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A MASTER'S THESIS

# PUBLIC CITY BUS FLEET REPLACEMENT AND ASSIGNMENT DECISIONS CONSIDERING TOTAL COSTS OF CARBON EMISSIONS AND BUS FLEET OWNERSHIP

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# ABSTRACT

## PUBLIC CITY BUS FLEET REPLACEMENT AND ASSIGNMENT DECISIONS CONSIDERING TOTAL COSTS OF CARBON EMISSIONS AND BUS FLEET OWNERSHIP

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This thesis aims to determine the assignment of an assortment of public city bus types to a given set of routes to minimize the total cost of ownership involving social costs of carbon emissions in addition to the traditional cost elements such as financing, operating, and maintenance. To this end, we use the public transport system of İzmir, Turkey, as our testbed. We formulated a mixed-integer linear program to determine the number of buses of each type to operate on each route and the respective daily cost, which cannot be solved due to its large model size. A simpler version, assuming that a single type of bus is operated on a route, is formulated and solved. Then, its outputs are used as input for a shortest path formulation to determine the replacement and retention decisions over a study period of 12 years. Our results indicate that the currently-owned diesel buses are favored in most of the fairly flat routes whereas electric and hybrid buses are preferred for routes with aggressive road grades. We also investigated the effects of social cost of carbon emissions and the first cost of electricity- and hydrogen-based buses. Our analyses showed that the first cost has a significant effect on the life-cycle costs, assignment and replacement and retention decisions tilting the scale in favor of electric buses.

**Keywords:** Assignment, Carbon Emissions, Total Cost of Ownership

# ÖZET

## ŞEHİRİÇİ OTOBÜSLERİNİN FİLO YENİLENME VE ATANMA SÜRECİNİN KARBON EMİSYON VE FİLO SAHİPLİĞİ MASRAFLARININ İNCELENEREK SAPTANMASI

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Bu tezin amacı, yatırım, işletme ve bakım gibi geleneksel maliyetlere ek olarak otobüse sahiplik maliyeti ve karbon salınımının sosyal maliyetini göz önünde bulundurarak farklı belediye otobüs tiplerinin önceden belirlenmiş rotalara atanmalarına karar vermektir. Sayısal çalışma için İzmir'in belediye otobüs sistemini kullandık. Hatlara atanacak değişik tipteki otobüs sayılarını ve maliyetlerini belirlemek için kurduğumuz karışık tam sayılı programlara modeli, boyutunun büyüklüğü sebebiyle çözülemediğinden her hata bir otobüs tipi atanacak varsayımı kullanılarak basitleştirilmiş ve çözülmüştür. Bu modelin çıktıları, 12 yıllık değiştirme ve elde tutma kararlarını içeren bir plan oluşturmak için kurulan en kısa yol problemine girdi olarak kullanıldı. Sayısal sonuçlara göre, eğimi daha düz olan rotalara dizel, değişken ve çok eğimli rotalara ise elektrikli ve hibrit otobüsler atanmaktadır. Elektrikli ve hidrojen ile çalışan otobüslerin satınalma ve karbon salınımı maliyetlerindeki değişiklerin etkileri de incelenmiş ve analizler sonucunda, elektrikli otobüslerin satınalma maliyetlerindeki değişimlerin toplam ömür maliyetlerinde, atama, değiştirme ve elden çıkarma kararlarında en etkili parametre olduğu saptanmıştır.

**Anahtar Kelimeler:** Atama, Karbon Salınımı, Toplam Sahiplik Maliyeti

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## LIST OF ABBREVIATIONS AND SYMBOLS

### Abbreviations

| | |
|---|---|
| BIP | Binary Integer Programming |
| CNG | Compressed Natural Gas |
| CPI | Consumer Price Index |
| EPA | Environmental Protection Agency |
| ESHOT | Elektrik, Su, Havagazı, Otobüs ve Troleybüs |
| FCHJU | Fuel Cells and Hydrogen Joint Undertaking |
| FEC | Fuel and Emission Calculator |
| GHG | Greenhouse Gas |
| ICE | Internal Combustion Engine |
| LNG | Liquefied Natural Gas |
| MIP | Mixed Integer Linear Programming |
| NPV | Net Present Value |
| TCO | Total Cost of Ownership |
| TTW | Tank to Wheel |
| TUIK | Turkish Statistical Institute |
| U.S. | United States |
| WTT | Well to Tank |

