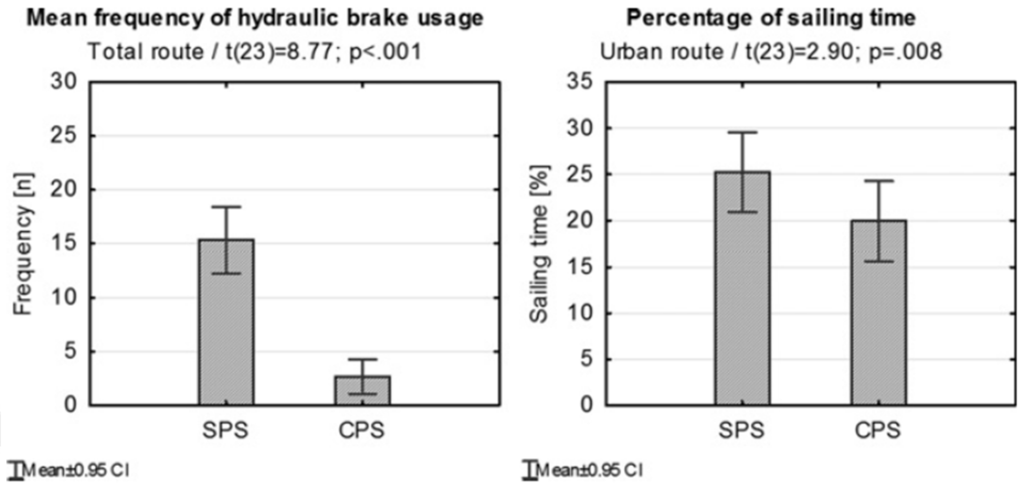


Figure 2.6. Mean frequency of hydraulic brake usage (left) and percentage of sailing time in urban areas (right) per pedal solution (Schmitz, 2013)

Also, the spent and recuperated energy per pedal solution is given in Figure 2.8:

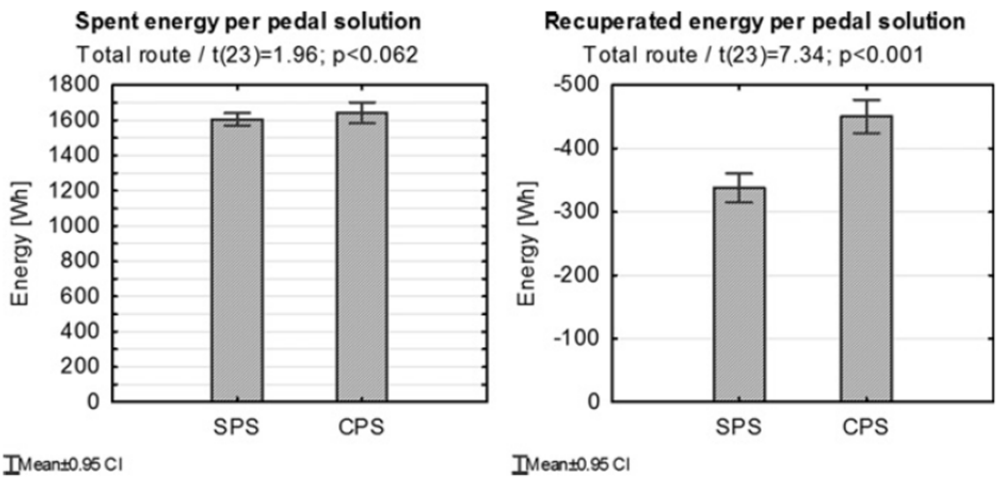


Figure 2.7. Retrieved (left) and recuperated (right) energy (in sum) per pedal solution (total route) (Schmitz et.al., 2013)

They have interviewed with drivers after all test drives. They obtained these results according to interviews with the drivers:

- The electric brake was used more frequently in urban areas in the CPS condition compared to the SPS condition
- Sailing was most frequent when subjects drove in the SPS condition
- Driving with the CPS made the drivers believe that they were driving more energy efficiently compared to the SPS condition
- The drivers rated the CPS as significantly more usable for driving energy efficiently than the SPS
- The participants reported that it is easier to regenerate energy during the CPS condition, since the power gauge delivered exact information
- Using the CPS resulted in about 6% less energy consumption compared to the SPS

Schmitz and other researches bringed light that drivers prefer combined pedal solution over the split pedal solution because they believe that driving can be more efficiently with combined pedal solution. They investigated that CPS changed drivers' behaviour. When drivers are used to use hydraulic brake less often, the less energy was needed. So, the CPS has led to a more efficient driving behaviour compared to the SPS. It appears that this paper would be a base study for long-term effect and future considering for different combined pedal solutions (Schmitz, 2013).

Also, Sahil Arora who is from Sinhgad Academy of Engineering, discussed the combined pedal solution completely different point of view. He dealed with mechanical design and construction of one pedal which is accelerator and brake processes are operated together. He has approached mechanically to the combined pedal solutions as divergently from other researchers.

What strikes is the difference in his research is that he proposed detailed design, three dimensional modelling, prototype production and testing of mechanism of combined pedal system. The detailed design of combined pedal mechanism is modelled with CATIA program within the scope of his research and he prepared a prototype for testing his design.

He propose the 3D (three dimensional) modelling of the mechanism in CATIA program which is depicted in Figure 2.9:

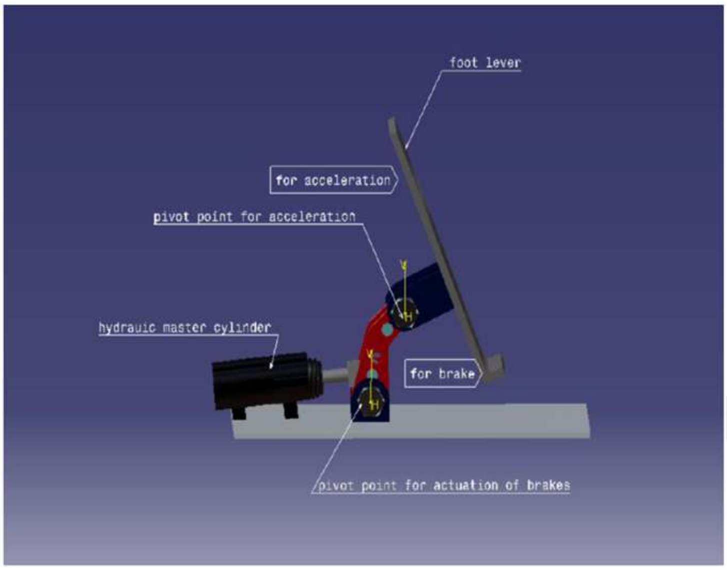


Figure 2.8. 3D modelling of the mechanism in CATIA (Arora, 2016)

The working mechanism processes have divided into three parts in his research:

- Acceleration
- Braking
- Neither acceleration nor braking

In his design, upper half of foot lever moves in downward direction and lower half of pedal moves in upward direction to accelerate. In order to kept the support in stationary position, there is a spring which is for providing resisting force during throttling. The position of foot during acceleration is given in Figure 2.10:

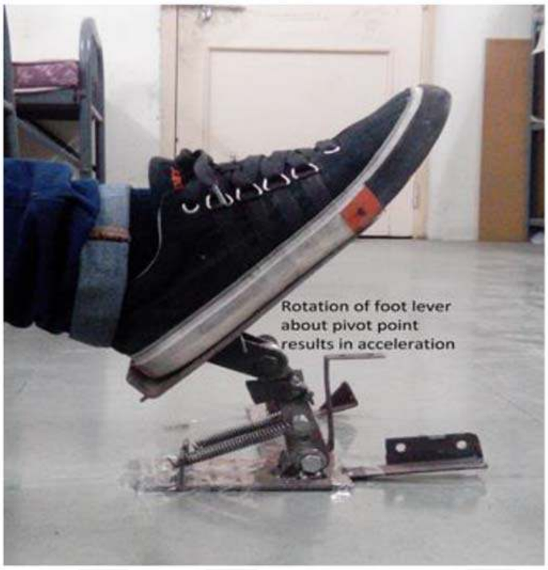


Figure 2.9. During acceleration (Arora, 2016)

On the other hand, in order to brake, the foot lever and support both moves in linear direction such that, there would be no acceleration of the vehicle in this position. Again, with the help of spring, driver can decelerate the vehicle or come to full stop without actuation of throttle. The position of foot for braking is shown as in Figure 2.11 in Arora's article:

Figure 2.10. During braking (Arora, 2016)

According to his design, in third position of foot provides neither acceleration nor braking. This situation called as "sailing" or "coasting" in literature. In this situation, the vehicle can roll freely without spending energy. The vehicle can make regeneration of energy in this mode. Arora's design enables sailing mode when foot is positioning as Figure 2.12:

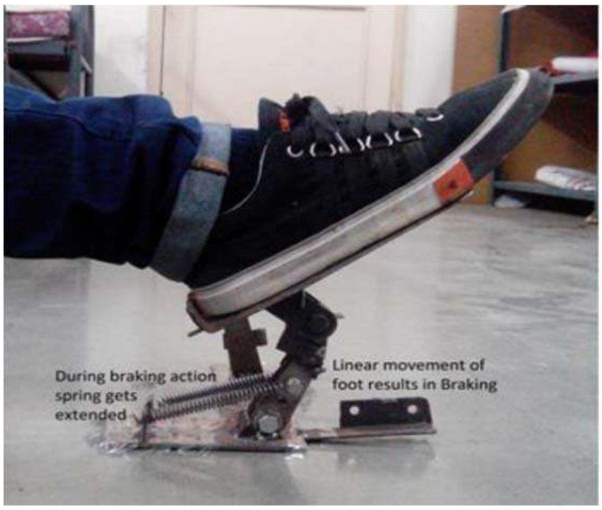


Figure 2.11. Neither acceleration nor braking position (Arora, 2016)

As known, many investigations have been done about the new driving modes and all of them is viewed and summed up above. But these investigations that are especially focused on one pedal driving have very limited number. Generally, the great majority of reviewed articles have focused to one pedal driving applications on passenger cars. There is no study about application of one pedal driving to an electric bus in literature, no such information or application has found during literature review. This is a very new and state of the art technology driving methods for all electric vehicles. Some parts of this technology is still investigated and improved by related scientific peoples. The aim of this study is to contribute developing one pedal driving algorithms for commercial electric buses.It is believed that the results at the end of this study should be useful for comparison of conventional driving and one pedal driving modes in terms of energy efficiency, ergonomy and safety. Also, this study can provide more analytic solutions for proving superiority of one pedal driving modes for especially electrical buses.

3. MATERIALS AND METHODS

Electric mobility becomes trending issue than ever in transportation sector. The essential part of electric mobility is the use of electric vehicles. The electric vehicle is a type of vehicle which primarily powered by an electric motor drawing power from a rechargeable energy storage device. Electric vehicle receives electricity by plugging into the grid and store it in batteries (Dericioğlu et.al., 2016).

From the outside, the vehicle does not appear to be electric. In most cases, electric cars are created by converting a gasoline-powered car. Often, the only thing that clues the vehicle is electric is the fact that it is nearly silent.

Basically, an electric vehicle has:

- An electric motor.
- A vehicle controller.
- A rechargeable battery.

The electric motor gets its power from motor drive and motor drive gets its power from rechargeable battery. The electric vehicle operates on an electric/current principle. It uses battery packs to provide power for the electric motor. The motor then uses the power received from the batteries to rotate a transmission and the transmission turns the wheels. Four main parts make up the electric vehicle: the pedal potentiometer, batteries, motor drive and electric motor.

The theory of operation for electric vehicle can be summarized like that: when the driver steps on the pedal the potentiometer activates and provides the signal that tells the motor drive how much power it is required to deliver. There are two potentiometers on accelereator pedal for safety. The motor drive reads the the accelerator pedal position in percentage from the potentiometers, regulates the power accordingly, takes the power from the batteries and delivers it to the motor.

The working principle of electric vehicles are simple but there are many challenges for using electric vehicles such as cost, limited range and lack of enough infrastructures for battery charging systems. Like any transformative new technology, electric vehicles create a variety of economic development opportunities in despite of its challenges. While the electric vehicle market is still at a relatively early stage of development, it is poised to reshape industries and communities the world over (Clean Energy Economy).

The most remarkable and distinguishing feature of electric vehicles can be range length in commercial area. In order to increasing range and possibility of regenerative braking, the different driving modes are identified such as one pedal driving. One pedal driving mode can provide continuous torque modulation and also help to increase range of electric bus via regenerative energy recuperation. The comparison of conventional and one pedal driving modes in terms of torque modulation is given in Figure 3.1:

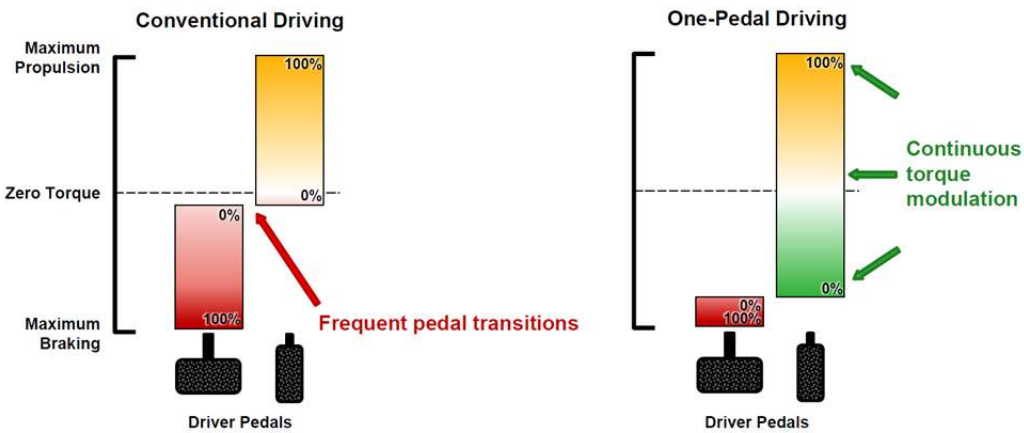


Figure 3.1. Comparison of conventional and one-pedal driving (Michaluk, 2017)

On the other hand, one pedal driving decreases the rate of using brake pedal and largely reduce the brake pedal losses. A special traction torque management algorithm is developed for one pedal driving mode. The algorithm consists of initialization, torque control, fault management and shutdown state machines.

