ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

ECONOMIC EVALUATION OF URBAN ELECTRIC BUS CHARGE STATIONS: CASE OF EINDHOVEN, THE NETHERLANDS

M.Sc. THESIS

Çağrı YILMAZ

Energy Science and Technology Division
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ELEKTRİKLİ OTOBÜSLERİN ŞARJ İSTASYONLARININ EKONOMİK YÖNDEN İNCELENMESİ: EINDHOVEN, HOLLANDA ÖRNEĞİ

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Çağrı Yılmaz, a M.Sc. student of ITU Institute of Energy student ID 301141006, successfully defended the thesis entitled "ECONOMIC EVALUATION OF URBAN ELECTRIC BUS CHARGE STATIONS: CASE OF EINDHOVEN, THE NETHERLANDS", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 04 May 2018
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To my grandmother,

FOREWORD

I aimed to analyse the cost effect of electric buses which will be effective in reducing GHG emissions in transportation for the environment.

First of all, I would like to thank my advisor, Prof. Dr. Gülgün Kayakutlu for her understanding and precious support. She has always spared time for me during my study.

I would like to thank to all my teachers who have always supported me during my graduate study.

And sure, I would like to thank my dear spouse who has never left me alone and support my all studies.

June 2018

Çağrı YILMAZ
(Naval Architecture
And Marine Engineer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

CIVITAS : City Vitality and Sustainability
CNG : Compressed Natural Gas
COP : Conference of Parties
FAME : Fatty Acid Methyl Ester
GHG : Greenhouse Gas
HVO : Hydrotreated Vegetable Oil
IEA : International Energy Agency
LNG : Liquid Natural Gas
LPG : Liquid Petroleum Gas
US : United States

LIST OF TABLES

Page

LIST OF FIGURES

Page

ECONOMIC EVALUATION OF URBAN ELECTRIC BUS CHARGE STATIONS: CASE OF EINDHOVEN, THE NETHERLANDS

SUMMARY

Global warming effects with heavy storms and hot days make countries take emissions seriously. Hence, European cities gradually announce zero emission projects in the public transportation sector. Transportation using battery electric buses plays important role in zero emission projects. In the Netherlands, government targets zero emission for city buses in public transportation by 2030. This obviously means replacing the fossil fueled buses with electric buses. However, the problem that arises with electric buses is the infrastructure of battery management and battery charging.

This research aims to optimize electric bus recharging processes considering minimum total annual cost. A mixed integer linear optimization model was developed to determine location, capacity of charge stations and recharging duration for the buses. In addition, the positive effect of social emissions costs because of the zero emission buses were considered. The optimization model was tested on eight city bus lines in town center of Eindhoven, the Netherlands. The results provide economic analysis for different locations of the charge stations and different recharging durations for fast charge operations.

ELEKTRİKLİ OTOBÜSLERİN ŞARJ İSTASYONLARININ EKONOMİK YÖNDEN İNCELENMESİ: EINDHOVEN, HOLLANDA ÖRNEĞİ

ÖZET

Küresel ısınma sonucu iklim değişikliğinin günden güne artmakta olan etkileri, dünya ülkelerinin emisyon konusunu ciddiye almalarına sebep olmuştur. Şehir nüfusu ve şehirleşme, dünya genelinde yıldan yıla artış göstermektedir. Bu artış şehirlerin hava kalitesini ve doğal çevresini ciddi şekilde etkilemektedir. Hava kalitesinin korunabilmesi, kentsel sürdürülebilirliğin sağlanabilmesi ancak toplu yaşam alanlarındaki sera gazı emisyonlarının azaltılması ile mümkün olabilecektir. Şehirlerin sera gazı emisyonlarının önemli bir kısmı ulaşım kaynaklıdır. Bu nedenle, şehir plancıları, özellikle son yıllarda toplu taşıma kullanmanın emisyonların azaltılması konusundaki önemine vurgu yapmaktadırlar. Emisyonların azaltılmasında toplu taşımanın ön plana çıkarılması ve geliştirilmesi konuları önem taşımaktadır. 195 ülke tarafından imzalanmış ve 2016 yılı sonlarında yürürlüğe girmiş olan Birleşmiş Milletler Paris İklim Anlaşması çerçevesinde, küresel ısınmanın önlenebilmesi konusunda özellikle sera gazı emisyonları üzerinde durulmaktadır. Bu konu ile ilişkili olarak, Paris Anlaşması da ulaşımın çeşitlendirilerek emisyonların azaltıldığı ulaşım tiplerinin yaygınlaştırılması üzerine yoğunlaşmaktadır. Avrupa Birliği, çevreci ulaşım konusunda yapılacak yatırımlarda gerekli finansal desteklerin şehirlere sağlanacağını belirtmiştir.

Son yıllarda sıfır emisyonlu toplu ulaşım sistemleri şehirlerin ve şirketlerin gündeminde önemli bir konuma gelmiştir. Şehir içi toplu ulaşımda sera gazı emisyonlarının büyük çoğunluğu otobüsler tarafından salınmaktadır, bu durum emisyonların azaltılması konusundaki çalışmaları şehir içi otobüsler üzerinde yoğunlaştırmıştır. Günümüzde yaygın olarak kullanılmakta olan geleneksel fosil yakıtlı otobüsler en yüksek egzoz gazı salımına sahiptirler. Sıfır emisyonlu otobüsler olarak değerlendirilen ve son yıllarda öne çıkmakta olan otobüs tipleri elektrikli otobüslerdir. Hidrojen yakıt hücreli otobüsler de faaliyetleri sırasında sıfır egzoz emisyonuna sahiptirler. Ancak hidrojenin elde edilmesi ve bunun için gerekli olan sistemlerin altyapı maliyetleri sebebi ile yaygın olarak kullanımının kolay olamayacağı görülmektedir. Bu durum hidrojen yakıt hücreli otobüslere göre maliyet ve altyapı yatırımları açısından daha uygun olan elektrikli otobüsleri ön plana çıkarmaktadır. Bilinen birçok otobüs firması mevcut durumda üretimine devam ettikleri fosil yakıtlı otobüslerin yanı sıra elektrikli otobüsler konusunda da üretim ve ar-ge çalışmalarını sürdürmektedirler. Önemli metropollerin başlatmış olduğu, fosil yakıtlı otobüslerin satın alımlarını kademeli olarak durdurma kararları da otobüs üreticilerini, elektrikli otobüsler konusunda çalışmalarını hızlandırmaya yöneltmiştir. Son yıllarda büyük ilerleme kaydedilmiş olan batarya kapasiteleri ve hızlı şarj sistemleri elektrikli otobüslerin günden güne yaygınlaşmasını sağlamaktadır.

Hollanda hükümeti sıfır emisyonlu yeşil otobüs taşımacılığı konusundaki proje çalışmasına 2012 yılında başlatmıştır. 2016 yılında resmi olarak duyurulan projede, 2025 yılından itibaren yeni fosil yakıtlı otobüs alınmayacağı, 2030 yılına kadar da

ülkedeki tüm otobüslerin sıfır emisyonlu olmasının hedeflendiği belirtilmiştir. Bu da açıkça fosil yakıtlı ulaşım araçlarının yerini elektrikli araçların alacağını ortaya koymaktadır. Elektrikli otobüslerin, fosil yakıtlı araçların yerini alarak yaygınlaşabilmesi için dikkate alınması gereken bazı önemli konular bulunmaktadır. Araçların şarj stratejileri bu konuların başında gelmektedir. Taşıma faaliyetlerinin sürdürüleceği bölgenin coğrafi özellikleri, taşınacak yolcu potansiyeli, rotaların uzunlukları ve buna benzer operasyon açısından önemli konular dikkate alınarak şarj stratejileri oluşturulmakta ve bu şarj stratejileri dahilinde araç ve şarj istasyonları seçimleri gerçekleştirilmektedir.

Bu çalışmada, karma tam sayılı doğrusal programlama ile minimum yıllık toplam maliyet dikkate alınarak elektrikli otobüslerin şarj olma süreçleri optimize edilmiştir. Model, otobüsün şarj istasyonuna ulaşmak için gerçekleştirmiş olduğu seyahat ve şarj olma maliyetleri ile şarj istasyonu yatırım ve bakım maliyetlerinin toplamını içermektedir. Model, hızlı şarj sistemleri içeren ve sadece tek bir konumda şarj edilebilen bir şehir içi elektrikli otobüs filosu için geliştirilmiştir. Çalışmada, elektrikli otobüslerin, hatlarındaki ilk duraktan son durağa kadar olan her bir seyahati "sefer" olarak tanımlanmıştır. Elektrikli otobüsler, şarj işlemlerini ancak art arda gelen iki sefer arasında, şarj için yeterli zaman varsa gerçekleştirebilmektedirler. Otobüs şarj istasyonları, otobüslerin çalışma saatleri dışında park halinde bulundukları, "depo" olarak adlandırılan, otobüs park alanında bulunmaktadır. Sadece bir adet depo vardır ve depo tüm seferlerin birleştiği nokta olan ana istasyonun yakınında konumlanmıştır. Her bir sefer ana istasyondan başlamakta veya ana istasyonda sonlanmaktadır. Şarj istasyonları depoda bulunduğu için sadece ana istasyonda son bulan seferlerden sonra şarj mümkün olabilmektedir. Örneğin bir elektrikli otobüs ilk seferini ana istasyondan havalimanına yapacaktır. Otobüs havalimanına ulaştığında ilk seferini tamamlamış olacaktır. Havalimanında şarj istasyonu bulunmadığı için şarj olamayacaktır. İkinci seferini yapmak üzere tarife kalkış zamanı geldiğinde havalimanından kalkacak ve ana istasyonda seferi sonlanacaktır. Eğer batarya şarj durumu azalmışsa ve bir sonraki seferinden, yani üçüncü seferinden önce şarj olması için yeterli zaman varsa, şarj için depoya seyahat edecek ve tarifeli seferi başlamadan önce şarjını tamamlayıp ana istasyona geri dönecektir. Böylece model ile otobüslerin şarj zamanları da gün içine yayılarak optimize edilmiştir.

Geliştirilmiş olan bu model Hollanda'nın Eindhoven şehrinin mevcut hızlı otobüs sistemi üzerinde test edilmiştir. Eindhoven yönetimi, sıfır emisyonlu yeşil otobüs taşımacılığı çalışması kapsamında belirlenmiş olan otobüs filolarının sıfır emisyona dönüştürülmesi sürecini başlatmıştır. 2016 yılı sonunda, Eindhoven Hızlı Otobüs Sistemi olarak adlandırılan ve sekiz hızlı otobüs hattından oluşan filo, sıfır emisyonlu araçlar ile yenilenmiştir. Sekiz otobüs hattında hizmet veren fosil yakıtlı otobüslerin yerini, sıfır egzoz emisyonuna sahip kırk üç adet elektrikli otobüs almıştır. Bu sekiz otobüs hattı, Eindhoven şehir merkezinde bulunan, Eindhoven Merkez İstasyonu olarak da adlandırılan tren garında kesişmektedir. Bu istasyon aynı zamanda her bir hattın terminalidir. Elektrikli otobüslerin deposu merkez istasyonun yakınında bulunmaktadır. Tüm şarj istasyonları ve şarj altyapıları depoda konumlandırılmıştır. Her bir araç gün içerisinde hızlı şarj işlemi için depoya gelmektedir. Eindhoven'da, depoda mevcut durumda kurulu olan hızlı şarj istasyonları 450 kW güç çıkışına sahip olup, on adet hızlı şarj istasyonu bulunmaktadır. Şarj işlemleri, gündüz sefer aralarında, hızlı şarj istasyonlarıyla yaklaşık beş dakikalık sürelerde gerçekleştirilmektedir. Otobüslerin tümü gece depoya park edilmekte olup, geceleri

50 kW güç çıkışına sahip standart şarj istasyonları ile sabah seferleri başlayana kadar şarj edilmektedirler. Depoda araçların tümüne yetecek kadar normal standart hızda şarj edebilen istasyon bulunmaktadır. Otobüsler ilk seferlerine tam şarjlı batarya ile başlamaktadırlar. Bu kısıtlar ve şartlar göz ününe alınarak elektrikli otobüslerin optimum şarj zamanlarının tespitini amaçlayan optimizasyon modeli CPLEX Solver ile çözülmüştür.