### Symbols

| | |
|---|---|
| C | Celsius |
| $CO_2$ | Carbon Dioxide |
| g | Gram |
| kg | Kilogram |
| km | Kilometer |

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND

Climate change affects all countries around the world. According to the Environmental Protection Agency (EPA), carbon dioxide ($CO_2$) is the most emitted gas (81.6%) by daily activities (industrial or otherwise) of human beings among all the greenhouse gas (GHG) emissions in the U.S. (EPA, 2019). Transportation-related activities, one of the most common daily activities, constitute the 36.7% of this amount. International Association of Public Transport (UITP) pointed out that public city bus transit system is the most widely used transportation mode in the world (63%) and and its use increased 18% from 2000 to 2015 (UITP, 2017). In addition, oil and natural gas are still the primary energy sources in the transportation sector. The most common bus propulsion system in public transport is used by conventional buses (i.e., diesel and compressed natural gas (CNG) buses). Conventional buses in which traction power is achieved by internal combustion engines have higher GHG emission and air pollution compared to electric buses. Conventional buses use oil and natural gas as fuel. UITP statistics brief released in 2019 points out that the most frequently used propulsion systems were diesel buses (50%), diesel with additives and biodiesel (17.4%), and CNG (10.5%) (Saeidizand, 2019). These three bus types dominated the 78% of all public bus fleet around the world. International Energy Agency's report revealed that oil and natural gas were the second (34.6 %) and third (20.5 %) most $CO_2$ emitted fuel types in the world (International Energy Agency, 2019).

Other than conventional buses, various other types of city buses (e.g., hybrid, overnight full electric, opportunity full electric, hydrogen fuel cell) exist and are used. Electrification level of a bus is the major determinant of the resultant GHG emission levels. Consequently, electric alternatives to existent gas-powered city buses are generally considered as greener choices which may help reduce the transportation-related carbon footprint. However, operational and maintenance requirements, characteristics and corresponding costs are reported to be significantly affected by driving conditions (congestion, average speed, frequency of stops, road grade, passenger load, weather and climate, etc., as well as the bus type). A life-cycle cost analysis is most useful in this case since a selection is required from alternative bus types that serve the same purpose and transportation, operating and maintenance costs constitute a significant portion of the life-cycle costs, especially for electric buses.

Municipalities are required to provide public transportation to their communities. A common mode of the transportation service is public city buses. Municipalities have many different bus type choices while forming their bus fleets. Environmental and economic performances of different public city bus types have been previously studied. Environmental aspects investigated in the existing body of literature is mostly about quantification and comparison of GHG emission levels, whereas economical aspects are mostly about the still-developing manufacturing technologies and materials required for production of electric buses and their components. However, environmental and social-cost implications are yet to be investigated in a joint matter. This thesis will consider social costs of carbon emission as market value of the total carbon emitted by assignment of different public city bus types to routes. Different than the existing aforementioned studies, this thesis will focus on determining the optimal assignment of public city bus types to a given set of routes under various driving conditions by incorporating a social cost of carbon emissions into the total cost of ownership.

## 1.2 OBJECTIVES

Public authorities make some decisions while building a city transportation network. Some of these decisions are fleet renewals and bus-route assignments, which are generally made using heuristic approaches. In this study, we investigate the use of exact methods in providing a systematic and applicable approach to making decisions for fleet design.

In this thesis, our aim is to determine the optimal assignment of an assortment of public city bus types to a given set of routes to minimize the total cost of ownership involving social costs of carbon emissions in addition to the traditional cost elements such as financing, operating, maintenance and turned-away passenger cost.