In initialization state, the vehicle goes directly to standard mode driving when ignition is on. The switch information is expected for executing one pedal driving mode algorithms. When the driver push the “One Pedal Driving Enable Button”, the algorithms are begin to execute and check the system requirements for safe one pedal driving process.

In control phase, the dicharge status, pedal status and fault messages are controlled. If every conditions are met, the system goes to one pedal driving mode. After that, the driver can drive the electric bus only using with accelerator pedal. In order to achieve this correctly and driving sequence is selected.

The driving sequences of one pedal driving can be divided into three main segments:

1. Accelerating
2. Coasting
3. Braking

The algorithm in the vehicle software which decides whether these segments can be active or not, determines the segment by looking at the percentage of accelerator pedal and applies positive or negative torque values according to the accelerator pedal position.

As long as the percentage of accelerator pedal position is below 45%, braking is active and the vehicle does not start to accelerate. When the accelerator pedal position percentage is between 45% and 55%, the vehicle moves freely at constant speed. If it is initially moving, when the percentage of accelerator pedal position is greater than 55%, the amount of traction torque of motor which is demanded by the vehicle increases and the vehicle begin to accelerates.

During driving, traction torque is controlled according to whether the vehicle is in accelerating, decelerating or coasting modes, in this way, the driver can carry out the driving with using only one pedal. When the percentage of accelerator pedal position falls below 15%, the service brake (disc brake) engages.

After the driving sequence is determined, system goes to torque control state. In torque control state, the needed torque value request is send to Motor Electronic Control Unit for accelerating or decelerating according to evaluation. Motor Electronic Control Unit sends this request to Motor Drive as torque commands. The electric motor supply the required positive or negative torque to the tires. The regenerative braking procedure is the most important part of this driving mode. During driving, the brake pedal usage is almost nearly 0%, for this reason, the chance of energy recovery is very high.

If any fault occurs in system during one pedal driving, system directly goes to fault management state. In this state, the tolerance time intervals were determined for every spesific fault. The speed of vehicle, status of one pedal driving mode switch, the validity of accelerator pedal position signal and status of motor is checked and fault detection algorithms are being executed.

The system goes to shutdown state after tolerance time and one pedal driving mode is disabled. The vehicle return to standard driving mode and it can be driven only in standard mode unless the vehicle is restarted.

The operating logic of one pedal driving mode is summarized in the flowchart given in Figure 3.2:

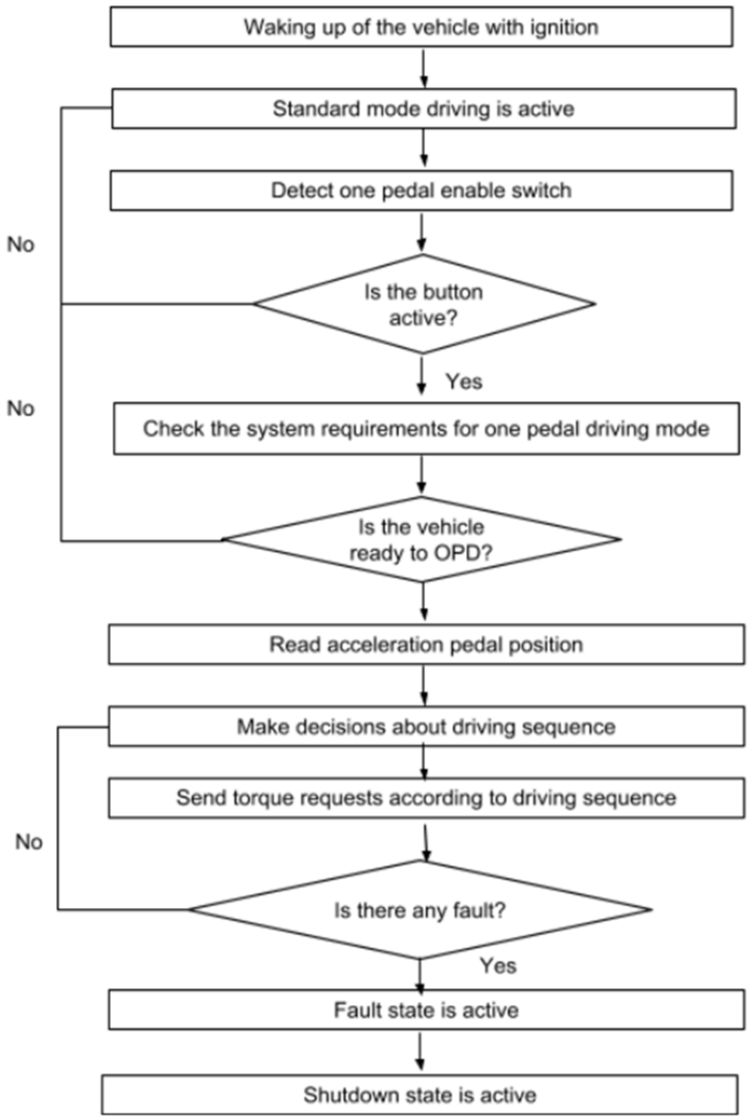


Figure 3.2. Flowchart of one pedal driving

In following paragraphs, the powertrain system and equipments of selected electric bus are presented. Also, communication standard between the equipments is explained.

3.1. Powertrain of an Electric Bus

An outline of powertrain of electric bus that were utilized in this study is presented. The powertrain is responsible of transferring mechanical energy to the traction wheels. The power is provided with the help of battery in electric vehicles. The voltage and energy capacity play very important role on generated torque by an electric motor. The powertrain system consists of electric motor, DC-DC converter, DC-AC inverter and electronic control units of these equipments.

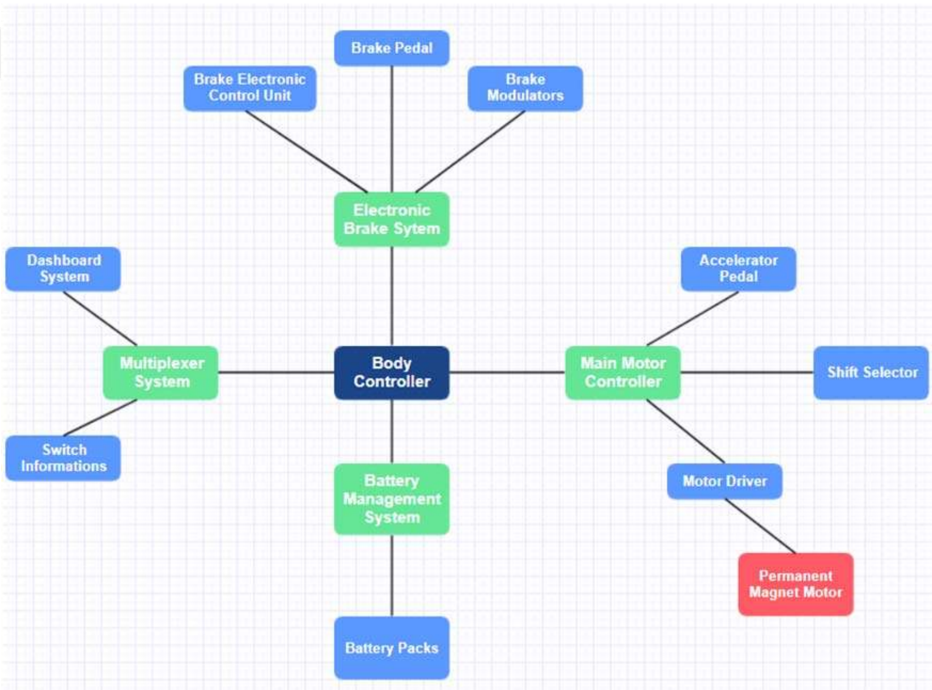


Figure 3.3. Powertrain of an electric vehicle as block diagram

In electric vehicles, there is an electronic control unit which is responsible of reading digital and analog driver's input and managing important traction processes and communicate with other devices with a special communication protocol. The torque to be produced by motor is determined according to driver's input by this control unit. These inputs can be acceleration pedal position, request of changing gear or brake pedal position.

The analog input signals can be received from accelerator pedal position (as voltage level), shift selector requests (N,R,D,1,2,3) by Motor Electronic Control Unit.

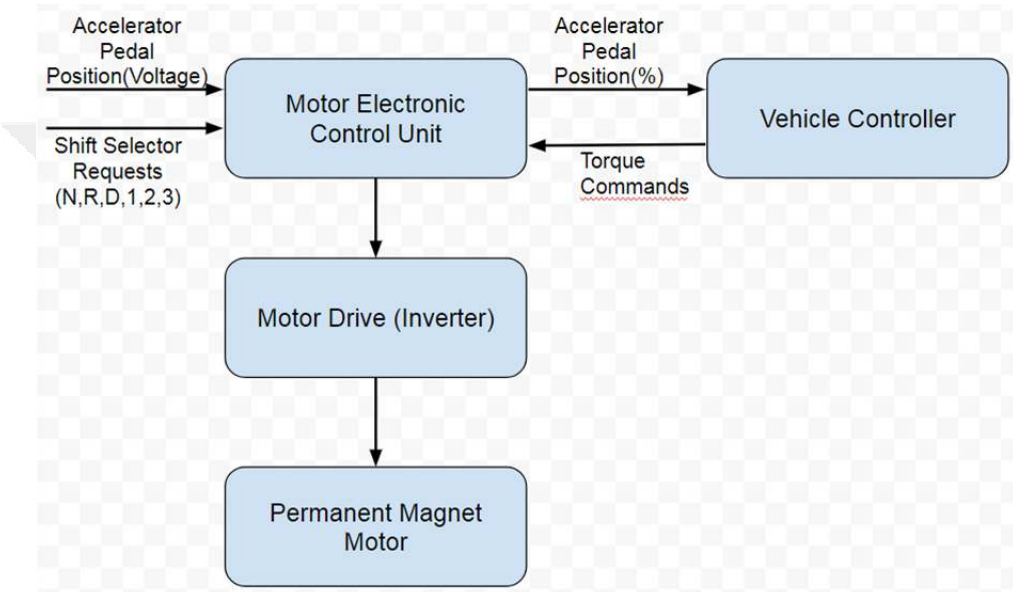


Figure 3.4. Block diagram of analog inputs of Motor Electronic Control Unit

In contrast to analog signals, the digital signals can be received from many different systems such as park brake, dashboard switches, brake pedal, battery management system and etc. All digital and analog inputs are gathered in the multiplexer system. The block diagram of motor control process during one pedal driving is depicted in Figure 3.5:

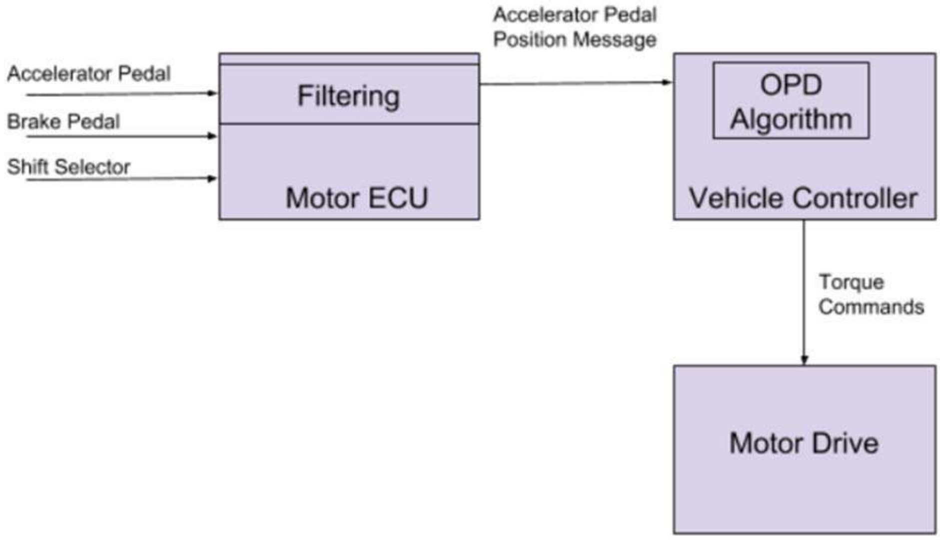


Figure 3.5. Block diagram of motor control process during OPD mode

Including the Motor Electronic Control Unit, other all devices or systems in an vehicle communicates with each other via special communication protocol namely Controller Area Network (CAN).

An electric vehicle is primarily powered by an electric motor that draws from a rechargeable energy storage devices. Motor Electronic Control Unit and Motor Drive manage the electric motor together via CANBUS communication protocol. Motor Drive is actually an inverter that is used for adjusting motor speed, motor state, motor angle and torque values. Motor Drive implies these adjustments according to messages that are received from Motor Electronic Control Unit via CANBUS. The Motor Drive is used for torque management applications in electric vehicles. It utilizes the latest technology of automotive grade insulated-gate bipolar transistors (IGBT) to deliver the industry's highest specific power and current densities (TM4 Product Specification, 2010).

Figure 3.6. Motor Drive

Interior permanent magnet synchronous motors (IPMSMs) have been considered as the potential candidates for electric vehicle applications due to their compact structure with small size and weight, high torque to inertia ratio, high efficiency, wide speed range, low noise, and robust operations. Focusing on the EV-traction application, a fast and robust torque response of the IPMSM drive is required to meet the instantaneous torque demand commanded by the driver through the accelerator pedal action. Moreover, the IPMSM drive should have a quick torque/speed recovery capability after subjected to sudden system disturbances (Justo et. al., 2016).

In this study, a interior permanent magnet synchronous motor has been used for traction source which is designed for mid-duty EV trucks and buses. This motor technology uses permanent magnets in order to get fast torque response. The motor topology is based on an inverted rotor technology that maximizes the use of the magnets and reduces the amount of material. The high torque/low speed of the system is designed to directly interface with standard axle differentials without the need for an intermediate gearbox. (TM4 Product Specification, 2010).