Çalışmada, şarj istasyonlarının konumlarının ve şarj sürelerinin değişimlerinin, şarj operasyon maliyetleri üzerindeki etkileri incelenmiştir. İlk olarak şarj istasyonu konumunun etkileri gözlenmiş olup, şarj operasyonlarını kolaylaştırmak adına, şarj istasyonları seferlere yakın bir konuma alınarak çalışma gerçekleştirilmiştir. Eindhoven'da, mevcut durumda, otobüsler seferlerini tamamladıktan sonra şarj edilebilmesi için depoya yol alırken hem zaman kaybı hem de bataryalarda ekstra enerji tüketimi gerçekleşmektedir. Depoya şarj için yapılan bu yolculuk operasyon için ekstra bir maliyet oluşturmaktadır. Zaman ve enerji kaybını azaltabilmek için depoda bulunan şarj istasyonlarının, depo yerine merkez istasyonda, her bir otobüsün merkez istasyonda sonlanan seferinin sonunda konumlandırıldığı durum incelenmiştir. Şarj istasyonları seferlerin son durağına taşındığında model ile elde edilen şarj operasyon maliyetinin ilk duruma göre yaklaşık %35 oranında azaldığı görülmüştür. Otobüslerin ihtiyaç duyduğu günlük toplam şarj sayıları da ilk duruma göre azalmıştır. Şarj operasyonları için otobüslerin ekstra mesafe katetmeleri, zaman kaybına neden olurken aynı zamanda operasyon maliyetlerini de arttırmaktadır.

Bir diğer inceleme konusu da otobüslerin şarj sürelerinin maliyetler üzerindeki etkisidir. Mevcut durumda otobüslerin şarj süreleri beş dakikadır. Şarj süreleri birer dakika arttırılarak ve azaltılarak model üzerinde denenmiştir. Model, beş dakikadan daha kısa şarj süreleri için çalıştırıldığında, daha kısa şarj süreleri bu otobüslerin çalışma koşulları için yeterli miktarda enerji sağlayamadığından sonuç bulunamamıştır. Sekiz dakikadan daha uzun şarj süreleri için de sefer tarifeleri nedeni ile yeterli zaman aralığı bulunamadığı için sonuç bulunamamıştır. Bu nedenle, Eindhoven mevcut sefer tarifesi ve koşulları için mümkün olan şarj süresi aralığı beş ila sekiz dakikadır. Beş, altı, yedi ve sekiz dakikalık şarj süreleri için model çalıştırılmış ve sonuçlar karşılaştırılmıştır. Şarj süreleri arttıkça toplam şarj sayılarının azaldığı görülmüştür. Şarj süreleri beş dakikadan sekiz dakikaya çıkarılırken, toplam şarj sayıları %40 oranında azalmıştır. Şarj sayıları ile benzer olarak şarj operasyon maliyetlerinin de azaldığı görülmüştür. Şarj operasyon maliyetleri de aynı şarj süreleri artışında yüzde %15 oranında azalmıştır. Şarj sürelerinin uzatılmasının maliyetleri olumlu yönde etkilediği gözlemlenmiştir.

Bu incelemelerin yanında, sıfır emisyona sahip otobüsler sayesinde sağlanmış olan sosyal emisyon maliyetlerinin pozitif etkileri de hesaplanmıştır. Fosil yakıtlı otobüsler tarafından doğaya bırakılan zararlı egzoz gazları olan NO_x, $PM_{2,5}$ ve CO_2, sıfır egzoz gazı emisyonlu otobüsler tarafından yayılmadığından, bu araçların çevreyi negatif yönde etkilememesi önem taşımaktadır. Sosyal emisyon maliyetleri, yetkili kurumlar tarafından hesaplanan, sera gazı emisyonlarının çevreye ve halka vermiş olduğu zarar için birim fiyat olarak belirlenen, ülkeler ve sektörlere göre farklılık gösteren negatif etki maliyetleridir. Bu çalışmada Hollanda'da ulaşım sektörü için hesaplanmış olan sosyal emisyon maliyetleri baz alınmıştır. Sıfır emisyonlu otobüslere geçilmesi ile sosyal emisyon maliyetlerinin önüne geçildiği belirtilmiş ve bu önemli maliyet birimleri gösterilmiştir.

Sonuçlar hızlı şarj işlemleri için farklı konumlarda ve farklı araç şarj sürelerinde ekonomik analizler sağlamaktadır. Egzoz emisyonlarının ortadan kalkması sebebi ile sağlanmış olan pozitif çevre etkisinin de maliyetler yönünden göz önünde bulundurulması gereken olumlu bir girdi olarak görülebileceği gösterilmiştir.

1. INTRODUCTION

Urbanization is increasing day by day in all over the world. Cities are becoming larger than every previous day. More than the half of the world has been living in cities since 2008 [1]. In the first half of the century number of people living in urban areas is going to increase according to the projections and this increase is estimated to be 3 billion people more until 2050 [2]. Additionally, in 2016 54% of total population lived in cities, in Europe this ratio was 75% [3].

Environment and public health is being affected by climate change and air quality is being decreased [4]. To sustain the quality of city life is a big challenge and also infrastructure is vital at this point [5]. Making city life better and sustainable is possible with protecting the environment.

In recent years urban planners are encouraging the use of public transportation to reduce pollution which is a way to protect the environment. Choosing public transportation improvement is a right option to realize this goal. To achieve the goal, several policies and agreements were released such as Paris Agreement.

The Paris Agreement has a goal of increasing the sense of responsibility for climate change globally [6]. Announced in December 2015 as the first agreement accepted by 195 countries and entered into force in November 2016. The Paris Agreement stated that increase in average global temperature should be fixed 2°C above pre-industrial level [7]. Within Paris COP21, it is declared that greenhouse gas (GHG) emission will be reduced by 70% in 40 years until 2050 [4].

Also, countries are encouraged to force with climate change effects [6]. The Paris Agreement establishes connection between today's climate policies and climate-neutrality at the end of the century. With participation of cities, other subnational authorities, civil society, the private sector and others, Paris Agreement is being worked against climate change [7].

Changing transport systems to zero emission base should be the main task for cities and corporations [8]. Some major cities have begun to take important actions for zero emissions in the urban areas. Public transport operator of Paris activated first electric bus line in Paris in 2016 [9]. Mayor of London Sadiq Khan declared in 2016 that 11 major cities like New York, Los Angeles, Copenhagen, Hamburg and Amsterdam decided to terminate phase by phase the procurement of pure diesel buses by the end of 2020. The cities are cooperating to make manufacturers produce more zero emission buses and make clean bus technology cheaper. It has been decided to supply 1.000 units of electric and hydrogen buses within the next 5 years. In transport system, buses constitute 2% of CO_2 emission but in cities they are effective in CO_2 and pollutant emissions up to 20% and also noise pollution [10].

Transport electrification is strongly related with decarbonisation and it is dominating actor in International Energy Agency (IEA) scenarios to decarbonise the energy system [9]. For public transportation, full electric and electric hybrid buses are rational alternatives for green life [11]. Based on the zero emission transportation, the aim of the study is to optimize electric bus recharging processes considering minimum total annual cost for an urban public transportation network.

In this study, previous researches have been reviewed about electric bus recharging processes. Especially, the rapid development of fast charging and battery technologies in recent years is a reason for becoming widespread of the electric buses. Thus, there are not many current researches on this subject. Due to this gap electric bus recharging scheduling is determined to analyse. At this point, Eindhoven has been selected for the new and large electric bus fleet that it has. Eindhoven urban bus network has 8 lines that are fully operated with electric buses. 43 electric buses are serviced on these lines. All the data about Eindhoven bus network and fast bus charging systems are collected and charging schedule model is created.

This thesis is organized as follows; Section 2 describes the types of buses. Section 3 describes the battery electric bus charging. Section 4 introduces the mathematical model which is a “Mixed Integer Linear Programming” formulation and definitions of parameters and variables. Section 5 displays the case study and model run on CPLEX Studio IDE 12.7.1. Section 6 gives the results of the solver. Finally, Section 7 summaries the study and reviews about results with a conclusion.

2. TYPES OF BUSES

According to Policy Note of City Vitality and Sustainability (CIVITAS), co-financed by the European Union, there are 5 types of buses: Battery electric bus, fossil fueled bus, hybrid bus, biofueled bus, hydrogen fuel cell bus [12]. Commonly used bus types are fossil fueled and electric buses.

2.1 Battery Electric Bus

Electric bus has an electric motor instead of a diesel engine to drive and the rechargeable battery supplies the energy to the electric motor. The electricity provided by the grid system is used to recharge the battery with charge stations.

Buses play a crucial role in ensuring sustainable transport into cities and makes connections to a wide range of population of rural areas. On the other hand, diesel buses are obstacle for a sustainable transportation due to CO_2 emissions. Buying low emission buses is a clear way as an alternative to diesel buses, besides, low emission buses have lower life-cycle cost which is a benefit for bus operators. Under normal conditions electric buses have zero tailpipe emission but if it was considered that the heaters were working with diesel fuel, the emission would occur. Diesel is a source of emission and pollution. However, electric heating is also a source of extra energy consumption for the battery [13].

Trolley buses which are wired from the top can be seen as the electric buses in the past. New technologies allow people to create rechargeable electric buses without wires. The battery electric buses have some critical aspects that make the bus operators think. One of the important aspects is ability to operate all day without charging and the other one is possibility to be recharged on route. In today’s conditions, the suitable buses are available in both cases. A battery that allows bus to operate all day have a significant weight. It is hard to carry this large battery because all other equipments related to wheel should be strengthened and all of these mean increase in vehicle weight. Increase in the vehicle weight causes more energy consumption. Large battery also causes decrease in vehicle free volume for the passengers. Therefore, large battery means higher energy consumption and less passengers. It is the reason for less preferred by bus manufacturers and bus operators. More preferred option in electric bus operations is the possibility to be recharged on route. This is possible with fast charging while the passenger is getting on/off the bus. Studies show that fast charging extends the battery life instead of medium or overnight charging and does not require extra infrastructure cost. Fast charging or opportunity charging is charging with an overhead contact named as pantograph [14]. This system makes the bus weight and complexity minimum.

Battery technology works on lithium ion chemistry mainly. In recent years there has been some advancements in battery technology and it has been stated that with the reduction of battery there will be capacity increase and life extension up to 7 years or more in the future [13].

The ranges of electric buses depend on battery capacity and charging methodology. Generally, the range changes between 30-300 km and battery capacities change between 76-340 kWh. The range is also affected by topography, heating and cooling systems and driving style [13].

Battery electric buses are quiet and comfortable for passengers in terms of noise pollution. Many of the diesel bus manufacturers also manufacture battery electric buses such as VDL, Volvo, Man, Iveco, and Irizar [13]. Since their capability and zero tailpipe emission properties, it is appropriate to be used in city center. High purchasing cost is the negative aspect of the battery electric buses.

The number of battery electric bus was nearly 345.000 in 2016 all over the world, which is 2 times of 2015 number. There is a significant increase in electric buses usage in previous years. China, surprisingly takes place in the top of ranking in the electrification of buses with the amount of 343.500 in 2016. In 2016, Europe had 1.273 electric buses and US had 200 [9].

2.2 Fossil Fueled Bus

Fossil fuel includes coal, petroleum and natural gas which are non-renewable resources. The biggest concern is the depletion of the fossil fuel reserves. The other concern is amount of released GHG, especially CO_2. GHG emissions from fossil fuel burning are the highest [12].

GHG emissions happen from carbon dioxide, methane and nitrous oxide that are accepted as CO_2 equivalent for global warming after a hundred years of evaluation [13].

Buses operating with fossil fuel use diesel, CNG, LNG and LPG. LPG was famous for buses in previous years but fueling infrastructure required expensive investment and also LPG was harmful for engine durability. LNG buses' range is long but it requires expensive investment as well [15]. In this situation, diesel or CNG buses are best option between fossil fuel bus types.

The European Union have regulations and standards on emissions for all types of vehicles. The "Euro Standards" was composed beginning in 1992 with increasingly strict standards implemented every few years and the first "Euro Standards" was named "Euro I". The standards were introduced in tiers from Euro I to Euro VI. The most recent standards are Euro VI, which become effective in 2013, were published in 2009. All standards are located in Table 2.1 [16].

Table 2.1: Euro standards for heavy-duty engine emissions.

Tier	Date	CO	HC	NOx	PM	Smoke
Euro I	1992 (<85 kW)	4,5	1,1	8,0	0,612	
	1992 (>85 kW)	4,5	1,1	8,0	0,36	
Euro II	October 1996	4,0	1,1	7,0	0,25	
	October 1998	4,0	1,1	7,0	0,15	
Euro III	*Voluntary EEV (October 1999 to January 2013)*	1,5	0,25	2,0	0,02	0,15
	October 2000	2,1	0,66	5,0	0,10 0,13[a]	0,8
Euro IV	October 2005	1,5	0,46	3,5	0,02	0,5
Euro V	October 2008	1,5	0,46	2,0	0,02	0,5
	January 2013	1,5	0,13	0,4	0,01	

a: for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

EEV – enhanced environmentally-friendly vehicles

The European Union Commission especially dwelt on the two tailpipe emission gases, NO_x and PM, and defined as these gases whose emissions needed to be reduced [13]. From Euro V engine to Euro VI engine, emission of NO_x has been reduced by about 75% and emission of particulate matter, PM, has been reduced by more than 50% as shown in Table 2.1. NO_x reduction system and particle filter system have been added to Euro VI diesel engine to reduce the emissions [12].

Although Euro VI buses have similar costs, operational performance and infrastructure requirement with Euro V buses, tailpipe emission rates are very different [12].

Diesel fuel is the most common type of fossil fuels for the heavy-duty vehicles. The energy capacity of diesel fuel is very high for the engine performance and thus it is preferred especially for the heavy-duty vehicles. Diesel buses have a long driving range that is about 900 km because of the energy density. Refueling time of the buses are relatively short which is about 5-10 minutes [12].

Besides the tailpipe emissions of diesel buses, the other negative aspect is their noise emissions. The noise emission has been relatively reduced in modern diesel buses but still not completely prevented. The main advantages of diesel buses are their lower investment and maintenance costs than the other bus types and their high operational performance.

CNG is the relatively new type of fossil fuel used in buses. Engines for natural gas are well developed engines and they have been developed especially in the last decades. The energy consumption of natural gas engines higher than diesel engines therefore the efficiency of natural gas engines is somewhat lower than diesel engines' efficiency [15].

Operational performance of CNG buses is accepted approximately similar as operational performance of diesel buses in recent years [15]. CNG buses have lower CO_2 emission. Before Euro VI standards, the main difference between natural gas engines and diesel engines was the emissions. But with Euro VI standards, the reduction in emissions of diesel buses removed this advantage of CNG buses [12].

CNG buses have 350-400 km driving range and refueling time is about 5-10 minutes. The refueling times are the similar for diesel and CNG buses. The noise emission of CNG buses is less than diesel buses. However, disadvantage of CNG is necessity of specific filling infrastructure that consists of compressor and tank for pressure and fast filling. Another negative aspect of natural gas buses is purchase cost, it is higher than diesel buses [15].

2.3 Hybrid Bus

Hybrid vehicles use two types of sources to power the motor; internal combustion engine and an electric drive system like electric motor/generator and battery and/or capacitors [12].

Generally, a hybrid bus has a diesel engine but sometimes additional equipments may be used. There are a lot of types of hybrid system operating at the present time. In classical diesel buses, the kinetic energy resulting from the bus movement converts to the thermal energy at the moment of braking. If the bus gets slower, the energy gets lost. In a hybrid bus, the kinetic energy is stored for further need, it does not get lost. When the bus gathers speed, the stored energy is sent to wheel and share the diesel engines' load thus fuel saving and reduction of CO_2 is achieved because of the reduction of load on the diesel engine [13].

There are two types of hybrid buses which shows the relation between the engine and the axle. There is a mechanical propulsion between the engine and the axle, in addition to that the hybrid equipment is also supported by mechanical propulsion provided by the engine. The engine drives both of the axle and the hybrid equipment in parallel at the same time. This is called as parallel hybrid. If the parallel hybrid bus has an electrical problem, the vehicle can be driven using the diesel engine so this is an avantage of parallel hybrid buses. In series hybrid, the engine and the axle are separated. The engine provides energy for the hybrid equipment and the hybrid equipment drives the axle in series hybrid [13].

There is a possibility of being battery dominant in serial hybrids, if so, they are called "plug-in hybrid electric" or "extended range electric vehicle". Plug-in hybrid electric buses are supplied energy from electric grids to charge the battery. There can occur zero emission range due to the battery capacity. The charging infrastructure is required for the plug-in hybrid electric types.

Hybrid buses have 600-900 km driving range and the refueling time is about 5 minutes. While driving with the electric motor, the noise emission of hybrid buses is lower. However, the disadvantage of hybrid buses is purchase cost, it is about 50-60% upper than diesel bus [15].

2.4 Biofueled Bus

Biofuels are produced from biomass in the form of liquid or gaseous fuels. Biomass is produced from organic matter such as wood, oil and other matters with different methods of production processes. In order to decrease GHG emissions and pollution, biofuels are renewable alternatives to fossil fuels but it is obligatory to be produced under sustainable conditions [17]. Otherwise, environment and public health may be harmed.

100% biodiesel that is known as B100 or blend of biodiesel and standard diesel that is known as B20 or B30 can be bought by fleet operators. The numbers next to “B” represent the mixture ratio of biodiesel and diesel, for instance, in B20 biodiesel consists of 20% biodiesel and 80% diesel. Biogas consists of methane, carbon dioxide and other chemicals [13].

The quality of fuel depends on the generations of biofuels. 1st generation biofuel is a cheaper one and has less quality. 2nd generation biofuel is a high quality production and expensive. Due to a higher quality of the hydrotreated vegetable oil, HVO, than the fatty acid methyl ester, FAME, the engine’s compatibility is better for HVO [12].

1st generation biofuels are produced from harvested biomass such as wheat, palm oil. European Union does not support 1st generation biofuels even it has 10 years past because of their unhealthy effects. The biggest effect can be seen on food prices and food security because biomass is being used for fuel production not for nutrition. The other effects of 1st generation biofuels production are deforestation, loss of biodiversity and increase in CO_2 emissions [12].

European Union is supporting 2nd generation biofuels because they are produced from non-food crop waste. The disadvantage for this type is non-availability for large quantities [12].

Euro VI buses can be compared in terms of operational performance, infrastructure, costs and local emissions with diesel which run on HVO and FAME. Feedstock and production process affect the GHG emissions for biofuels. CNG bus fuels can be made from biomethane and bioCNG [12].

2.5 Hydrogen Fuel Cell Bus

Fuel cell electric buses which have hybrid technology use both hydrogen and battery. They have electric motor that is powered by battery and hydrogen stored in gaseous tanks on the roof of the bus [18]. Hydrogen is an energy carrier rather than energy source, having a large capacity to store energy [19].

Hydrogen can be produced of electrolysis of water and this method is the environmentalist method for the hydrogen production. It can also be produced in different ways such as reformation of natural gas.

Hydrogen fuel cell buses have zero tailpipe emissions, in this way they improve air quality in cities. They are much quieter than conventional fossil fueled buses [20]. Hydrogen fuel cell buses have the longer range than 300 km and it can be refueled in shorter time than 10 minutes. Hydrogen fuel cell buses are well suited to city transportation [21].

The capital cost of a conventional Euro VI diesel bus is lower than a hydrogen fuel cell bus. If the price of hydrogen increases, correspondingly operational costs increase. Hydrogen produced from steam methane reformation is cheaper than the price of produced by water electrolysis. The maintenance cost of the hydrogen buses is the similar to the hybrid buses'. But also, the maintenance cost includes other related costs such as fuel cell and hydrogen storage tanks costs [13].

3. BATTERY ELECTRIC BUS CHARGING

Determination of the charging strategy is the crucial in operation of electric bus fleet. The recharging needs vary by the type of bus, route and the city conditions. For electric bus fleets, only one recharging per day may be enough or multiple recharging may be required. These charging strategies are important and it should be taken into account at the first stage of the operation. Less energy consumption in comparison to buses with combustion engines, less noise, less GHG emissions and lower lifecycle costs can be provided with the use of correct charging technology [5].

The required energy capacity for buses is another important factor. Battery electric buses have higher battery capacity than cars. Therefore, the required energy capacity for recharging of the buses needs high power supply from the grid infrastructure. In particular for fast charging with opportunity chargers at 300-600 kW required very high power supply and that means a higher-capacity energy infrastructure. Thus, required infrastructure investments for the energy supply should be considered.

Electric buses have rechargeable batteries and can be recharged in two ways: on depot or on route. The capacity of the battery and the route are the main factors for the determining of the charging strategy. The charging strategy is important to determine the recharging way. In depot charging, the recharging operation is carried out at the depot. Depot charging requires a large battery due to being recharged only at night or downtime. Buses are recharged with a plug-in charger between 2-8 hours. Depot charging needs less-complex fleet deployment and charging infrastructure, on the other hand, requires garage updates [22].

On route charge or opportunity charge (Oppcharge) is the second type of electric bus charging system. It is a fast charging technology within 5-10 minutes which charges at the bus stops. Opportunity charge requires a small battery and an overhead pantograph with a road embedded charger [22].