The permanent magnet synchronous motor which is used in this study as shown in Figure 3.7:

Figure 3.7. Permanent Magnet Synchronous Motor

In this study, the torque management algorithms is developed for mentioned permanent magnet motor and its motor electronic control unit to use in one pedal driving mode. The different torque control methods are researched for selecting appropriate method for managing electric buses' traction system.

A literature review has been made related with one pedal driving and torque control methods for electric vehicles. Finally, the developed torque management algorithms for one pedal driving mode are simulated on a test bench. After simulations, these algorithms are downloded to the 100kW electric buses. The experimental test results and comments will be given in following chapters.

3.1.1. Communication Structure on Powertrain of Electric Vehicle

3.1.1.1. CANBUS (Controller Area Network BUS)

The Controller Area Network (CAN, also known as CANBUS) is a vehicle bus standard designed to allow electronic control units and devices to communicate with each other in applications without a host computer. As an alternative to conventional multi-wire looms, CANBUS allows various electronic components (such as electronic control units, microcontrollers, devices, sensors, actuators and other electronic components throughout the vehicle) to communicate on a single or dual-wire network data bus up to 1 Mb/s. The CANBUS is a message based protocol, designed originally for multiplex electrical wiring within motor vehicles, but also can be used in many other contexts (Mucevski, 2015).

Typically the CANBUS is made up with two wires, CAN-H (CAN High) and CAN-L (CAN Low) which connect to all the devices in the network. The signals on the two CAN lines have the same sequence of data, but their amplitudes are opposite. So if a pulse on the CAN-H line goes from 2.5V to 3.75V then the corresponding pulse on the CAN-L line goes from 2.5V to 1.25V (opposite than CAN-H). The amplitudes of CAN-H and CAN-L are depicted in Figure 3.8:

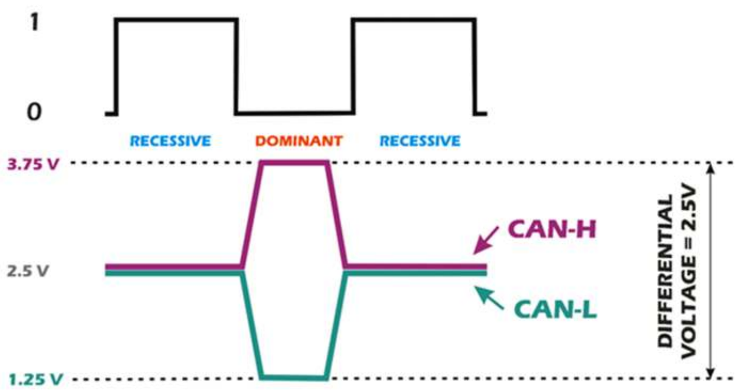


Figure 3.8. CAN-H and CAN-L Differential Output (Mucevski,2015)

3.1.1.2. SAEJ1939 Communication Protocol

SAE J1939 is used in the commercial vehicle area for communication in the commercial vehicle. SAE J1939 uses CAN (Controller Area Network, ISO11998) as physical layer. It is a recommended practice that defines which and how the data is communicated between the Electronic Control Units within a vehicle network. Typical controllers are the Engine, Brake, Transmission, etc… (Vector, 2010).

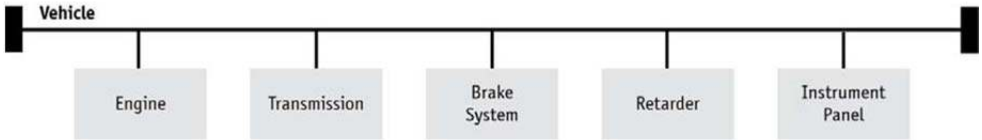


Figure 3.9. Typical J1939 vehicle network (Vector, 2010)

The particular characteristics of J1939 are:

- Extended CAN identifier (29 bit)
- Bit rate 250 kbit/s
- Peer-to-peer and broadcast communication
- Transport protocols for up to 1785 data bytes
- Network management
- Definition of parameter groups for commercial vehicles and others
- Manufacturer specific parameter groups are supported
- Diagnostics features

In order to understand the messaging structure of SAE J1939, the parameter groups must be examined.

3.1.1.2.a. Parameter Group

A parameter group is a set of parameters belonging to the same topic and sharing the same transmission rate. The length of a parameter group number is not limited to the length of a CAN frame. Usually a parameter group has a minumum length of 8 bytes require a transport protocol for transmission (Vector, 2010).

3.1.1.2.b. Interpretation of the CAN Identifier

The CAN identifier of a J1939 message contains Parameter Group Number (PGN), source address, priority, data page bit, extended data page bit and a target address. The identifier is composed as follows:

Table 3.1. CAN Identifier (Vector,2010)

Priority	Extended Data Range	Data Page	PDU Format	PDU Specific	Source Address
3 bit	1 bit	1 bit	8 bit	8 bit	8 bit

- With Protocol Data Unit (PDU) format < 240 (peer-to-peer), PDU specific contains the target address. Global (255) can also be used as target address. Then the parameter group is aimed at all devices. In this case, the PGN is formed only from PDU format.
- With PDU format >= 240 (broadcast), PDU format together with the Group Extension in the PDU specific field forms the PGN of the transmitted parameter group

3.1.1.2.c Parameter Group Number

Each parameter group is addressed via a unique number – the PGN. For the PGN a 24 bit value is used that is composed of the 6 bits set to 0, PDU Format (8 bits), PDU Specific (8 bits), Data Page (1 bit) and Extended Data Page (1 bit).

There are two types of Parameter Group Numbers:

- **Global PGNs** identify parameter groups that are sent to all (broadcast). Here the PDU Format, PDU Specific, Data Page and
  Extended Data Page are used for identification of the corresponding Parameter Group. On global PGNs the PDU Format is 240 or greater and the PDU Specific field is a Group Extension.

Figure 3.10. Global PGNs (Vector, 2010)

- **Specific PGNs** are for parameter groups that are sent to particular devices (peer-to-peer). Here the PDU Format, Data Page and Extended Data Pare are used for identification of the corresponding Parameter Group. The PDU Format is 239 or less and the PDU Specific field is set to 0.

Figure 3.11. Specific PGNs (Vector, 2010)

3.1.1.2.d Suspect Parameter Number (SPN)

A suspect parameter number is assigned to each parameter of a parameter group or component. It is used for diagnostic purpose to report and identify abnormal operation of a Controller Application (CA).

The SPN is a 19 bit number and has a range from 0 to 524287. For proprietary parameters a range from 520192 to 524287 is reserved (Vector, 2010).

3.1.2 Choosen CAN Messages for OPD Procedure

In order to implement one pedal driving, several systems must communicate with each other via determined CAN messages. CAN messages provide the working of the whole system in a coordinated manner and it increase communication safety. A lot of CAN messages are choosen for one pedal driving procedure in this study. These choosen CAN messages can be divided into two main categories for two main operations: **“Acceleration”** and **“Deceleration”**.

In one pedal driving mode, the acceleration and deceleration operations are calculated according to only accelerator pedal position unlike the standard driving. So, it is expected that driver must select one of the driving modes with the help of switch.

After the selection of the driving mode, the first message will be **“Driving Mode Selector”** for starting any selected procedure. Vehicle Controller must send this message to Motor Electronic Control Unit according to the information coming from multiplexer unit. This message consists of options for selecting available driving modes. The length of this message is 2 bits and so it releases four options to drivers :

- Standard Driving Mode
- Autonomous Driving Mode
- One Pedal Driving Mode
- Not available

Motor Electronic Control Unit is the receiver of this message and it answers the selected driving mode requests. This selection will be implemented in initialization state. Thus, an algorithm will be executed in compliance with selected driving mode.

Acceleration requests is evaluated according to acceleration pedal position percentage as a result of OPD’s rationale. The **“TSC1 (Torque/Speed Control 1)”** message is used for managing and answering torque requests. TSC1 message will provide to make speed, torque or speed/torque control of the electric bus. It consists of these parameters which are given in below Table 3.2:

Table 3.2. Parameters of TSC1 message (SAE j1939)

Message Name	Parameter Name
TSC1	Engine Override Control Mode
	Engine Requested Speed Control Conditions
	Override Control Mode Priority
	Engine Requested Speed/Speed Limit
	Engine Requested Torque/Torque Limit
	TSC1 Transmission Rate
	TSC1 Control Purpose
	Engine Requested Torque - High Resolution
	Message Counter
	Message Checksum

Deceleration requests is achieved by messages which are send to Motor Electronic Control Unit, Motor Drive and Braking System. In a similar way of acceleration, the deceleration procedure begins with TSC1 message. Negative torque requests should be sended by Vehicle Controller and Motor Electronic Control Unit must answers these requests almost immediately because of safety issues.

In addition to TSC1 message, in some cases **"XBR (External Brake Request)"** message will interfere in to implement braking actions. In general, XBR message is used for brake control by an external device. For one pedal driving, the mentioned external device is selected as Vehicle Controller for controlling the braking process. The "External Acceleration Demand" signal of XBR message will be sended to Braking System from Vehicle Controller for evaluating and applying braking procedure externally. The deceleration and full braking demands is sent by Vehicle Controller to Braking System and then, Braking System receives these demands. The brake system has to process the demanded negative acceleration to decelerate the electric bus.

Table 3.3. Parameters of XBR message (SAE j1939)

Message Name	Parameter Name
XBR	External Acceleration Demand
	XBR EBI Mode
	XBR Priority
	XBR Control Mode
	XBR Urgency
	XBR Message Counter
	XBR Message Checksum

Also, **“TC1 (Transmission Control 1)”** message is sent to Motor Drive or electric motor from Motor Electronic Control Unit in deceleration procedure. The data length of this message is 8 byte and this message is a command signal which is used for simply disengaging the driveline. When vehicle is in one pedal driving mode, TC1 message takes an important place for deceleration procedure.The whole new defined and choosen messages and its important signals are given in below:

1. **Acceleration**
   - **Driving Mode Selector message (from Vehicle Controller to Motor Electronic Control Unit) – (Newly Defined)**
   - ➢ **00 :** Standard Driving Mode
   - ➢ **01 :** Autonomous Driving Mode

- **10 :** One Pedal Driving Mode
- **11 :** Not available

- **TSC1 message (from Vehicle Controller to Motor Electronic Control Unit)**
  - Engine Override Control Mode
  - Override Control Mode Priority
  - Engine Requested Torque / Torque Limit
  - Engine Requested Torque - High Resolution
  - TSC1 Control Purpose
  - Message Checksum

2. **Deceleration**

- **TSC1 message (from Vehicle Controller to Motor Electronic Control Unit)**
  - Engine Override Control Mode
  - Override Control Mode Priority
  - Engine Requested Torque / Torque Limit
  - Engine Requested Torque - High Resolution
  - TSC1 Control Purpose
  - Message Checksum
- **XBR message (from Vehicle Controller to Braking System)**
  - XBR Priority
  - XBR Control Mode
  - XBR EBI Mode
  - External Acceleration Demand
- **TC1 message (from Motor Electronic Control Unit to Motor Drive)**
  - Disengage Driveline Request

3.1.3 Checksum Calculations of Selected CAN Messages

The TSC1 (Torque/Speed Control 1) and XBR (External Brake Request) messages require the checksum calculation for increasing the safety. The checksum calculations are evaluated according to SAEj1939 Standard.

The XBR message checksum is used to verify the signal path from the demanding device to the brake controller on electronic brake systems. The 4 bit XBR message checksum is calculated using the first 7 data bytes, the 4 bit message counter and the bytes of the message identifier. The TSC1 message checksum is used to verify the signal path from the transmitting device to the receiving device. The message checksum is calculated using the first 7 data bytes, the message counter and the bytes of the message identifier (SAE J1939-71, 2011-03).

The checksum calculation is achieved in a faster ECU than Vehicle Controller. So, the rapid faults can be easily detected with the help of checksum values when one pedal driving mode is active. If the checksum values of related ECUs are conflicted, the system goes to fault management and one pedal driving mode is disabled. If any checksum fault occurs, the vehicle can be driven in only standard mode.

3.2 Torque Management Algorithms in PLC Application Program

The torque management process is implemented via the communication between the Motor Electronic Control Unit and Motor Drive. The torque management process comprise of the peripheral activation and validation of system integrity before activating the traction system and allowing actual driving. The system then responds to the user's signals from the user input interfaces (such as drive selector, accelerator and brake pedals) and commands the traction system accordingly through the exchange of the associated CAN protocol messages.

The software development for torque management process implemented with Logi.CAD program which has powerful graphical programming environment and KIBES-32 software tool. This software offers opportunity to make both online and offline tests on electric bus. It supports the development of function blocks and programs. Also, it allows configuration and organization of tasks and resources and provides a series of additional components for testing, diagnosis and maintenance. Being an efficient and flexible system, Logi.CAD especially meets the demands of OEM partners. It is hardware independent and can be adapted to several automation system easily.

The KIBES-32 software tool is used to develop the PLC application program, to test it either online or offline and to download it. KIBES® based electronic components can be programmed easily with high flexibility by using this software tool.

Benefits and Features

- Full graphical software tool chain
- Fast development
- Regular software updates are provided
- Easy to learn and use
- Even small customers participate on our regular technology updates, driven by the main international vehicle manufacturers

Technical Data

- The software is based on logiCAD, an object-oriented programming system according to IEC 61131-3
- It supports the IEC-languages Function Block Diagram, Sequential Function Chart, Ladder Diagram and Structured Text

- Fully graphical Off-line simulation and On-line test
- Automatical generation of executable and downloadable code
- Resource Type to adjust onto specific target systems
- Version and revision management integrated
- Internal documentation management integrated

In addition to the Logi.CAD program, "CANalyzer software (CAN Analyzer)" is also used for transmitting and receiving the CAN messages which are used in vehicle communication. CAN protocol is the best known communication system in the automotive industry. It is also used in real-time applications when the security is very important. CANalyzer is the comprehensive software tool with intuitive operation for analysis of bus communication. CANalyzer can be used to check that the CANBUS messages exists and sending or receiving correctly. It can also be used for logging data. When the all software development stage is completed, the software tested in the test bench and checked with the help of CANalyzer tool. According to the test results, some errors in the CANBUS are identified and revised.