Electric buses charging system has two main subdivision for the infrastructure technology: plug-in charging and opportunity charging. Opportunity charging also is divided in two parts: inductive charging and conductive charging. The definitions of these technologies are explained as following.

3.1 Plug-in Charging

Plug-in charging is a type of charging with a wired connection, as shown in Figure 3.1 [5]. It is a low price, basic and efficient way for buses to be charged overnight or daytime. There are some categories for plug-in charging units such as slow (15 kW), fast (22-30 kW) and rapid (50 kW). It is recommended to balance overnight charging every several days according to maintain the battery stability and durability [13]. EVolt, Siemens, Heliox and ABB are the vendors of plug-in chargers.

3.2 Opportunity Charging

It is a product of proved technology and also called fast charge. It can be used due to requirements such as driving schedules of buses. An external connection that charges the bus provides a small battery thus, the passenger capacity increases and maintenance costs decrease. Also, the standards are internationalized so safe driving and traveling is possible. Fast charge is flexible for different bus types and grids [23].

3.2.1 Inductive charging

Magnetic coils, which are the components of charging source and the vehicle, are the main points of inductive charging. Two coils' interaction occurs a magnetic field and energy is accessed in this field without any necessity for a physical interaction between electric bus and the charger. Thus, at the moment of connection, the corrosion level is decreased [24].

It is sometimes possible to recharge vehicle on the route however, many of the charging systems are set up in bus stations when the route ends. With "top-up" batteries the vehicle is able to be opportunity charged for ten or lower minutes if the available equipment has power up to 200 kW [13].

3.2.2 Conductive charging

In the terms of conductive charging, transfer of energy is actualized from the charge station with a conductor, as shown in Figure 3.2 [5].

Pantograph for conductive charging can be set either at middle or beginning/ending stops. With an automated process electric bus takes the energy by pantograph which is an efficient transfer. This transfer has a high power capacity like 150-600 kW within several minutes. Location of charging units is essential in urban areas. To make the use flexible, chargers can be built indoors or outdoors [5].

ABB, Heliox and Siemens are the providers for charge infrastructure. European bus manufacturers Irizar, Solaris, VDL, Iveco and Volvo made an agreement about dual operational process with the providers [25]. Thus, a standardization between charging infrastructure and electric buses granted.

Figure 3.1: Plug-in charging.

Figure 3.2: Opportunity conductive charging with pantograph.

4. METHOD AND PROPOSED MODEL

4.1 Mathematical Model

Mixed integer linear programming has been selected to use in this thesis. Linear programming is defined as maximizing or minimizing the objective function under the constraints. In mixed integer programming, different from linear programming, at least one of the variable must be an integer value.

4.2 Proposed Model

In this section, the problem is to determine the electric buses recharging scheduling for a transportation network. This network consists of 8 lines and one transit center. The transit center is also the main station of each line. Every line has 2 termini and the transit center-main station is one of these termini. There is only one depot where the buses park out of working hours. The depot is located nearly 1 km far from the transit center. Each electric bus leaves from the depot to carry out the scheduled trip in the morning and returns to the depot when the daily trips are completed at night. Every trip has a start and end time. The trips either start from the transit center or termini of existing line. There is a time mostly between two following trips carried out by the same electric bus. The depot is equipped with charging stations that provides slow and fast charging for electric buses. The electric buses can be recharged with slow chargers during the night when parked at depot. During the day, the electric buses only can be recharged with fast chargers at the time between the trips at depot. Meanwhile, fast charging is defined as opportunity charging. In this thesis, recharging scheduling is based on opportunity charging.

To prepare this study, some assumptions are determined. First of all, all the lines have the same conditions such as topography. Secondly, consumed charge is related to driving distance. Thirdly, all chargers are opportunity chargers and they are the same. Finally, the duration of recharging is constant.

First, to create a model; sets, parameters and variables using in the model are defined. B is the set of trips, H is the set of opportunity charging stations, T is the set of time. i and j indices describe following two trips, $i, j \in$ B. $h_{1,2,..}$ are the opportunity charge stations, $h_{1,2,..} \in$ H. Time covers from the start time of the first trip to the end time of the last trip in a day. s_i defines the start time of trip i, f_i defines the end time of trip i. d is the charging duration for each opportunity charging. The electric buses can be recharged between two following trips, in other words, the bus can be recharged between f_i - end time of trip i and s_j – start time of trip j, if there is a possible time to recharge. This time interval between two trips must be enough for recharging duration, d. For instance, the end time of trip i is 10 and the start time of next trip j is 20, the opportunity recharging activity duration is 5 units. In this situation, if charge station is located near the termini, this means there is no need more time for arriving the charge station from termini, the recharging activity can be started at 11. On the other hand, the recharging activity can start at 12, 13, 14, 15, but cannot start at 16 because of next trips' start time. t defines start time of recharging activity, $t + d \leq s_j$. The possible recharging start time between trip i and j for this bus are 11, 12, 13, 14 and 15. The set of O contains these possible recharging times for all trips.

All sets, parameters and variables were defined as:

All sets:

B	set of trips
H	set of opportunity charge stations
T	set of time
O	set of possible recharging times
P	set of depot trip

All parameters:

s_i	start time of trip i
f_i	end time of trip i
$h_{1,2,3..}$	opportunity charge stations
d	charging duration
R_{max}	maximum energy of battery for a fully-charged
R	usable energy of battery

α charging rate

l_i length of trip i

l_{ih} distance between the start/end point of trip i and charging station h

e_{min} minimum energy level that the battery should have

c_t cost of unit bus travel

c_e charging costs in unit time; refers to the electricity costs

c_f fixed costs per charge station; includes purchase and installation costs

c_m maintenance cost per charge station

A number of operating days per year

λ annualized factor

All variables:

$X_{it}^{h} = 1,0$; If the bus in trip i uses the charge station h at time t, 1; otherwise, 0.

$Y_h = 1,0$; If the charging station h is used, 1; otherwise, 0.

E_i ; the remaining energy in the battery before trip i.

A mixed integer linear programming model is created based on the article written by Wang et al. [26]:

$$\text{Cost} = \sum_{i \in B} \sum_{t \in O} c_t l_{ih} + c_e d \; A X_{it}^{h} + \sum_{h \in H} (\lambda c_f + c_m) Y_h \qquad (4.1)$$

The objective function (4.1) is to minimize annual total operating costs of electric bus recharging system. It consists of two parts. The first part of function contains from the end point of trip to the charge station travel costs and recharging costs, the second part of function contains charger costs.

Subject to:

$$\sum_{h \in H} X_{it}^{h} \leq 1 \forall i \in B \qquad (4.2)$$

Constraint (4.2) defines the electric bus can be recharged at only one charge station at the same time.

$$E_i + \sum_{h \in H} (\alpha d - l_{ih}) X_{it}^{h} \leq R_{max} \forall i \in B \qquad (4.3)$$

Constraint (4.3) defines sum of the remaining energy in the battery and the recharged energy cannot exceed the maximum energy limit of battery at bus.

$$E_j = E_i + \sum_{h \in H} (\alpha d - l_{ih}) X_{it}^h - l_j \ \forall i, j \in B \tag{4.4}$$

Constraint (4.4) defines the energy changes of two following trips.

$$E_i \geq e_{min}, \forall i \in B \tag{4.5}$$

Constraint (4.5) defines the minimum energy of battery.

$$\sum_{t \in O}^{t+d-1} X_{it}^h \leq 1 \ \forall t \in O \tag{4.6}$$

Constraint (4.6) defines one charger can recharge only one electric bus at charging period.

$$E_i = R, \forall i \in P \tag{4.7}$$

Constraint (4.7) defines initial energy for an electric bus for the first trip in a day.

5. CASE STUDY

5.1 Eindhoven

There are three stages in government of the Netherlands which are the state, the province and the municipalities. Eindhoven is the 5th largest city in The Netherlands and first in southern part of the country. Eindhoven is a municipality of North Brabant province. It has an area of 1.370 km^2, which is 3.3% of the country, 21 municipalities, 729.000 inhabitants and 54.000 businesses. There are a lot of parks and natural beauties so the city is called as “green” [27].

In the Netherlands, the Green Deal Zero Emission Bus Transport was started in 2012 and the National Government, public transport authorities and bus transport operators accepted in 2016 declares that this deal is about realizing the zero emission bus transportation affordably by defining the “zero emission” requirement for all buses in public transportation. There is a goal of finishing the diesel bus procurement by 2025 and converting the Netherlands bus fleet, nearly 5.300 buses, into zero emission completely by 2030. This is being proved by 40% of newly procured buses in 2016 are fully electric in Eindhoven [10].

The developed model was applied to the existing bus rapid transit network in Eindhoven, the Netherlands. The bus rapid transit network of Eindhoven consists of 8 bus lines; 400, 401, 402, 403, 404, 405, 406 and 407, as shown in Table 5.1. Most bus stops of the line 405 and 406 are the same, only a few stops are different and so line 405 and 406 are operated by the same buses.

There is a transit center that connects these 8 lines in the center of Eindhoven. The transit center is also the main station of Eindhoven. Each trip on these lines starts or ends at the Eindhoven Station. The trip describes the journey from the start terminus to last terminus.

Table 5.1: The lines fully operated by electric buses in Eindhoven.

Line	First Trip Start Time	Last Trip End Time	Number of Daily Trips	Average Trip Duration (min.)
400	06:39	00:07	158	21
401	05:34	00:31	185	23
402	05:49	00:40	128	32
403	06:23	00:19	119	26
404	07:45	18:35	90	22
405 - 406	05:59	00:31	249	23
407	06:37	20:29	94	21

43 battery electric buses took the place of fossil fueled buses and have started operation by the end of 2016 on these 8 lines as shown in Figure 5.1 [28]. The depot, where is the parking area of buses outside of service hours, is located 1 km far from Eindhoven Station. Electric bus charging units are also located only at the depot. All the buses are parked and slow recharged all night and, besides, the buses come to the depot for opportunity recharging between two following trips in day.

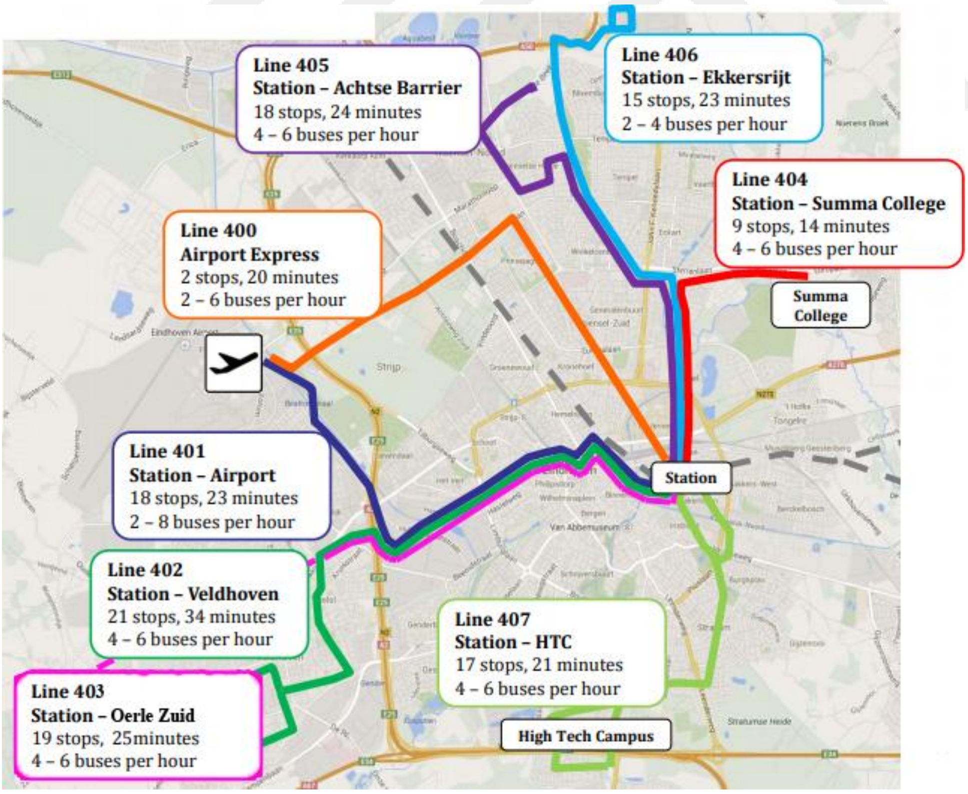

Figure 5.1: Eindhoven electric bus lines.

1023 scheduled trips are operated by 42 electric buses on weekdays [29]. All of the buses start their first trip with fully charged battery and when the battery needs to be recharged, the bus can be recharged at depot in between the two trips. The opportunity chargers have 450 kW power outlet, therefore ultrafast recharging is possible with pantographs of the charge stations. Opportunity charging is not possible at the end of each trip because of the depot location. It is possible only trips that end at Eindhoven Station [30]. For instance, the line between Eindhoven Station and Airport and trip 1 starts from Eindhoven Station to Airport. When the bus arrives to Airport, it cannot be recharged. Trip 2, is the following trip for that bus, starts from Airport to Eindhoven Station. When the bus arrives to Eindhoven Station, if there is enough time for recharging before the following trip, the bus can be recharged at the depot. The summary table of buses, lines and trips shown in Table 5.2.

Table 5.2: Summary of buses, lines and trips.

Bus	**Line**	**Trip - i**	**Start Time of Trip - s_i**	**End Time of Trip - f_i**	**Bus**	**Line**	**Trip - i**	**Start Time of Trip - s_i**	**End Time of Trip - f_i**
1	400	1	06:39	07:00	25	404	591	07:45	08:06
1	400	2	07:13	07:34	25	404	592	08:07	08:29
1	400	3	07:52	08:13	25	404	593	08:35	08:56
1	400	4	08:23	08:44	25	404	594	08:57	09:19
1	400	5	09:02	09:23	25	404	595	09:25	09:46
:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:
8	401	159	05:34	05:56	30	405	681	05:59	06:20
8	401	160	06:00	06:24	30	406	682	06:36	07:00
8	401	161	06:56	07:18	30	406	683	07:01	07:24
8	401	162	07:26	07:50	30	406	684	07:36	08:00
8	401	163	08:06	08:30	30	406	685	08:01	08:24
:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:
15	402	344	05:49	05:53	38	405	925	20:41	21:02
15	402	345	05:53	06:24	38	405	926	21:26	21:51
15	402	346	06:43	07:11	38	405	927	22:05	22:26
15	402	347	07:11	07:42	38	405	928	22:54	23:16
15	402	348	07:43	08:13	38	405	929	23:20	23:41
:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:
24	403	586	18:10	18:36	42	407	1019	17:03	17:29
24	403	587	19:24	19:51	42	407	1020	17:37	17:53
24	403	588	19:58	20:21	42	407	1021	17:53	18:17
24	403	589	21:54	22:19	42	407	1022	18:37	18:53

24	403	590	22:28	22:51	42	407	1023	18:53	19:17

For the simplification of the model, a minute range has been accepted for the time. The earliest trip starts at 05:34 in the morning and this time was set at “0”, the last trip ends at 00:40 at night and this time was set at “1146”. The bus service duration is 1146 minutes. All times for all operations are shown in minutes in this range. The distance from Eindhoven Station to the depot is 1 km. The connection and disconnection time of bus pantograph to charger for recharging operations has been assumed to be totally 1-1,5 minutes. Considering all, the time from Eindhoven Station to charge station to Eindhoven station, without charging duration, has been assumed to be 4 minutes.

The battery pack capacity of the buses is 180 kWh**.** The battery should never have energy less than 10% of full capacity and should not be recharged more than 95% with fast charge [31]. For that reason, the active capacity of the battery in use is about 85% of its full capacity, 153 kWh.

Charging duration for each bus, d, has been assumed to be 5 minutes. The charging rate factor, α, has been calculated to be 7,5 kWh per minute. It refers the charging capacity of the charger per minute (450 kWh/60 minutes). Minimum energy, e_{min}, has been recognized as 15% of battery full capacity, 27 kWh, for arriving to the depot in exceptions. The electricity cost per minute, c_e, is € 0,13 in the Netherlands [32,33]**.** The travel cost, c_t, has been assumed to be € 0,20 per km based on maintenance costs for electric bus. The fast charge station fixed cost per station, c_f, has been assumed to be € 250.000 and the fast charge station yearly maintenance cost per station, c_m, has been estimated to be 3% of the investment cost, € 7.500 [34]. The useful life of the buses has been estimated to be 15 years and the interest rate is 10%. The capital recovery factor (A/P, interest, useful life of the bus-n) was used for the calculation of the annualized cost factor, λ, (A/P, 10%, 15) = 0,1315 [35].

5.2 Model Run

The optimization model was run with parameters as defined in the previous sections. The model was solved using solver CPLEX Studio IDE 12.7.1.

6. RESULTS

6.1 Base Line

The optimal minimized annual cost was € 450.858. There were 523.598 constraints and 519.971 variables in the model. The annualized cost of needed charge stations, that contains charge stations' investment and maintenance costs, is € 323.000 and the annualized cost of recharging operations is € 127.858. Totally 380 charging operations were performed by 42 buses in the solution in a day. All trips, in which recharging operations were performed, and buses were listed, as shown in Table 6.1. Maximum 8 charge stations were used by the buses at the same time. Therefore, the cost of charge stations consists of 8 charge stations costs.

Table 6.1: Bus numbers performing in a day.

Bus	Trips (i) in which recharging operations were performed
1	2, 5, 6, 7, 8, 9, 10, 11
2	14, 16, 17, 18, 20, 21, 22
3	25, 27, 28, 29, 31, 32, 33
4	35, 38, 39, 40, 42, 43, 44
5	46, 49, 50, 52, 53, 54, 56, 57, 58
6	62, 63, 64, 66, 67, 68, 70, 71, 72
7	74, 77, 78, 79, 80, 81, 82
8	86, 87, 88, 90, 91, 92, 93, 94, 95, 96
9	99, 100, 102, 103, 105, 106, 108, 109, 110
10	112, 113, 116, 118, 119, 120, 121, 122, 123, 124
11	130, 131, 132, 133, 134, 135, 136, 137, 138
12	141, 142, 144, 146, 147, 148, 149, 150, 151
13	153, 154, 158, 159, 160, 161, 162, 163, 164, 165
14	169, 170, 172, 173, 174, 175, 176, 177, 178
15	179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191
16	192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204
17	205, 206, 207, 208, 209, 210, 211, 212, 213, 214
18	216, 217, 218, 219, 220, 221, 222, 223, 224
19	226, 227, 228, 229, 230, 231, 232, 233, 234, 235, 236
20	237, 238, 240, 241, 242, 243, 244, 245, 246, 247, 248
21	249, 250, 252, 253, 254, 255, 256, 257, 258, 259, 260
22	261, 262, 264, 265, 266, 267, 268, 269, 270, 271, 272
23	274, 276, 277, 278, 279, 280, 281, 282, 283, 284

Table 6.1 (continued): Bus numbers performing a day.

Bus	Trips (i) in which recharging operations were performed
24	286, 287, 288, 289, 290, 291, 292, 293, 294, 295
25	297, 298, 299, 300, 301, 302
26	305, 306, 307, 308, 309
27	311, 312, 314, 315, 316, 317
28	320, 321, 322, 323, 324, 325
29	328, 329, 330, 331, 332, 333
30	336, 337, 338, 340, 341, 342, 343, 344, 345, 346
31	349, 351, 352, 353, 354, 355, 356, 357, 358, 359, 360
32	362, 366, 367, 368, 369, 370, 371, 372, 373, 374, 375
33	378, 380, 381, 382, 383, 384, 385, 386, 387
34	390, 391, 392, 394, 395, 397, 398, 399, 400, 401, 402, 403
35	406, 409, 410, 411, 412, 413, 414, 415, 416, 417
36	420, 423, 424, 425, 426, 427, 428, 429, 430, 431
37	434, 437, 438, 439, 440, 441, 442, 443, 444, 445
38	448, 449, 450, 452, 453, 454, 455, 456, 457, 458
39	460, 462, 463, 464, 465, 466, 467, 468
40	470, 471, 472, 473, 474, 475, 476, 477
41	479, 480, 481, 482, 483, 484
42	485, 486, 487, 488, 489, 490, 491

Daily total driving distance and total number of recharging operations of each bus can be seen in Figure 6.1.

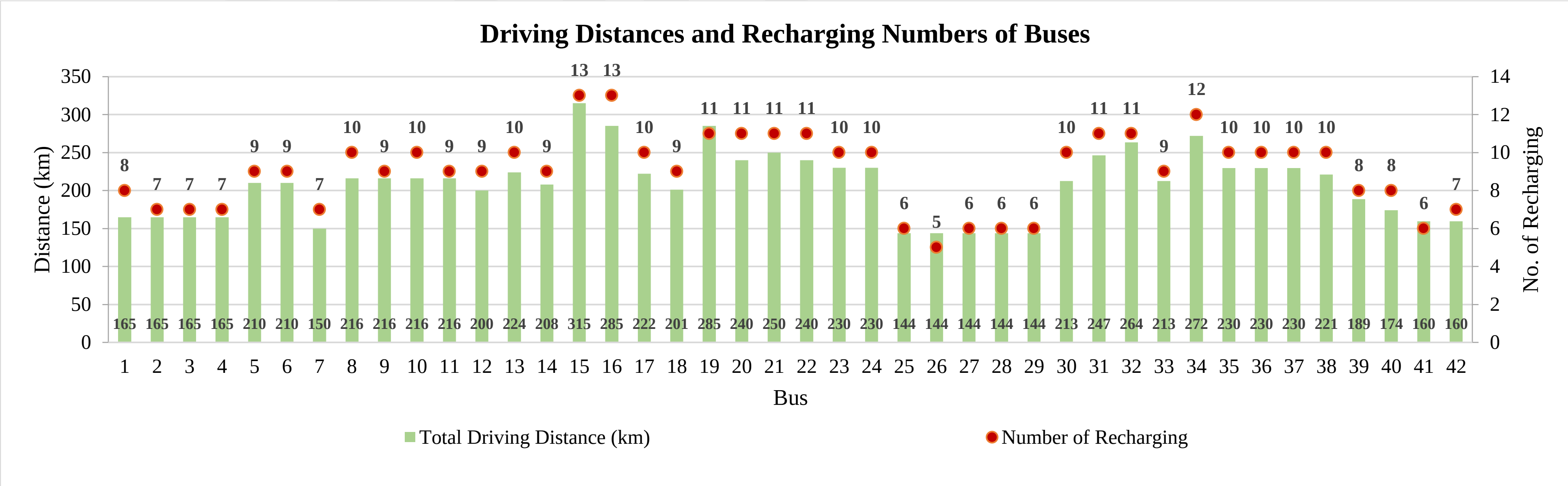

Figure 6.1: Driving distances and recharging numbers of buses.