The torque management algorithms has been divided into four state machines and they are together called as control state machines :

1. Initialization State Machine
2. Torque Management State Machine
3. Fault Management State Machine
4. Shutdown State Machine

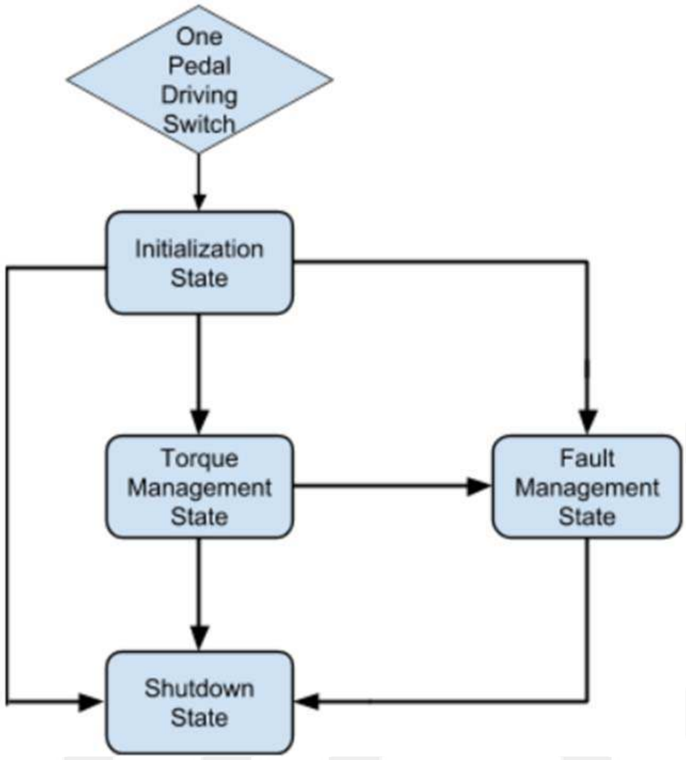


Figure 3.12. Control state machines

The control state machine algorithms begins with start-up procedure which is the first step of controlling the electric vehicle by waking up the important devices such as Motor Electronic Control Unit, DC/DC Converters, inverters and etc. This procedure related with power up of peripheral devices.

In automotive applications, power up process is start with “ignition”. The ignition signal must be asserted the system for start-up. Also, Motor Electronic Control Unit must be powered up for completing the procedure. The selected CAN messages are sended and received by vehicle management unit during this procedure.

Also, the precharge procedure is carried out in initialization state. Precharging is essential to limiting the inrush currents in high voltage DC systems during the power up procedure. Electric vehicles comprise of many large capacitive equipments such as permanent magnet motor, inverters and converters. This situation necessitates the precharging procedure.

3.2.1 Initialization State Machine

The system start-up is began with ignition signal and then this state

- waits to receive “Discharge Enable” from vehicle
- waits switch information from multiplexer unit
- waits to receive “Ready To Drive” signal from Motor Electronic Control Unit
- waits to “Driving Mode Selector” message from Vehicle Controller

Initialization state consists of waking up the systems of vehicle and checking the switch information. The different driving modes are presented to the driver such as standard driving, one pedal driving, autonomous driving. In this study, the one pedal driving algorithms are developed. In order to choose a driving mode, a switch is used on the dashboard. If the drivers prefer one pedal driving mode, the checking process is started. In Figure 3.14, the diagram of initialization state is given:

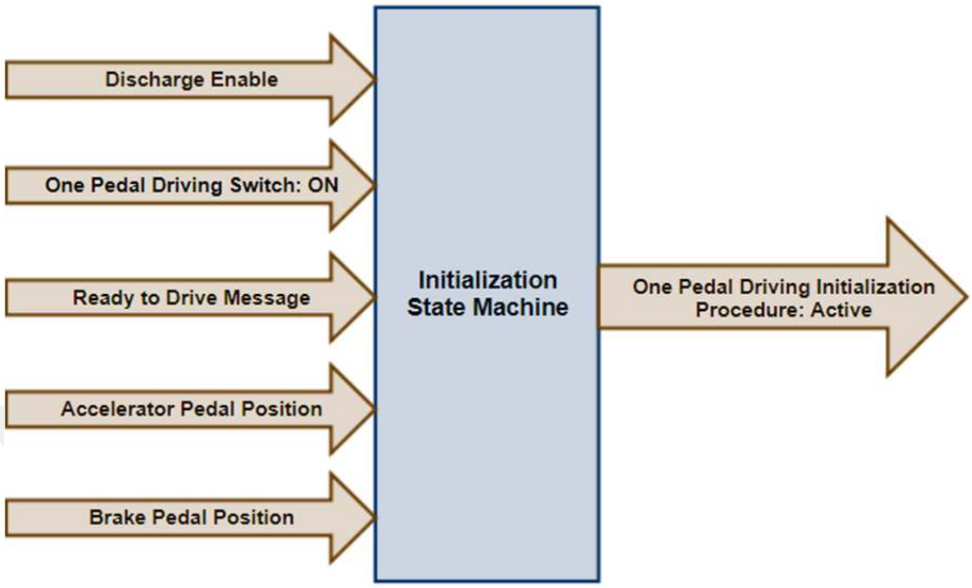


Figure 3.13. Initialization State Machine Diagram

First of all, algorithm checks that whether the vehicle allow to discharge or not. For discharging process, some conditions must be fulfilled. For instance, the Battery Management System (BMS) should send the “Discharge Enable”signal to the system. Also, the charging process should not be active and the charging plug should not be connected when the discharge process is continued.

The another important part of initialization procedure is receiving “Ready To Drive” message from Motor Electronic Control Unit. If this signal comes from Motor Electronic Control Unit, that means the electric motor of vehicle is ready for discharge procedures.

The other part of this state is checking the pressing percentage of accelerator and brake pedal. For OPD, the brake pedal position is received via “SAE j1939-Brake Pedal Position” signal. The data length of this message is 1 byte and data range is between 0 to 100%. The value of brake pedal position must be equal to zero for starting the one pedal driving.

On the otherhand, the accelerator pedal position is received via “Accelerator_Pedal_Position” signal. This message is sent from Motor Electronic Control Unit. The data length of this message is 1 byte and data range is between 0 to 100%. Motor Electronic Control Unit is directly connected to signal outputs of accelerator pedal and receives the voltage level of two channels of pedal. The voltage levels of channels are varies 0.55±0.05V to 2.1±0.1V and 1.1±0.05V to 4.2±0.1V respectively. The developed algorithms calculate the percentage value of accelerator pedal position according to received voltage values and transmits as a CAN message namely, “Accelerator_Pedal_Position". In order to start One Pedal Driving Initialization Procedure, the Accelerator Pedal Position must be greater than zero.

Besides, there exist one more message about accelerator pedal position which is transmitted from Motor Electronic Control Unit. This message called as “Accelerator_Pedal_Position_Status" and it indicates the validity of pedal position status. The data length of status message is 1 bit and there are two possible outputs. The values of message can be equal to only 0 or 1 and these values means that “Signal is correct” and “Signal is implausible” respectively. The accelerator pedal signal must be correct for OPD initialization process.

Also, there should be no faults in the vehicle during discharge process. If there is any fault on system (isolation, contactor, motor, BMS faults or etc...), system directly goes to “Fault Management State”. If all conditions are met without any fault, system goes to “Torque Management State”.

3.2.2 Torque Management State Machine

In this state, all acceleration and deceleration procedures are executed according to information which are send by Vehicle Controller. This state waits the faultless finish of initialization procedure for starting. Also, this state checks below information for availability of regenerative energy recuperation:

- Speed of electric vehicle
- State of Charge (%)
- Highest cell voltage value
- Regen Status message from Motor Electronic Control Unit

One pedal driving contribute to increase of energy recuperation via decreasing brake pedal usage. So, the one part of algorithm consists of management of regenerative braking operations. The algorithm helps to find the maximum availability point of regenerative braking. It increases the the ratio of recharging the batteries during driving. The most remarkable part of one pedal driving is raising energy efficiency of electric vehicle via regenerative braking. In this study, the comparison between standard driving and one pedal driving in terms of energy efficiency will be given in following chapters.

Actually, this state begins with torque request messages from Vehicle Controller. In this step, Motor Electronic Control Unit and Vehicle Controller must communicate very swiftly because of providing the safety of driver. These request messages are send to Motor Electronic Control Unit and it transmits the requests to Motor Drive. It is in charge of driving electric motor for required torque values. Vehicle Controller always control the generated torque values and motor speed via feedbacks from Motor Electronic Control Unit messages.

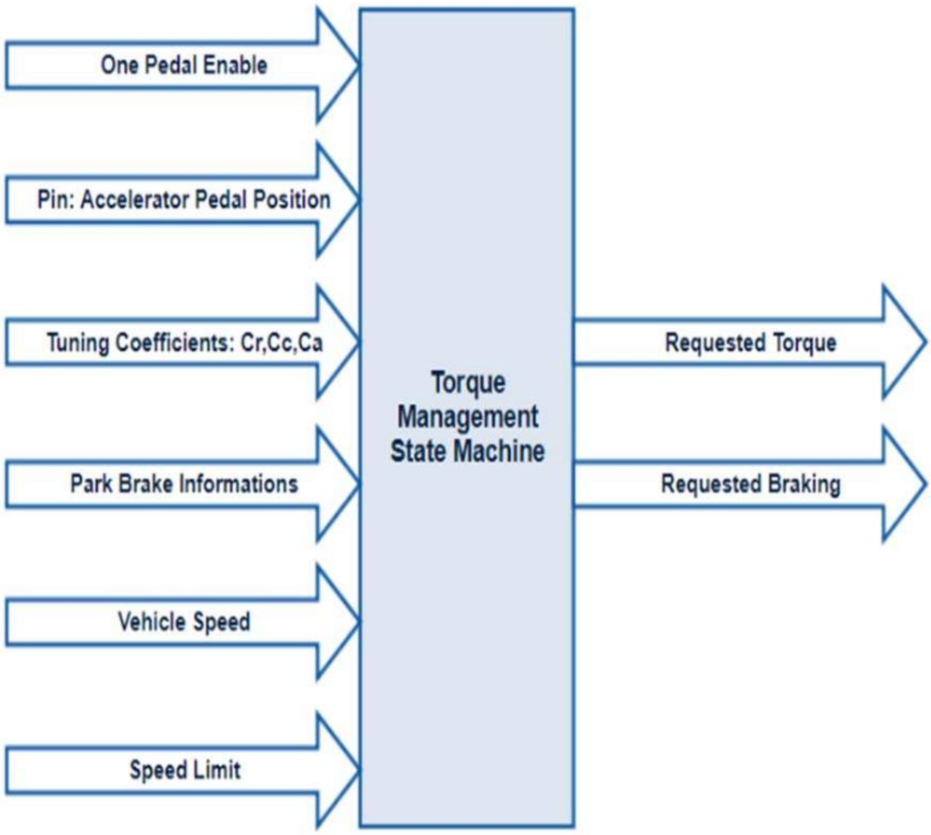


Figure 3.14. Torque Management State Machine

One pedal driving mode requires some operations for calculating requested traction torque limit and high resolution values. In this mode, the TSC1 message values are sent by Vehicle Controller. These calculations are made in the “OnePedalWithXBR” programming block. This block contains two function blocks for “Requested_Torque” and “Requested_Brake”. “Requested_Torque” output is used for sending the required positive or negative torque values to the Motor ECU. “Requested_Brake” is used for decelerate the bus via sending positive or negative acceleration values to the braking system. Also, programming block includes a structured text coding block inside.

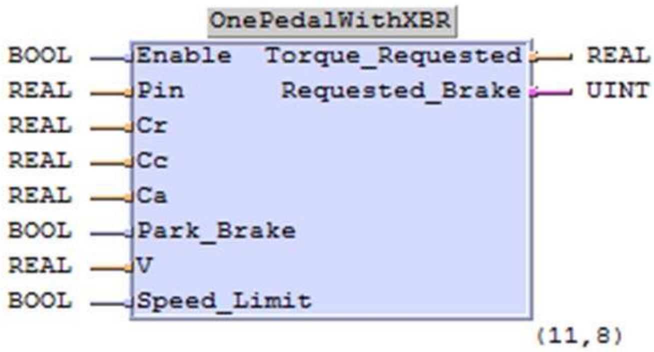


Figure 3.15. One Pedal Coding Block with external brake function

The "Enable" pin on OPD coding block waits information about activeness of one pedal driving button. If the driver choose one pedal driving mode via button on dashboard, the algorithms are began to executed. The accelerator pedal position is inquired via "Pin" input on coding block. Also, the retrieved pedal positions are filtered in this block.

"Cr, Cc and Ca" are determined as the tuning coefficients for calculating requested traction torque value and providing more smooth driving to electric bus drivers. The values of these coefficients are changing between 0.05 and 1.5. This tuning parameters had found via result of many different road test. Every test made with a different scenarios and the torque calculation process was observed. Also, the parameters were changed by test team online during road tests. Finally, the optimal results were found is given in Table 3.4:

Table 3.4. The values of tuning coefficients

Tuning coefficients	Numerical Values
Cr	1.5
Cc	0.05
Ca	1.0

Also, park brake information is received from multiplexer system as a driving requirement. The vehicle speed information is retrieved from Motor ECU and it is filtered for smooth driving. Finally, a speed limit is determined according to limit of electric vehicle. Speed limit is crucial parameter for stabilising the vehicle speed and also determining for driving sequence correctly.

The traction torque formulation in coding block is derived by using Table 3.5:

Table 3.5. The parameter values for developing OPD code

Parameter Values	Data Range	Operational Range	Minumum given value	Maximum given value
Accelerator Pedal Position	0 to 100 %	0 to 100 %	0	100
Requested Torque	-125 to 125 %	0 to 125% engine torque requests, -125% to 0% for retarder torque requests	125	250
Engine Requested Torque - High Resolution	0 to 0.875%	0 to 0.875%	0000	0111

Accelerator pedal position is evaluated in percent, the minumum and maximum values of accelerator pedal position is 0% and 100%.

The function of Requested Torque parameter is sending engine torquests and retarder torque requests to Motor ECU via TSC1 message.

High Resolution parameter displays an additional torque in percent of the reference engine torque. The parameter is used in combination with Requested Torque parameter. The resulting torque/torque limit is calculated by adding these two parameters (SAE j1939).

0000 = +0000%

0001 = +0.125%

0111 = +0.875%

1000 and 1111 = Not Available

First of all, the derived formula for requested traction torque value is calculated only considering of data ranges of parameters which is in above table. The formula of traction torque amount is given in Eq.1:

$$T = 2.25a + 25 \quad (1)$$

where T means requested percentage traction torque and a means accelerator pedal position percentage. Also, another formulation is derived for high resolution value according to chosen maximum and minumum values for electric bus:

$$R{=}0.07a \quad (2)$$

where R means high resolution and a means again accelerator pedal position percentage.

After this basic calculations, tuning coefficient, data ranges of related values and the other driving informations is took into consideration. Also, after numerous tests, it is clearly understood that the requested traction torque value is proportional to vehicle speed and accelerator pedal position. Final torque calculation formulas according to driving sequence are like below:

$$Tacc = -Cr * (44.0 - Pin) + 125.0 \quad \text{(Accelerating Sequence)} \quad (3)$$

$$Tcst = Cc * Pin + 125.0 \quad \text{(Coasting Sequence)} \quad (4)$$

$$Tbr = Ca * (Pin - 52.0) + 125.0 \quad \text{(Braking Sequence)} \quad (5)$$

where *Tacc* means requested percentage traction torque amount during accelerating sequence, *Tcst* means requested percentage traction torque amount during coasting sequence, *Tbr* means requested percentage traction torque amount during braking sequence, *Pin* means accelerator pedal position and *Cr* ,*Cc, Ca* are aforementioned tuning coefficients. The related flowchart is given in Figure 3.16:

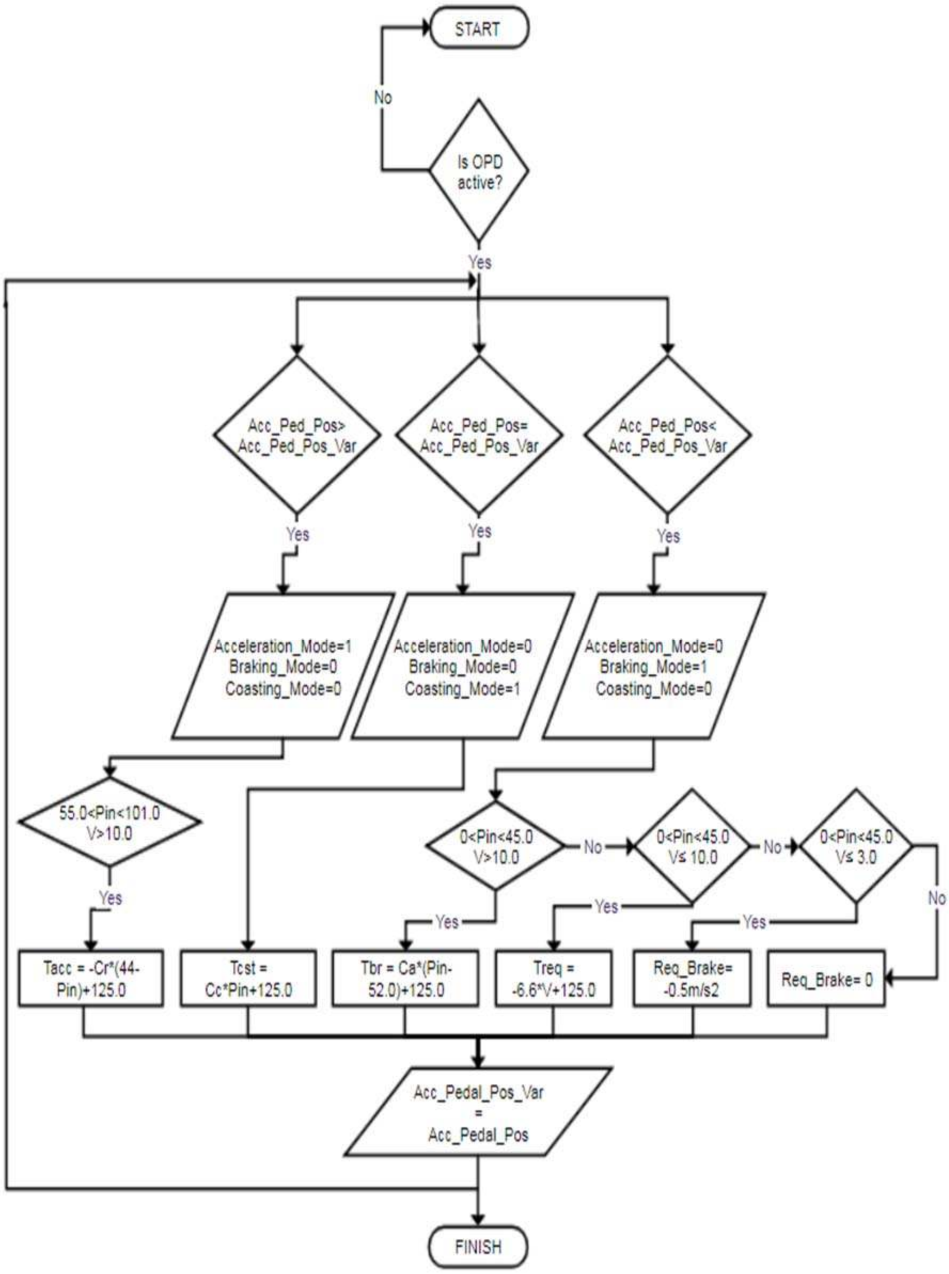


Figure 3.16. Traction torque management flowchart during OPD

The OPD coding block calculates the requested traction torque value according to these derived formulas and it transmits to output of block. Also, for sensitive calculation, it calculates the resolution for requested traction torque and it adds this value to calculated traction torque. So, the precise traction torque calculation is implemented.

When the algorithms are executed, if there is no messaging between Motor ECU and Vehicle Controller in 500 ms, a timeout occurs and system directly goes to Shutdown State. In this case, one pedal driving mode must be completely disengaged from system and driver should be immediately informed about timeout fault and the system must return to standard driving mode.

3.2.3 Fault Management State Machine

In fault management state, the errors which is related with one pedal driving is detected. In order to detect, a fault detection algorithm is executed and this algorithm waits below information from control units on powertrain system:

- **Discharge Enable Information:** If discharge enable message is not received or if a timeout occurs, the One Pedal Driving Fault Management State is activated.
- **Accelerator Pedal Position Status:** Accelerator Pedal Position Status has two different values : "0 and 1". If this status message is zero, the accelerator pedal position signal is implausible. In other condition, when the status message is equal to one, the accelerator pedal position signal is valid and true. During one pedal driving, this status should be equal to one, otherwise the fault management state is activated.
- **Motor ECU Message State:** If Motor Electronic Control Unit message state takes any of the values given in Table 3.6, the fault state is activated.

Table 3.6. Motor Electronic Control Unit message state values

Value (Hexadecimal)	**Output**	**Occurence**
16#01	Not Available	No communication on start-up, e.g., 1. Voltage Interruption on start-up 1. CAN interruption on start-up
16#10	Timeout	No communication during operation, e.g.: 1. Voltage Interruption while running 2. CAN interruption while running

- **Brake Pedal Position:** If brake pedal position is bigger than zero for two seconds during one pedal driving mode, the fault state is activated.
- **Actual Motor Torque Status:** It has two different values : “0 and 1”. If this status message is equal to zero, the motor torque signal is implausible. When this signal is implausible, the one pedal driving fault state must be active. If this status message is equal to one, the motor torque signal is correct and there will be no fault during one pedal driving.

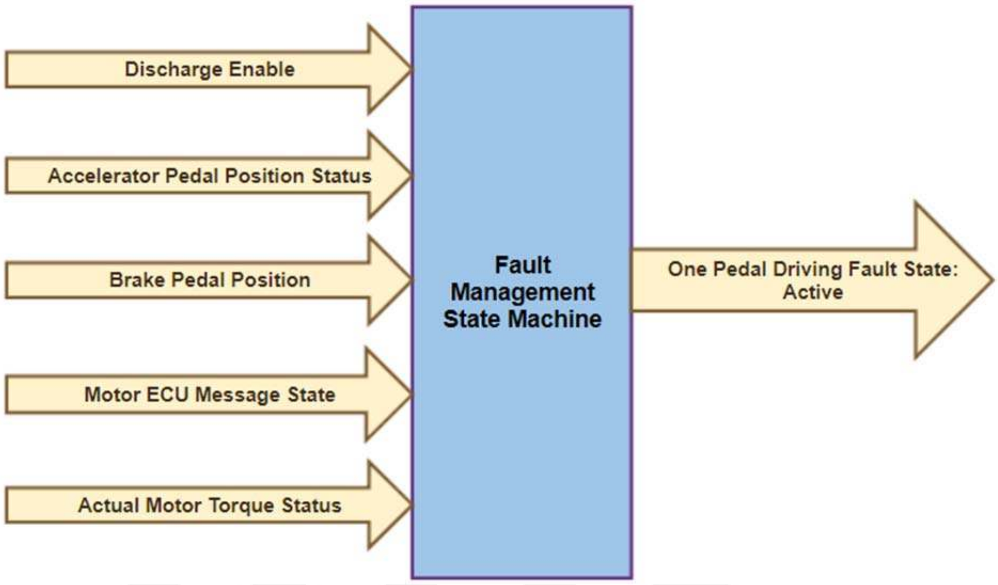


Figure 3.17. Fault Management State Machine

3.2.4 Shutdown State Machine

Shutdown state machine is the final part of one pedal driving algorithms. In this state, the all fault situations are evaluated and the system goes to shutdown state to disengaging the one pedal driving mode for providing driving safety. This state machine takes into account the status of ignition key signal, activity of one pedal driving fault state and emergency switch information.

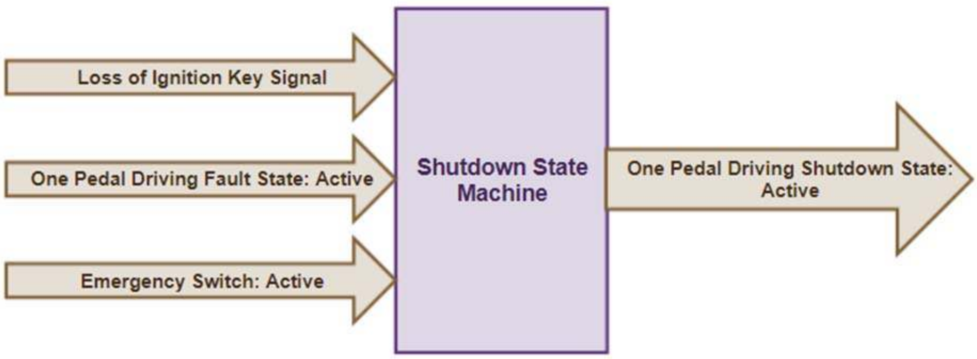


Figure 3.18. Shutdown State Machine

There are three conditions to pass shutdown state machine when one pedal driving mode is active. If ignition key signal is loss or one pedal driving fault state is active, the shutdown state machine algorithms are executed. The other reason for shutdown state can be activity of emergency state and if any of these faults occur, system disables the one pedal driving and goes to the standard driving mode without delay.

3.3. Torque Management Process

Torque management process is achieved by the reading the driver's interactions at the right time. This process is based on driving parameters and and driver's input such as pedal information, shift selector requests and etc.

The key specifications for the torque management are:

- Processing of the accelerator and brake pedal signals.
- Progressive application of the torque request (ramp up/down).
- Computation of compression and braking torque.
- Reduction of compression and braking torque at low speed.
- Smooth transition between forward and reverse motions.
- Computation of hill holder and creep torque.
- Drive selector change protection.

The different types of torque can be mentioned in an electric vehicles namely traction, compression, braking, creep and hill holder torque. All torque values must be considered when the torque calculation is implemented for an electric vehicle. In order to make correct calculation, the distinctness of these torque types must be understood clearly.

The traction force must be defined first to understand better the traction torque**.** The traction force is the friction force that the road surface applies on the wheel surface. Obviously, this force will cause a torque on the axis of each drive wheel (Car Physics, 2003):

$$T_{tr} = F_{tr} * r_w \tag{6}$$

where T_{tr} is the traction torque, F_{tr} is the traction force and r_w is wheel radius.

The **compression** applies deceleration torque to simulate engine compression when the throttle pedal is released. The compression torque command is related with the accelerator pedal position (TM4 Technical Guide, 2015).

Braking torque is the force applied at the brake wheel to stop the motion of the moving equipment. Assuming the operating conditions for the equipment are constant, a brake having a retarding torque equal to the full load torque of the motor to which it is applied is usually satisfactory (Engineers Edge, 2018).

Creep torque: Automotive vehicles typically have a vehicle technical specification that defines how fast the particular vehicle should accelerate from a stop when it is idling in gear and the driver applies no pressure to the brake pedal or the accelerator pedal. To accomplish this, the powertrain system is designed to apply a specific amount of torque when the vehicle is stopped, called **creep torque**.

This creep torque, then, acts against the brake application by the driver while the vehicle is stopped. Upon release of the brake pedal, the vehicle will begin to move, even without pressing on the accelerator pedal. In a vehicle with a conventional internal combustion engine, automatic transmission and torque converter, applying a creep torque is relatively easy since the engine is operating all of the time-even while the vehicle is stopped at a traffic light (US 7909730 B2, 2007).

Hill holder torque: When starting a vehicle from a stationary position on a steep incline, a driver has to coordinate the application and release of the clutch, brake and accelerator pedals in a manual transmission car. This scenario can be unsafe. Hill hold control systems assist the driver in these situations by keeping the brakes applied until torque from the engine is applied to wheels. This torque is called as **"Hill Holder Torque".** Depending on the manufacturer, hill hold control may also be referred to as hill-start assist or hill-start control (Clemson, 2015).

Torque management process takes into consideration of whole torque types on electric vehicle and combines these according to transmission direction. Final torque formula is given in Equation 7 :

Final Torque= Traction Torque + Creep Torque + Hill Holder Torque - Compression Torque - Braking Torque + Damping Torque (7)

In this study, the focus point is calculation of traction torque which is controlled by accelerator pedal position during one pedal driving.