6.2 Charge Station Location Analysis

This analysis for the situations that the fast charge stations located at the last stop of the trip. In the current situation, the charge stations located at the depot and each electric bus traveled to depot for fast charging after ending of the trip in a day. The travel duration for recharging is 4 minutes, 2 minutes to reach to charge station and 2 minutes to reach to the start point of the next trip after recharging. This duration can be defined as dead time. This distance that traveled by the buses is 2 km. If the charge stations locate at the end of the trip, time is saved that 4 minutes corresponding to the recharge at the depot. The buses could be recharged at the last stop of the trip.

When the solver run for this situation, the optimal minimized annual cost was € 407.708. The annualized cost of needed charge stations is the same as situation in depot charging, € 323.000 but the annualized cost of recharging operations is € 84.708. The annual fast charge operations cost was about 35% less than the situation in depot charging, as shown in Figure 6.2.

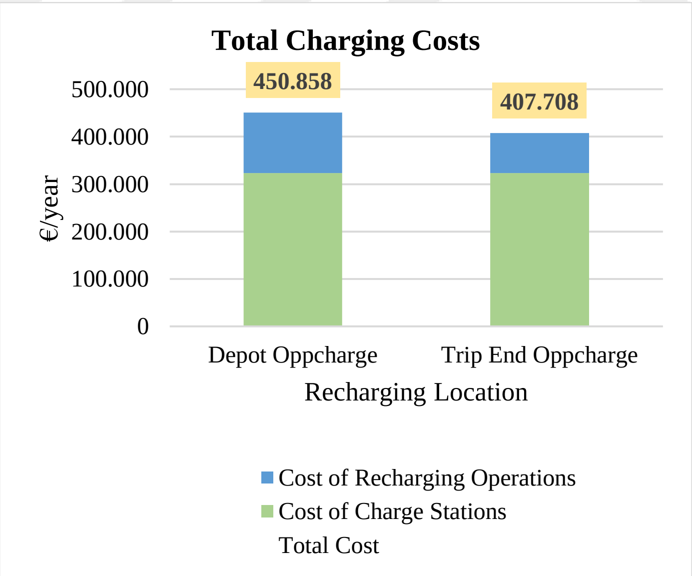

Figure 6.2: Total charging costs.

Totally 362 charging operations were performed by 42 buses in the solution in a day. 8 charge stations were used by the buses at the same time.

It has been seen that the charging operational cost save is about € 43.000 for this case.

6.3 Charging Duration Analysis

Charging duration is crucial in the operation of battery electric bus fleet. Charging duration strategy affects all phases of the operation such as scheduled of trips, selection of bus and all infrastructure works. The model was run with the different charging durations. There was no solution for the charging duration less than 5 minutes and greater than 8 minutes and it was run with charge duration range from 5 to 8 minutes. The solution was not found for the values less than 5 minutes because short durations of charging do not provide enough energy for the battery. On the other hand, the greater values than 8 minutes are too long for recharging in between two following trips. It does not fit the time schedule for trips.

The recharging start times related to recharging duration for each line were shown in Figure A.1, A.2, A.3, A.4, A.5, A.6, A.7. In these figures, it can be seen that from lower charging durations to greater charging durations number of recharging activities decreased. In addition to this, the first recharging activity of each bus in a day was deferred to the next trips with the increase of charging duration and it can also be seen in these figures. The increase in charging durations has reduced the frequency of recharging.

In Figure 6.10, the total number of recharging activities for each charging duration, 5, 6, 7 and 8 minutes, were shown. The total recharging activities decreased by about 40% while the charging durations increased from 5 to 8 minutes.

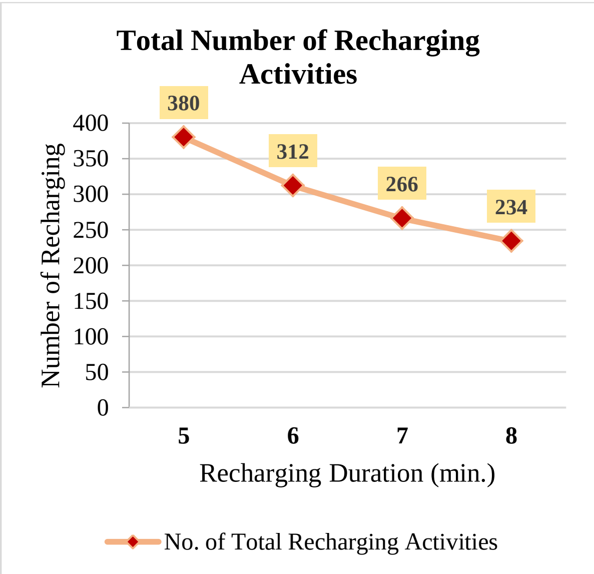

Figure 6.3: Total number of recharging activities.

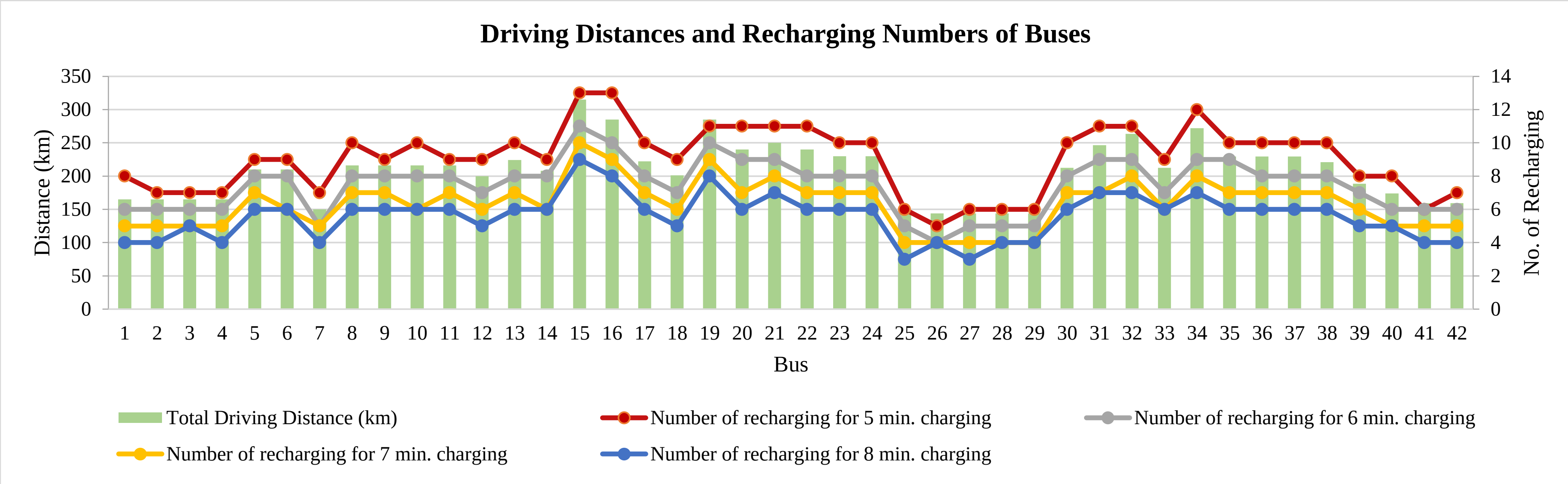

Figure 6.4: Driving distances and recharging numbers of buses for each recharging duration.

The total driving distances and number of recharging activities of each bus for each charging duration can be seen in Figure 6.11. From figure, with the increase in charging duration, the decrease in the number of recharging activities of each bus in a day can be seen. However, it can also be seen that when the total driving distance increased, similarly the number of recharging activities increased because of the energy consumption.

The result costs of the model for each charging duration were shown in Figure 6.12. In Figure 6.12, it can be seen that the recharging operation costs, the charge station investment and maintenance costs and the total costs. In all charging durations, maximum 8 charge stations were used by the buses at the same time. Therefore, the costs of the charge stations for each charging duration consist of 8 charge stations' costs. The optimal minimized annual costs were € 450.858 for 5 minutes charging duration, € 441.714 for 6 minutes charging duration, € 435.946 for 7 minutes charging duration and € 432.728 for 8 minutes charging duration. The annualized cost of needed charge stations is € 323.000 for each charging durations and the annualized costs of recharging operations respectively for 5, 6, 7 and 8 minutes charging durations were € 127.858, € 118.714, € 112.946, € 109.728. The cost of recharging operations decreased while the charging duration increased. The increase in the charging duration affected the operation cost positively, as shown in Figure 6.12.

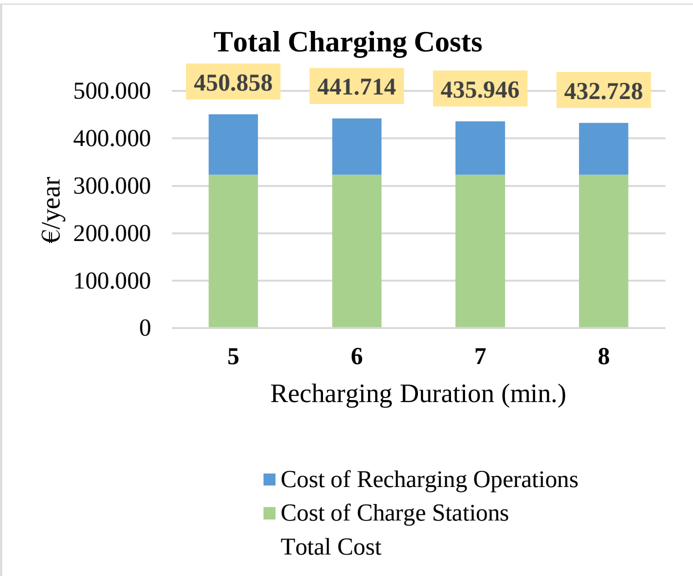

Figure 6.5: Total charging costs for each charging duration.

6.4 Effect of Social Cost of GHG Emissions

Social costs are estimates of the net damage to society caused by a 1 metric ton increase in the different types of GHG emissions [36].

Governments should consider the economic effects of climate change when they set their strategies. If the emission of million tons CO_2 is avoided with new policies, the financial benefit is not limited to only this, a damage of about 40 $ per ton is prevented and a net social benefit is accepted as that value [37].

The main tailpipe emissions that has been emitted by fossil fueled buses can be regarded as NO_x, $PM_{2,5}$ and CO_2. The tailpipe emissions rates for the diesel buses have Euro VI emissions standards are described as; NO_x emission rate, 0,5 g per km; $PM_{2,5}$ emission rate, 0,01 g per km; CO_2 emission rate, 1317 g per km [7,38].