3.4 Test Bench Studies

3.4.1 Test Bench Setup

In this thesis, the traction torque management is determined as focus point and a test bench is installed for obtaining accelerator pedal position in percentages. Because, the accelerator pedal position is the heart of the traction torque management and also one pedal driving algorithms. The whole traction torque calculations must be made pursuant to pressing percentage of accelerator pedal.

The test bench consists of an accelerator pedal, a multiplexer unit, a Vehicle Controller and on-off switch. In order to get more realistic and reliable simulation results, a real accelerator pedal which is used in electric buses is connected to test bench. The test bench operates at 24V level. The percentage values of accelerator pedal position was read from test bench before applied to electric bus. The picture of test bench is given in Figure 3.19:

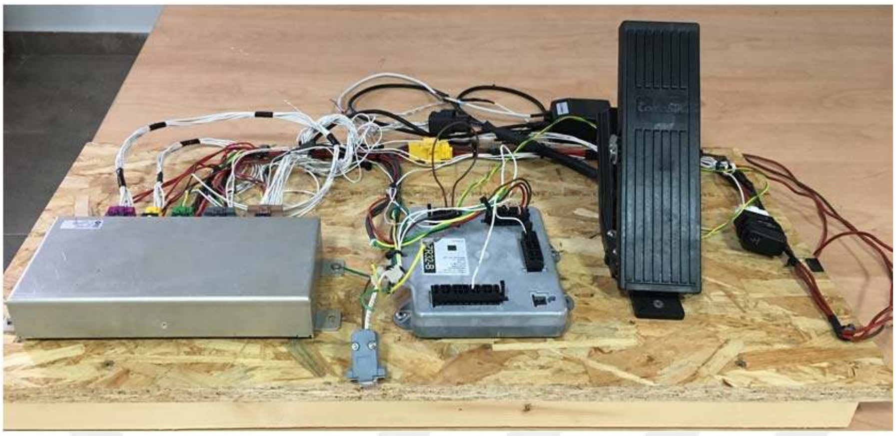


Figure 3.19. Test Bench

An accelerator pedal is used and percentage value of pedal is read via developed algorithms for traction torque applications. The electrical characteristic of used accelerator pedal is given in Table 3.7:

Table 3.7. Electrical characteristic of accelerator pedal (Comesys, 2012)

Input Voltage (Vcc)	5 Vdc ± 2%
Operation Current (Iop)	20mA (Normal), 25mA (Max)
Independent Linearity	± 2%
Signal Load	10kohms, C=4.7nF
Operating Temperature	-40°C to +85°C

The accelerator pedal has two position sensors which operate oppositely and independently of each other. If one of the sensors is failed, the other one is keep working as a spare so, the vehicle won't be affected from any sensor fault. The reason of using two sensor is to prevent sensor-induced faults. These sensors are responsible for determining of the accelerator pedal pressing percentage and transmitting this signal to the Motor ECU. Actually, the aforementioned sensors can consists of two potentiometers. These potentiometers provide adjustable resistance values for accurate measurements.

Figure 3.20. Accelerator Pedal on test bench

The connector of accelerator pedal has six pins for two different signal outputs. These are power input, signal output and ground pins for these signals. Also, in Figure 3.21, the circuit diagram for Sensor 1 and Sensor 2 of accelerator pedal is given:

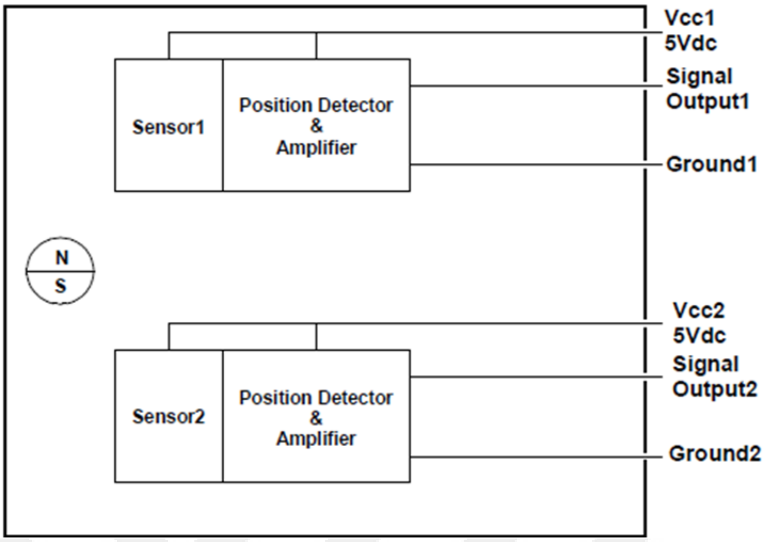


Figure 3.21. The circuit diagram of accelerator pedal (Comesys, 2012)

The signal output of sensors is changing according to accelerator position. The rate of changing can be detected by voltage changes on outputs. The range of change according to minumum and maximum accelerator pedal position is given in Table 3.8:

Table 3.8. Accelerator Pedal Position Values on Test Bench

Accelerator Pedal Position (%)		**Channel 1 (V)**	**Channel 2 (V)**
Min.	0	0.545V	1.083V
Max.	100	2.028V	4.098V

The other component of test bench is a multiplexer unit which is used for controlling digital and analog inputs. In common electronic installation on electric vehicles, multiplexer unit independently carries out control functions of systems such as interior and exterior lighting systems, wiper system, climate control system, door system, window regulator and etc. A failure of any individual system will not influence the whole system.

The most economical electronic multiplexer system must be provided with the most economical configuration to the electric vehicle manufacturers. Multiplex system provides an easy control method. Also, the other benefits of using multiplex system are following:

- reducing wiring and harnesses
- sharing a sensor for different purposes
- increasing ability
- enabling communication between all nodes on single network
- reducing development cost
- fast data communication
- short repairing time
- fast response system

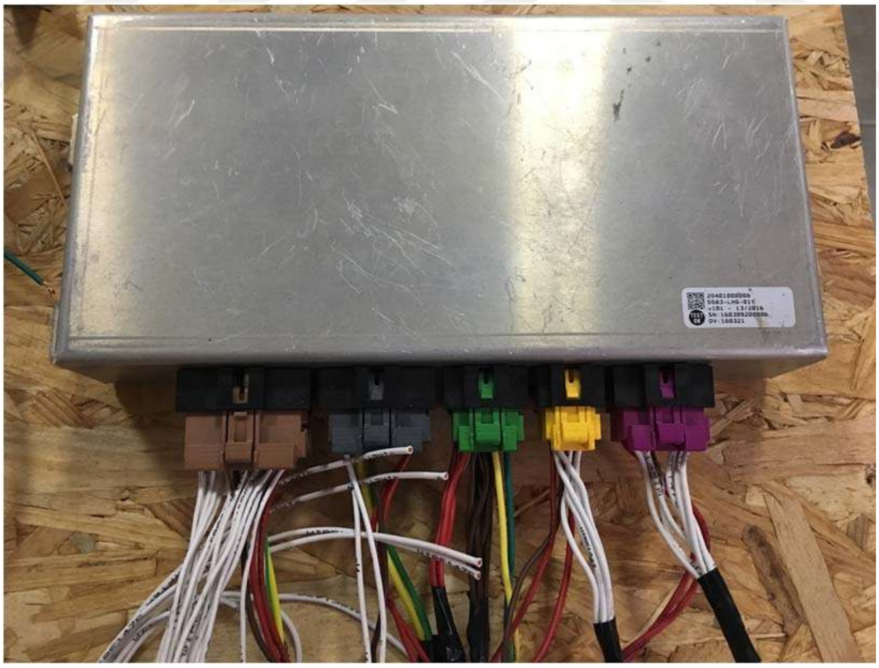


Figure 3.22. Multiplexer unit on the test bench

The "oMux" program was used for programming the multiplexer unit which is on the test bench. oMux is a software application with a functional block diagram interface conforming to the ISO 61131 standard for programming the multiplexer family of next generation automotive electronic control units. The user can define his own multiplexer system with oMux program and create any scenario with its easy and user-friendly interface. At the same time, the scenario within the device can be performed online via interface.

In this study, the digital input signal is called as "System_Enable," and analog inputs are called as "Accelerator Pedal Channel-1 signal (ACC_PEDAL_1)" and "Accelerator Pedal Channel-2 signal (ACC_PEDAL_2)". Also, there are three different digital outputs related with traction torque algorithms namely "Vacuum_Output", "Keep_Alive" and "Wake_up_Motor" signals.

The other component of test bench is Vehicle Controller. In Figure 3.23, the Vehicle Controller used in this study is seen.

Figure 3.23. Vehicle Controller (Continental, 2015)

The control mechanism of the test bench has established with this Vehicle Controller unit. The user's program is downloaded into this Vehicle Controller. It takes communication data via CANBUS network from vehicle's CAN Line. Also, it answers swift the request which is indicated on user's program.

3.4.2 Reading Accelerator Pedal Position on Test Bench

After setting up of test bench, the 24V supply voltage is applied and all components are activated. A visual control is made for all equipments on the test bench. If all components are active without any fault, the position of accelerator pedal is changed manually. In the meanwhile, a Can Logger tool is connected to designated CAN interface of Vehicle Controller.

The developed software for calculating accelerator pedal positions in percentages is downloaded into Vehicle Controller. The output channels of accelerator pedal is read within a CAN message separately as follows:

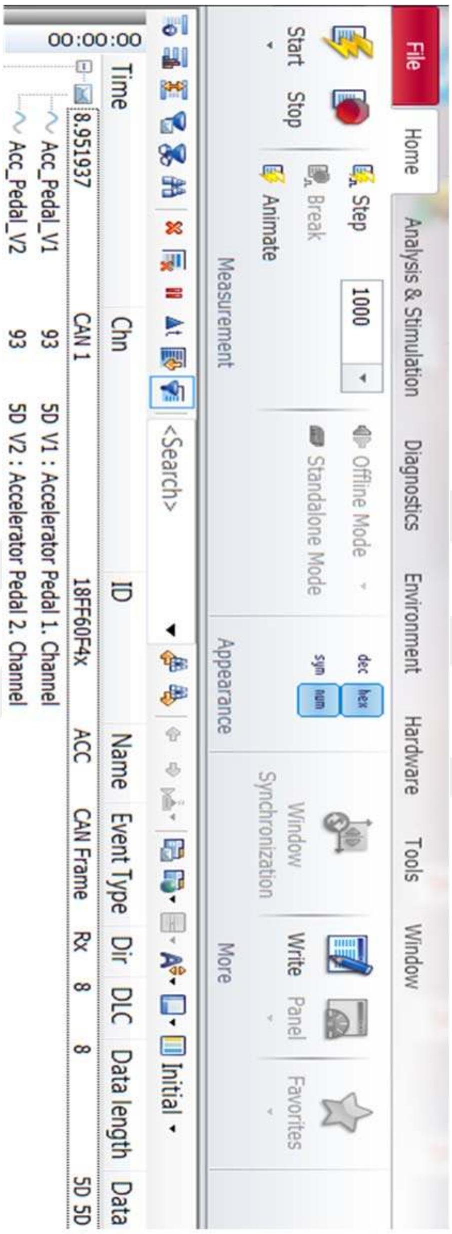


Figure 3.24 Reading of accelerator pedal output channel in percentages

Also, the changing positions are observed via CAN logger tool as following:

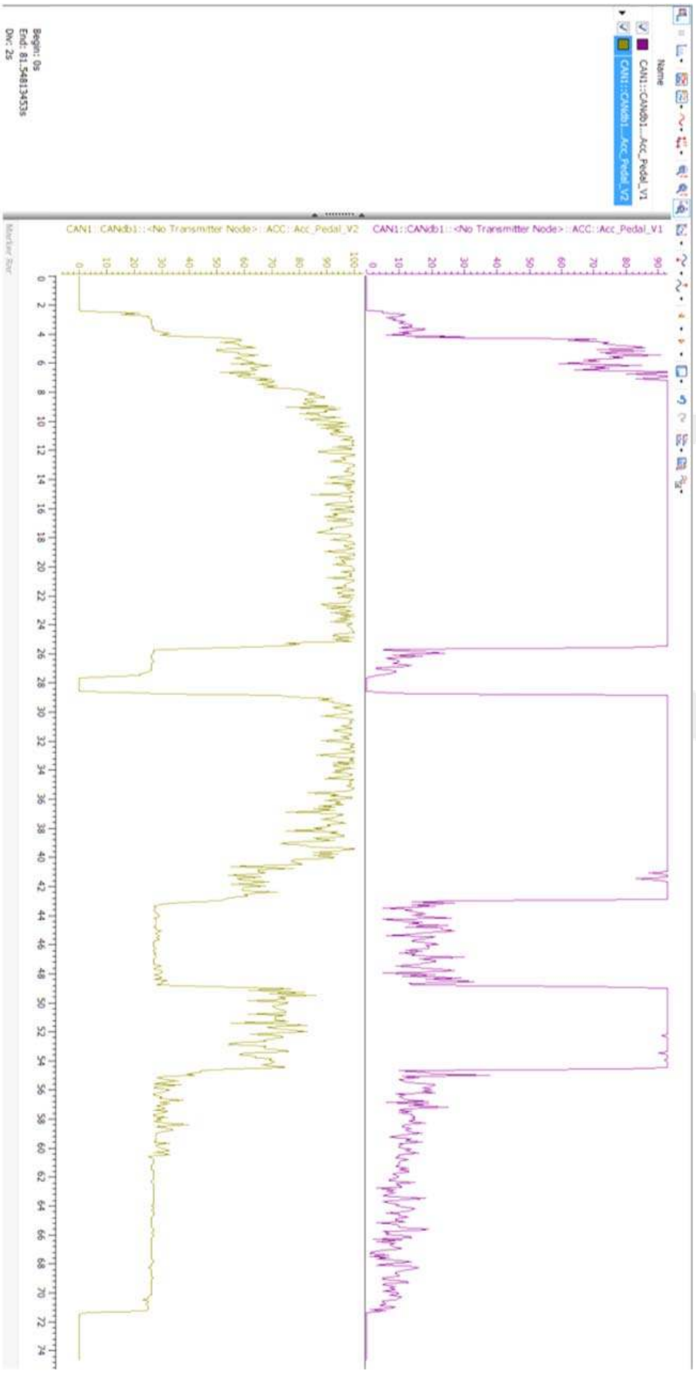


Figure 3.25. Output channels of accelerator pedal on CAN logger tool

The test bench results shows that the output channels of accelerator pedal position must be filtered with a appropriate method. The changing speeds of voltage outputs are very rapid so the filtering is required for accurate measurement of pedal position percentage.