The social costs of the emissions are based on the calculated costs for the transportation sector in the Netherlands and these costs have been used in the model. In the report of "Update of the Handbook on External Costs of Transport", the damage costs of $PM_{2,5}$ and NO_x emissions from transportation in the Netherlands for 2010 were calculated [39]. From the report of "Revealing the costs of air pollution from industrial facilities in Europe", the estimation of increase in the damage costs in between 2010 and 2020 was considered [40]. After all, the current values of the damage costs were calculated based on these two reports.

The social cost of NO_x, has been assumed to be 13.840 € per tonne for 2018. The social cost of $PM_{2,5}$, has been assumed to be 219.640 € per tonne for 2018 [39,40]. The social cost of CO_2, has been assumed to be 33 € per tonne [41].

The electric buses have zero tailpipe emission and the positive effect of zero emission can be included in the model. If all trips are operated by the diesel buses, the social costs effects per trip should be taken in consideration. Therefore, the positive effect of the zero emission on the environment has been calculated and added to the cost.

The total driving distance of 42 electric buses is 9.500 km per day in Eindhoven that includes dead travel for recharging operations. The total annualized costs of the tailpipe emissions were calculated as € 23.666 for NO_x, € 7.512 for $PM_{2,5}$ and € 148.637 for CO_2, as shown in Figure 6.13. By the replacement of 42 diesel buses with 42 battery electric buses, totally € 179.814 damage cost was prevented. This positive cost can be reduced from the total annualized cost of the model.

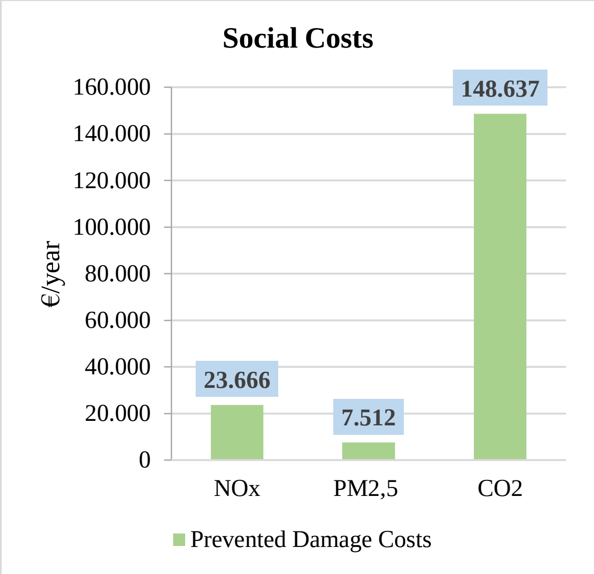

Figure 6.6: Social costs.

7. CONCLUSIONS AND RECOMMENDATIONS

In recent years, the use of alternative fuel buses to diesel buses for public transportation has been seen as a reduction of GHG pollution which is a way to protect the environment. The rapid development of fast charging and battery technologies has been effective in the widespread use of battery electric buses. The battery electric buses recharging operations have a great importance with operational processes and costs. Therefore, electric buses fast recharging scheduling is determined to analyse. Annual operational costs for fast recharging operations have been minimized.

In this study, electric bus fast charging scheduling optimization is solved with mixed integer linear programming for an urban public transit network. It is established on a real network of Eindhoven, The Netherlands. The research results indicate that the electric charge stations' locations and the recharging durations affect the cost of charging operations. The effect of charge stations location on costs calculated in this study was not small to be ignored, although the fleet has only 43 battery electric buses. The effect arising from charge stations location on costs will be higher for increasing number of electric buses and growing fleet. The second important factor that affected the costs was the recharging duration. Possible charging durations for the existing scheduling were solved in the model. It was observed that the recharging operation costs were positively affected while the recharging duration was increasing. In the study, finally, the social emissions cost effects were taken into consideration in the cost analysis. The positive cost of the zero emission buses were calculated. This zero emission positive effect is important and it should be considered by the bus operators in cities for the zero emission investments.

For the future research, one of the important topic of the electric bus operations is the type of buses which means type of battery at the same time. The effect of different types of buses and batteries on costs and charge strategies are recommended to be studied.

Another charge station location problem is that if the charge stations locate at all terminals, end stations of the lines, how the effect would be of this situation on charge strategies and the costs.

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APPENDICES

APPENDIX A: The recharging start times related to recharging duration for each line

APPENDIX B: Bus charge types

APPENDIX C: Charge stations at depot in Eindhoven

APPENDIX A

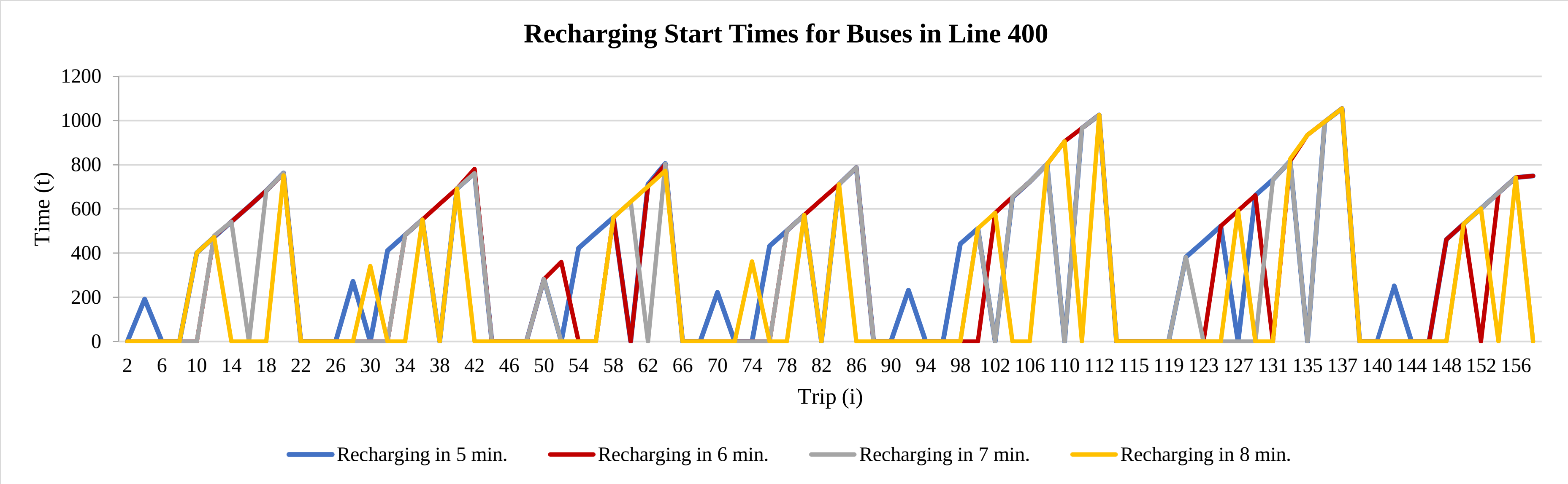

Figure A.1: Recharging start times for buses in line 400.

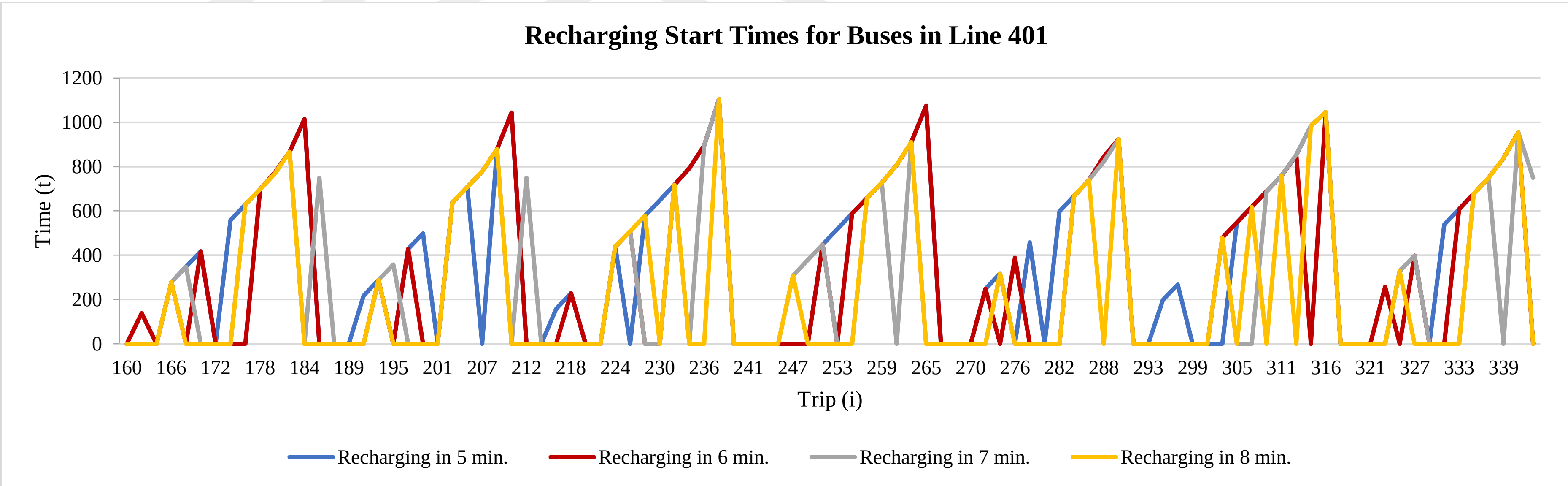

Figure A.2: Recharging start times for buses in line 401.

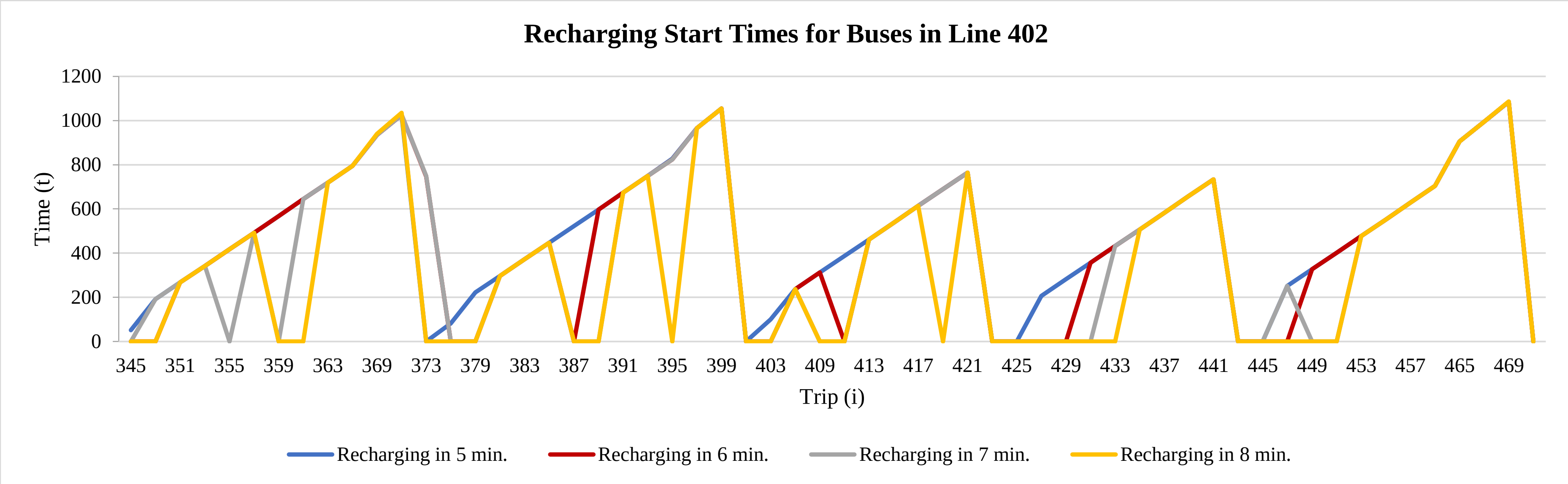

Figure A.3: Recharging start times for buses in line 402.