The developed algorithms are updated and corrected according to test bench results. Filtering operations were added into the developed software. The designation of driving sequence will be more reliable with accurate accelerator pedal position calculations. After the test bench applications, the updated software is downloaded into real electric bus. The conditions of tests and all driving scenarios is discussed in Experimental Test Results section.

4. EXPERIMENTAL TEST RESULTS

The developed one pedal driving software is downloaded into the Vehicle Controller. Following data and graphics are implemented with a CANlogger and a tracking application. Also, CAN analyzer tool provides comparison chance to the user via its powerful graphics and message features.

Tests were conducted in order to measure the effects of one pedal driving on the vehicle range and energy efficiency. Also, the test results include the different driver’s opinions and discuss the differences between drivers in terms of driving profile.

In one pedal driving tests, some test roads are selected and whole tests are implemented on these l routes. The selected electric bus weight is 12930 kg and the slope and altitude of test roads are always measured via tracking application during tests. The 12 meter test bus is shown in Figure 4.1:

Figure 4.1. 12 meter one pedal driving test bus

The first test is done in urban traffic. The route has traffic lights and also some stopping places are determined so, the driver has stopped here and after that he continued to driving. In this scenario, the driver tested the one pedal driving two times on local traffic and completed the route with standard driving for once. The reason of driving on one pedal driving mode for twice is that measuring of adaptation level of drivers. The expected result was that in second time, the drivers can perform more efficient driving thanks to the adaptation. Indeed, the expexted results are proved with energy recuperation ratios. All road and driving data which is obtained during first test will be given in following section.

The second test is done in a special test road with less traffic effect in contrast to first test. The aim of this test is decreasing the negative traffic effects such as traffic lights, excessive stop and go action so, the driver can complete the test route with constant speeds as best as he can do. Also, the test route is selected as longer than first route. The test drive is completed with once with the standard driving mode and once with the one pedal driving mode. The acquired information about one pedal driving will be given.

The third and final tests made on same track with second test. The lenght of road is kept same like second test but the driving scenario was different. Some special points are determined as stopping places and when driver reaches these points, he slowed down and came to full stop. The purpose of this test was implementing the simulation of real driving like the commercial bus driver e.g. picking up and dropping off passengers. Totaly, six different points are determined for stopping place and the driver came to full stop in these points. The test was repeated twice, once with standard driving mode and once with one pedal driving mode. The comparison data of these two test are presented in the following sections.

4.1. Different Road Tests with Same Driver

4.1.1 Urban Traffic Test Results

The first test is done in normal local traffic circumstances. The lenght of route was 9.8 km and the slope of test road was between 7-9% along the whole road. The satellite image of test road is given in Figure 4.2:

Figure 4.2. Satellite image of urban test road

The first tour on this road made with standard driving mode. The SOC, consumption and regenerative energy levels of electric bus with standard driving are given in Table 4.1:

Table 4.1. Energy levels of electric bus after standard driving

With Standard Driving	**Energy Consumption (kWh)**	**Regenerative Energy Recuperation (kWh)**	**Net Consumption (kWh)**
	15.6	5.3	10.3

During first tour, standard driving mode is used and the slope and altitude information are saved via a tracking application.

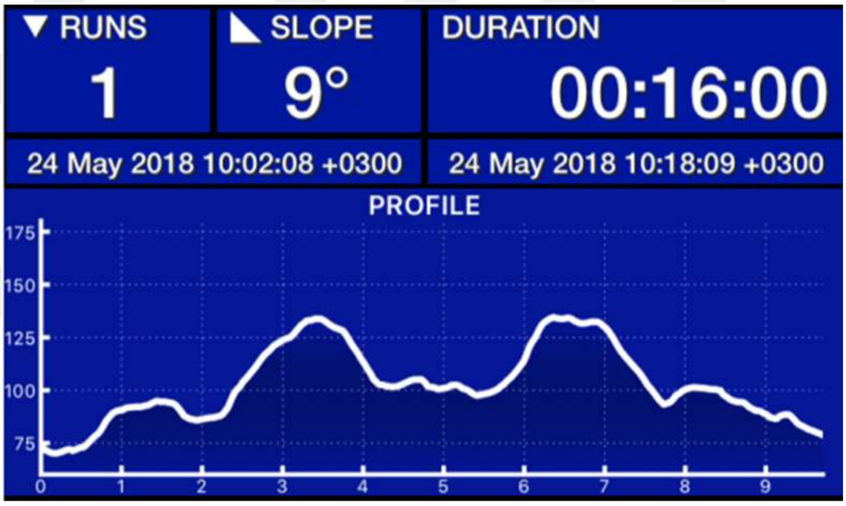


Figure 4.3. Altitude profile of test road

Also, the speed profile during standard driving is retrieved via this mobile appliation and given in Figure 4.4:

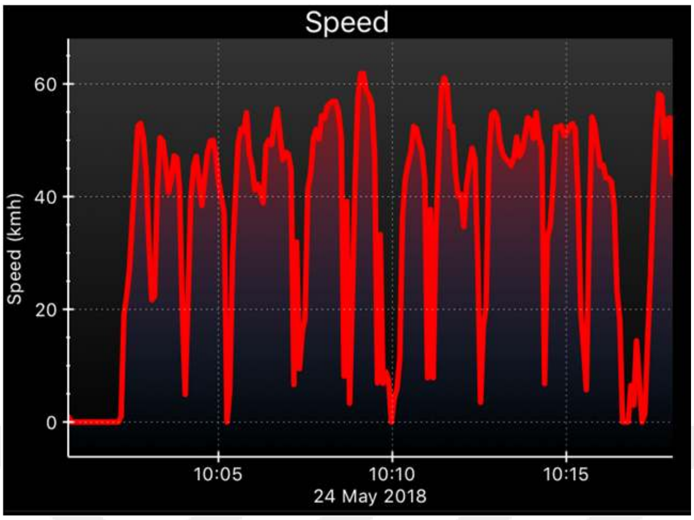


Figure 4.4 Speed profile of test bus during standard driving

Also, the actual motor torque was saved as a graphic via CAN logger tool. If torque values are under zero, it means that the electric bus doing regenerative braking. During regenerative braking, the charging of batteries is controlled by electric motor.

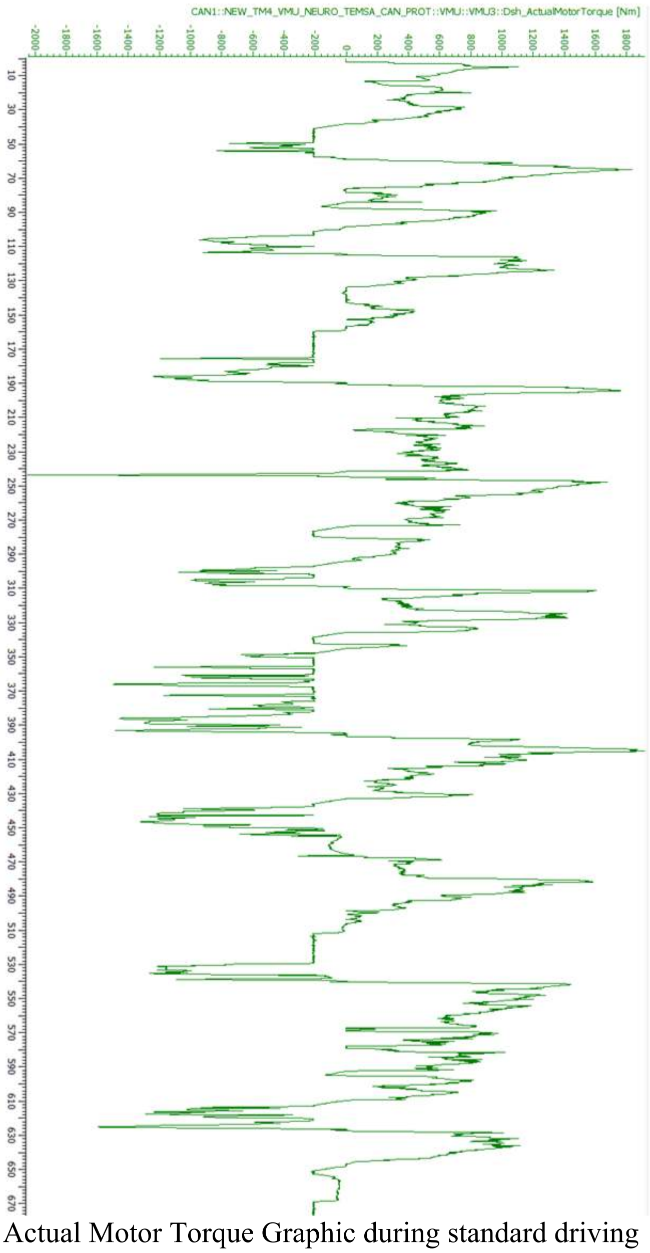


Figure 4.5. Actual Motor Torque Graphic during standard driving

In the second part of test, one pedal driving mode is enabled on same conditions. One pedal driving mode was tested twice in order to learn the adaptation rate of driver. The results of first one pedal driving test is given in Table 4.2:

Table 4.2. Energy levels after first one pedal driving test

With One Pedal Driving	**Energy Consumption (kWh)**	**Regenerative Energy Recuperation (kWh)**	**Net Consumption (kWh)**
	15.4	6.1	9.3

The comparison between driving with and without one pedal driving is given in Table 4.3:

Table 4.3. Consumption values with OPD and without OPD

	Energy Consumption (kWh)	**Regenerative Energy Recuperation (kWh)**	**Net Consumption (kWh)**	**Energy Recuperation Percentages (%)**
Without OPD	15.6	5.3	10.3	33.9
With OPD	15.4	6.1	9.3	39.6

The speed profile during one pedal driving mode is given in Figure 4.6:

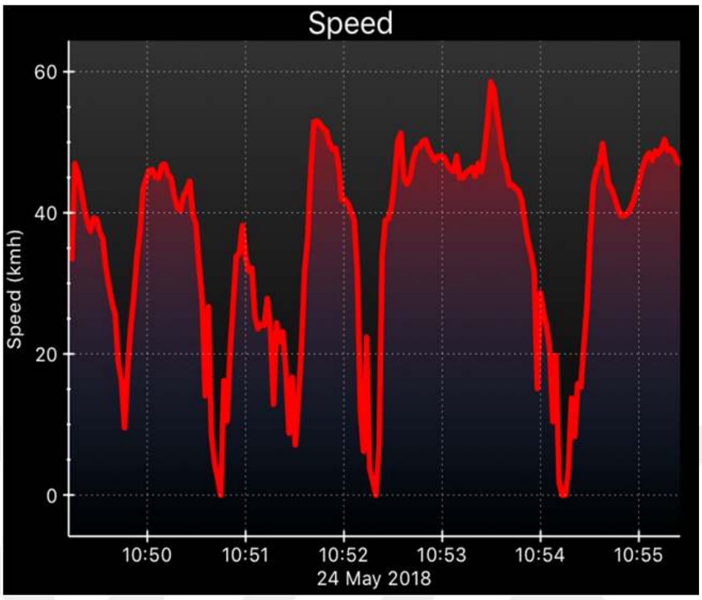


Figure 4.6 Speed profile of test bus during urban traffic test

In second test, it is observed that the driver has become more familiar with one pedal driving. He could implement smooth braking with the help of only accelerator pedal. The consumption and energy recuperation values are better than first one pedal driving by a narrow margin. The comparison results are given in Table 4.4

Table 4.4. Energy levels after second one pedal driving test

	Energy Consumption (kWh)	**Regenerative Energy Recuperation (kWh)**	**Net Consumption (kWh)**	**Energy Recuperation Percentages (%)**
During First OPD Test	15.4	6.1	9.3	39.6
During Second OPD test	15.4	6.4	9.0	41.5

The actual motor torque is saved during one pedal driving. The percentage of negative torque is much more than standard driving mode. It can be seen easily in Figure 4.7:

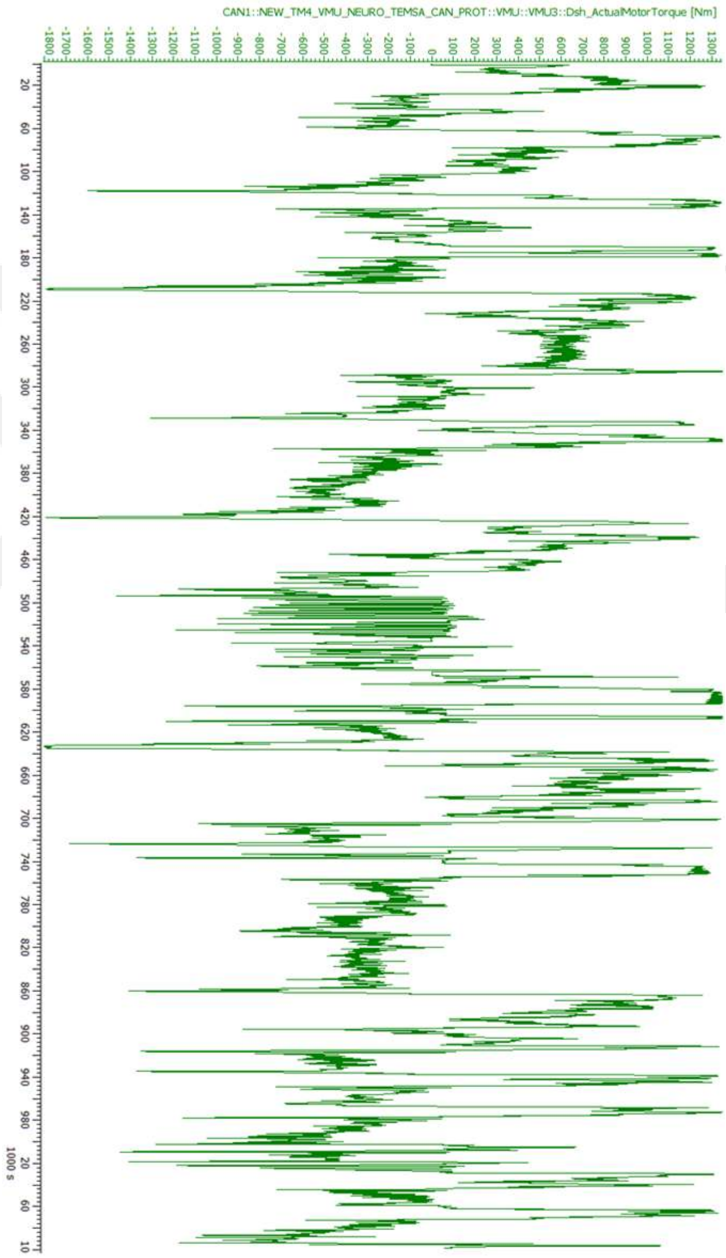


Figure 4.7. Actual Motor Torque graphic during one pedal driving

The graphics and comparison tables shows that one pedal driving is more efficient way for electric bus driving.