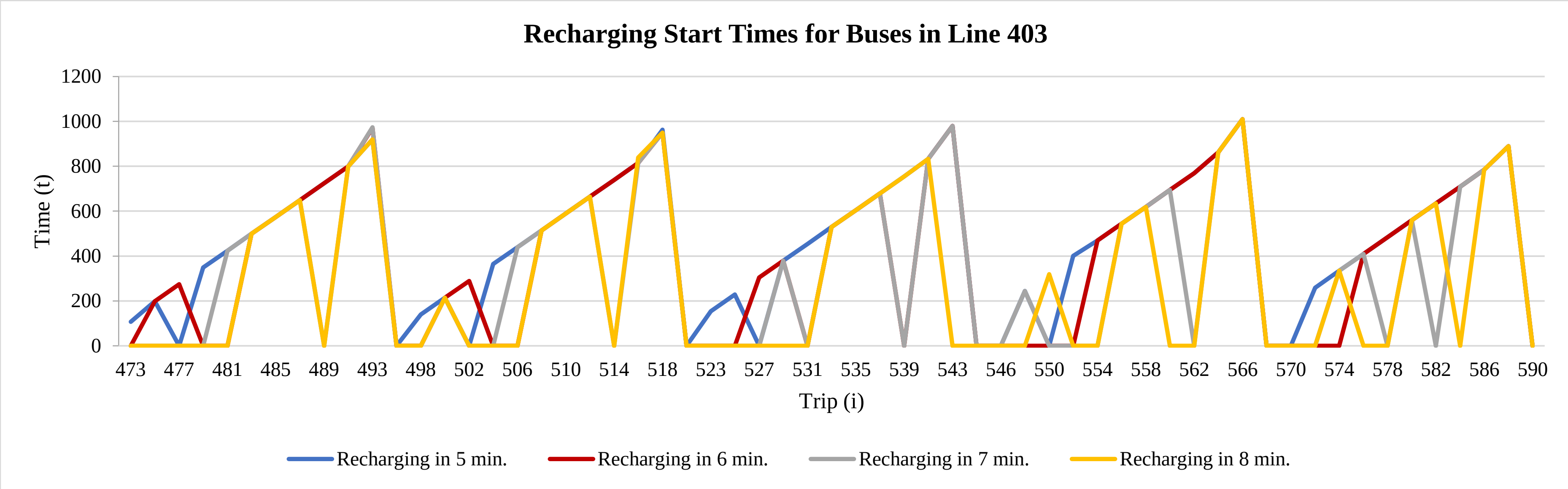

Figure A.4: Recharging start times for buses in line 403.

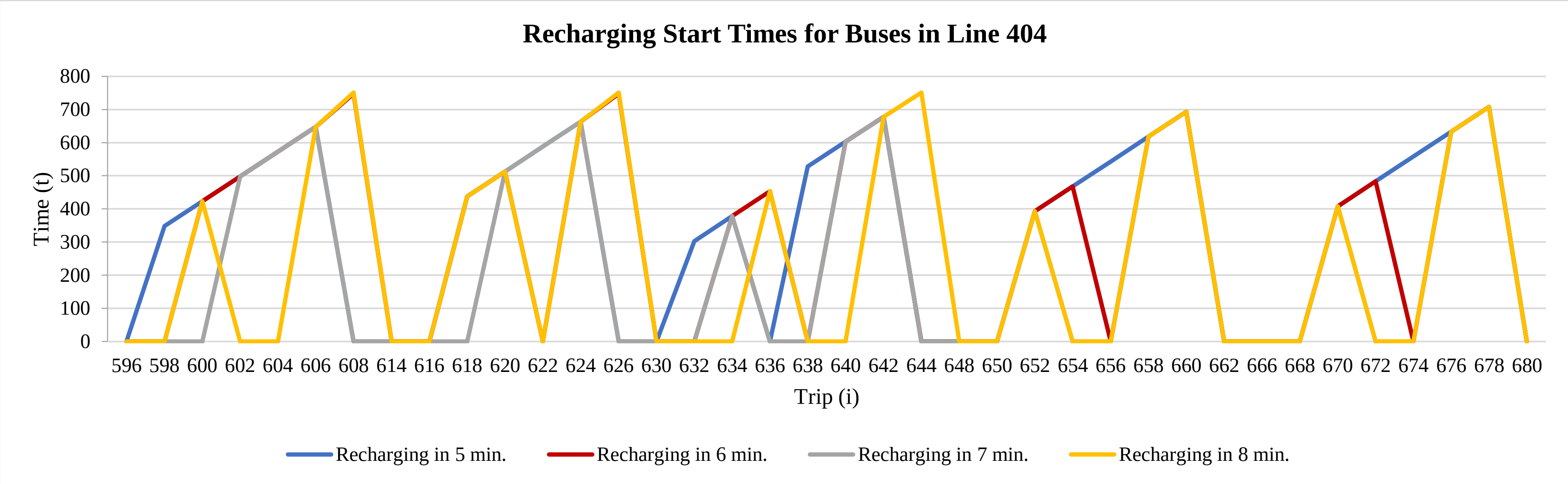

Figure A.5: Recharging start times for buses in line 404.

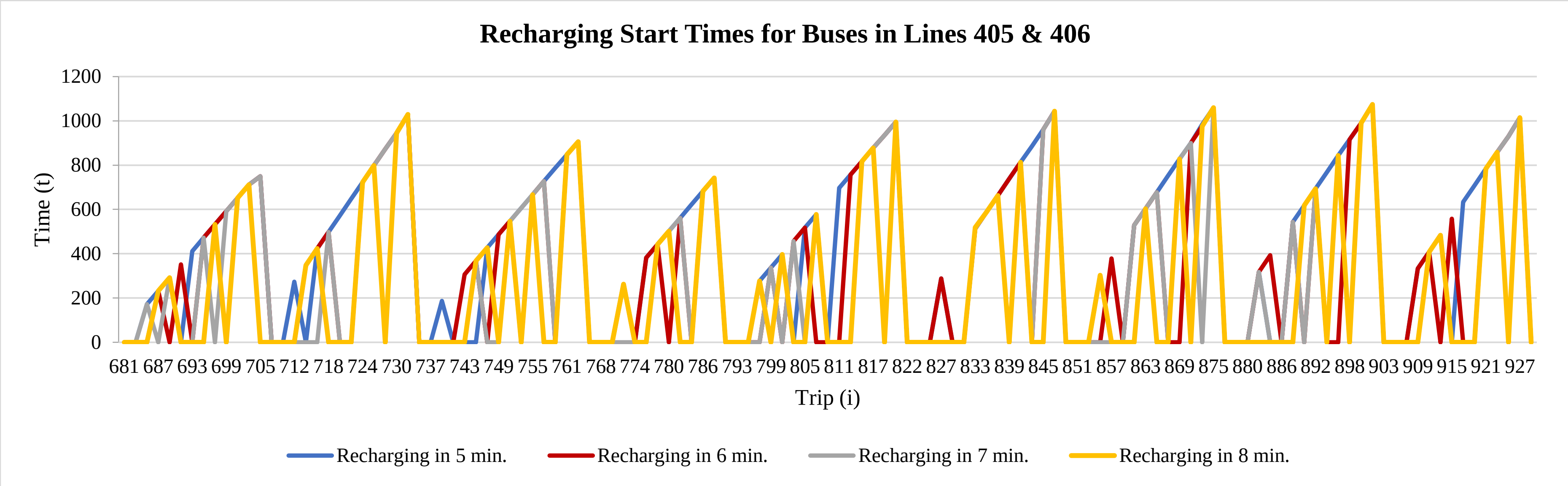

Figure A.6: Recharging start times for buses in line 405 and 406.

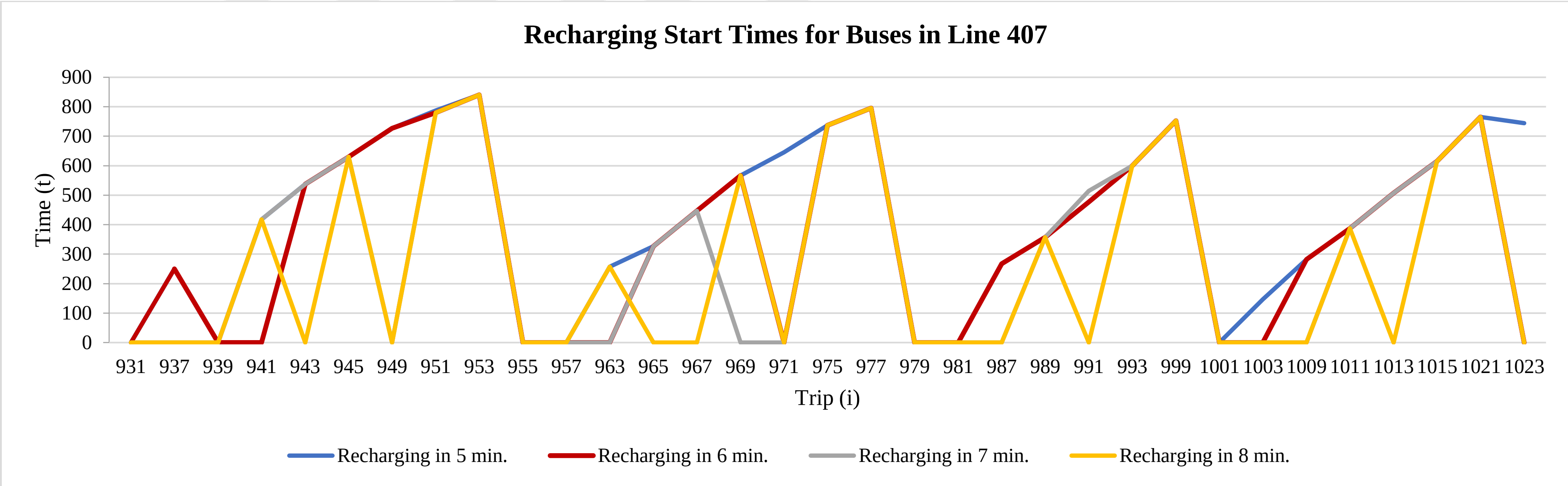

Figure A.7: Recharging start times for buses in line 407.

APPENDIX B

Figure B.1: Plug in charging.

Figure B.2: Outdoor opportunity conductive charging with pantograph.

Figure B.3: Indoor opportunity conductive charging with pantograph.

Figure B.4: Outdoor opportunity inductive charging.

APPENDIX C

Figure C.1: Eindhoven depot.

Figure C.2: Eindhoven depot indoor chargers.

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