Finally, the all consumption values are given in Table 4.5:

Table 4.5. Final comparison table

	Energy Consumption (kWh)	**Regenerative Energy Recuperation (kWh)**	**Net Consumption (kWh)**	**Energy Recuperation Percentages (%)**
Without OPD	15.6	5.3	10.3	33.9
During First OPD Test	15.4	6.1	9.3	39.6
During Second OPD test	15.4	6.4	9.0	41.5

4.1.2 Constant Speed Test Results

The constant speed tests are made in a special test road which is separated for electric bus in a facility. The lenght of route was 14.4 km and the slope of test road is between %4-7 along the whole road. The satellite image of test road is given in Figure 4.8:

Figure 4.8. Satellite image of test road

The first tour on this road made with standard driving mode. The energy consumption, regenerative energy level and net consumption level of electric bus during standard driving test are given as chart in Table 4.6:

Table 4.6. Energy levels of electric bus with standard driving

With Standard Driving	Energy Consumption (kWh)	Regenerative Energy Recuperation (kWh)	Net Consumption (kWh)
	13.2	1.7	11.5

During first tour, standard driving mode is used and the duration, slope and altitude profile is saved. In Figure 4.9, the altitude profile of test road is given:

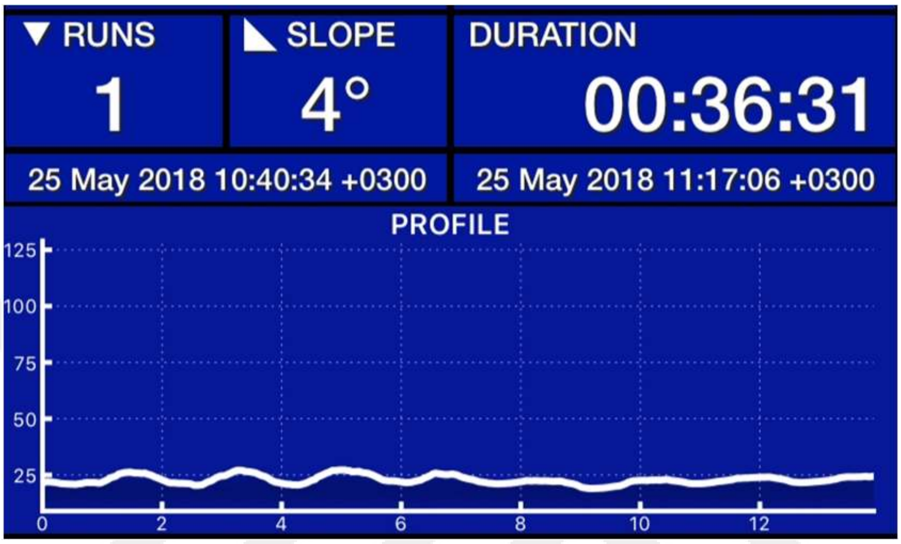
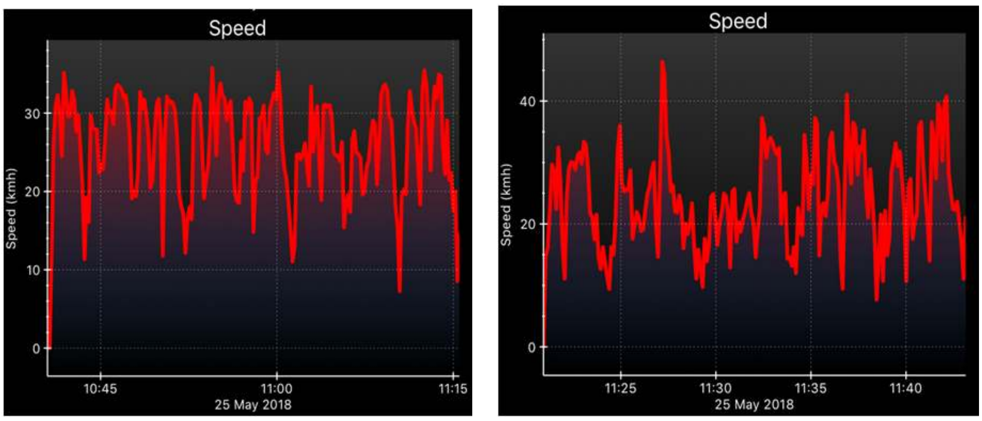


Figure 4.9. Altitude profile of test road

Also, the detailed speed profile is retrieved during standard and one pedal driving modes and given in Figure 4.10:



(a) **(b)**

Figure 4.10. Speed profiles during (a) standard driving and (b) one pedal driving

The second test was made with one pedal driving mode and the information about the consumption is given on Table 4.7:

Table 4.7. Consumption values during One Pedal driving

With One Pedal Driving	Energy Consumption (kWh)	Regenerative Energy Recuperation (kWh)	Net Consumption (kWh)
	13.9	4.3	9.6

After retrieving all consumption values for standard and one pedal driving modes, the values are compared according to energy recuperation percentages. The percentage of energy recuperation during standard driving is approximately 12.8 while the percentage of energy recuperation of one pedal driving is 30.9.

Table 4.8. Comparison Table for Energy consumption

	Energy Consumption (kWh)	Regenerative Energy Recuperation (kWh)	Net Consumption (kWh)	Energy Recuperation Percentages (%)
Without OPD	13.2	1.7	11.5	12.8
With OPD	13.9	4.3	9.6	30.9

According to final comparison table, the one pedal driving recuperation rate is approximately 2.4 times more of standard driving mode. This means one pedal driving presents to driver more efficient driving in comparison to standard driving.

4.1.3 Stop-and-Go Traffic Test Results

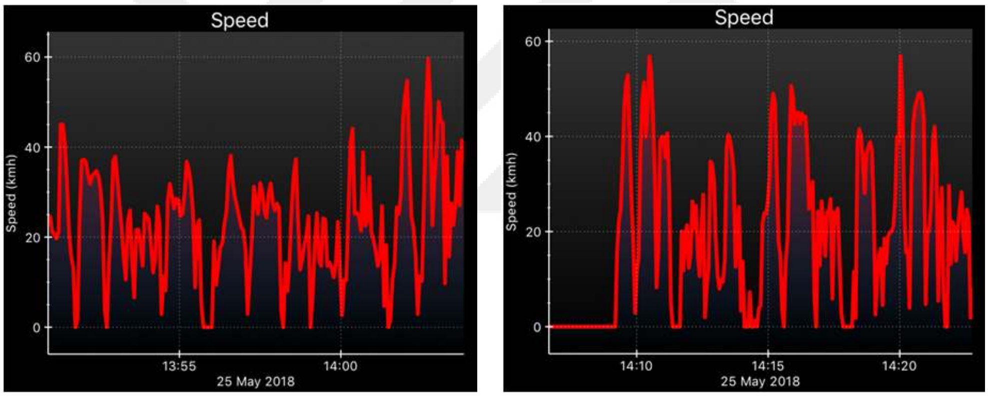
The stop-and-go traffic tests are made on same test road with constant speed tests. But this time, the lenght of route was decreased to 5.5 km.

The first tour on this road made with one pedal driving mode. The energy consumption, regenerative energy level and net consumption of electric bus during one pedal driving test are given in Table 4.9:

Table 4.9. Energy levels of electric bus during one pedal driving

	Energy Consumption (kWh)	Regenerative Energy Recuperation (kWh)	Net Consumption (kWh)
With One Pedal Driving	3.8	0.8	3.0

The detailed speed profiles during one pedal and standard driving are given in Figure 4.11:



(a) (b)

Figure 4.11: Speed profiles during (a) one pedal driving and (b) standard driving

In order to compare, the second test was implemented with standard driving mode and the energy consumption results are given in Table 4.10:

Table 4.10. Energy levels of electric bus with standard driving

With Standard Driving	Energy Consumption (kWh)	Regenerative Energy Recuperation (kWh)	Net Consumption (kWh)
	4.3	0.6	3.7

The final comparison table is given in table 4.11:

Table 4.11. Comparison Table for Energy consumption

Test Condition	Energy Consumption (kWh)	Regenerative Energy Recuperation (kWh)	Net Consumption (kWh)	Energy Recuperation Percentages (%)
Without OPD	4.3	0.6	3.7	13.9
With OPD	3.8	0.8	3.0	21.1

After all different scenarios on differerent roads, the result is that the one pedal driving is more efficient way for driving an electric bus for all traffic conditions. The range extension is a bottleneck for electric vehicle all the time. But according to test results using one pedal driving mode, this problem can be solved easily. Also, the tiredness of drivers can be decreased with using only one pedal for both acceleration and deceleration operations. The detailed results are given in conclusion part of this thesis.

4.2. One Pedal Driving Tests with Different Drivers

One Pedal Driving tests are made with three drivers in order to understand the adaptation level of drivers to new driving method. The bus drivers are selected for testing that correlation between energy efficiency and experience on one pedal driving.

In order to get correct results about adaptation test, it is required that the drivers have different experience levels on one pedal driving. The first driver has tried the one pedal driving one time before tests and the second driver never used the one pedal driving method. As for third driver, he has experienced on one pedal driving for a while. The expectation was that the adaptation level is directly affect the energy recuperation level. So as to test the this situation, a 3,8km long test road is selected and the slope of test road is measured between 4-7%. The result table about driver's performance is given in Table 4.12:

Table 4.12. Comparison Table for Different Drivers

	Total Energy Consumption (kWh)	**Regenerative Energy Recuperation (kWh)**	**Net Consumption (kWh)**	**Energy Recuperation Percentages (%)**
1st Driver	4,8	0,9	3,9	18,7
2nd Driver	6,5	1,4	5,1	21,5
3rd Driver	8,3	3,6	4,7	43,3

The first driver was inexperienced about one pedal driving and he used this driving mode for the first time in his life. His total energy consumption was not high as other drivers but also his energy recuperation is the lowest one among the drivers. As a result, his energy recuperation percentage is lower than the other two drivers.

As for second driver, his regenerative energy recuperation amount is higher than first inexperienced driver. Meanwhile, his total energy consumption is higher than first driver. But in the end, his energy recuperation percentage is higher than 20%. This values can be used as a proof of the relationship between energy recuperation values and adaptation level of driver. Since the second driver is more experienced, he performed more efficient driving with one pedal driving mode as against first driver.

The third driver is the most experienced driver about one pedal driving and his adaptation level was the highest in comparison with other drivers. According to test results, his energy recuperation percentage is the highest.

The results of this test shows that more experienced driver can be perform more efficient driving with one pedal driving method. Also, the common opinions of driver was that one pedal driving adaption process will be easy for drivers and it requires less effort for acceleration and deceleration. Also, the drivers said that, it will be easy to become widespread of this driving mode among the electric vehicle drivers with the help of lowness of energy consumption.

5. CONCLUSION

This thesis has presented the development of a new driving method for the commercial electric buses and the management of traction torque in an electric vehicle. Also, the calculation of accelerator pedal in percentages without any controller has done to detect how much it is pressed within the scope of this study. First of all, a acceleration pedal movement is converted to voltage signal and this voltage is measured. Then, an developed algorithm is executed to obtain the accelerator pedal position in percentages. This algorithm provides accurate and reliable calculation of acceleration pedal position for management of traction torque.

This research work has led to these important contributions to literature about one pedal driving methods for commercial electric buses:

- During this work, the energy saving performance of the one pedal driving method is analyzed and the results are shows that the energy recuperation rate in one pedal driving mode is higher than standard driving mode. It is easily said that the one pedal driving mode is more efficient than standard driving mode according to implemented different test results.
- In one pedal driving method, using of brake pedal is not necessary so; this driving mode can extend the lifetime of brake lining in electric buses. It can bring down the cost of an electric bus when it is in use.
- One pedal driving mode reduces the reaction time of driver because the driver can react to any disturbance with using only his/her one foot.
- The safe braking distance is shorter than standard driving mode because of using only one pedal during driving.
- Also, as a result of using only one pedal for accelerating and decelarating, it requires less driver efforf on stop-and-go traffic.

- One pedal driving reduces the accidents because it provides safer acceleration and deceleration process in contrast to standard driving mode.
- Also, it provides easier and more comfortable driving mode to drivers.
- The adaption period of drivers is very short and simple.
- With developing the one pedal driving mode, it has shown that the this new and state-of-the-art driving method can be used for commercial electric bus producers as an option in their electric bus.

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BIOGRAPHY

Çağla DERİCİOĞLU was born in Adana, Turkey in 1993. She completed her high school education in Adana and graduated from Ayşe Atıl Anatolian High School. She received her Bachelor degree in Electrical and Electronics Engineering Department from Çukurova University in 2015. After completion his B.S. education, she started MSc education in Electrical and Electronics Engineering Department in Çukurova University. She began her engineering career at Beta Transformatör and she had worked as a Research Engineer for a year. She has been working as an Research and Development Engineer in TEMSA Ulaşım Araçları San. ve Tic. A.Ş. since 2016. Her interest areas are Automotive Electronics, Power Electronics and Electric Vehicles.