## 1.3 ORGANIZATION OF THE THESIS

Chapter 2 reviews studies about public city buses and greenhouse gas emissions. Chapter 3 presents our research questions and describes the data collection process. Assumptions are stated and mathematical models are formulated in Chapter 4. Chapter 5 presents and discusses the solutions to mathematical models. Chapter 6 presents the influence of the social cost of carbon emissions and first costs on the decisions. Finally Chapter 7 concludes with a discussion and future work.

# CHAPTER 2

# LITERATURE REVIEW

Climate change is one of the major global problems in today's world. To reduce its effects, societies have started to take environmental precautions. One of the key steps that should be taken in reducing the climate change is to decrease the greenhouse gas emission rates. Two agreements were made in the last 30 years to specifically control and reduce GHG emission rates. The first one is the Kyoto Protocol which was assented in 1997 and was put into effect in 2005. According to this protocol, the countries which ratify the agreement should obey the predetermined and individual country-based GHG emission rates. In the first annex of this protocol, 36 developed countries and the European Union countries were expected to reduce their GHG emission rates by 5% between 2008 and 2012 according to 1990 rates. In 2012, these countries held a second meeting in which they agreed to reduce their emission rates 18% between 2013 and 2020 following the 1990 rates (United Nations Framework Convention on Climate Change, ndb). The second agreement was the Paris Agreement. Paris Agreement was signed by 197 countries and ratified by 187 countries except Iran, Turkey, Iraq, Angola, Eritrea, Kyrgyzstan, Lebanon, Libya, South Sudan, and Yemen. These countries that did not ratify the agreement emitted 4% of total GHG in the world (European Commission, 2019). The main aim of the Paris Agreement was to reduce the total GHG emission and limit the heat increase to maximum 1.5°C until 2100, when the estimated increase was calculated around 2.0°C unless the GHG precautions were taken (United Nations Framework Convention on Climate Change, nda). Thus, countries reported their GHG emission rates in every five-year period. 2005 emission rates were used as the base rate. Every country specified its own target emissions. For example, the U.S. declared that they would have decreased their GHG emission rates around 26 to 28% in 2025. India specified that they would have decreased their GHG emission rates by 33–35% in 2030. Additionally, developed countries would support developing countries on some areas such as technology exchange, education, finance to help them reduce their GHG emissions (Britannica, The Editors of Encyclopaedia, 2021). Other than the Kyoto Protocol and Paris agreement, the European Council also put some regulations in charge in order to confront and solve the climate change problem. One of these regulations aimed to decrease GHG emissions by 85%-90% by 2050 (European Commission, 2012).

Environmental pollution due to emissions are closely related to energy sources and their shares in total supply and consumption. Across the world, the share of oil supply in total energy sources were 32% in 2017. Oil is followed by coal and natural gas with 27.1% and 22.2%, respectively. Oil was the most consumed energy source (41%) and is followed by natural gas, biofuels, and coal (15.5%, 10.7%, and 10.5%, respectively). The transportation sector consumed 29% of all energy supplies. Also, 49.2% of oil supply is used by road transportation and 92.18% of the total energy consumption in transportation sector is supplied by oil products. Oil products are followed by natural gas (3.73%), biofuels (2.98%) and electricity (1.11%) (International Energy Agency, 2019). Turkey's primary sources of energy supply were oil (30.18%), natural gas (30.12%), and coal (27.30%) in 2017 (International Energy Agency, 2020). Regarding the energy consumption in Turkey, the primary sectors were manufacturing industry and transportation with percentages of 31% and 26%, respectively (International Energy Agency, 2020).

Reducing GHG emissions in the transportation sector is a step towards a cleaner earth. Song et al. (2018) compared three different diesel bus types (light, medium, and high duty) with electric buses in order to evaluate the life cycle GHG emission rates and their reduction. Their findings showed that electric buses have great potentials to reduce GHG emission rates under minimal electricity distribution and charging loss. The authors stated that clean electricity production mix is also an important factor while evaluating electric bus emission efficiency. Electrification of the transportation sector reduces the GHG emission, naturally helps overcome climate change problem and reduces the damages of fossil fuels to the earth. Increasing quantities of passenger cars and public buses is also contributing to the GHG emissions. Increasing public bus usage and simultaneously decreasing private passenger car usage can help decrease GHG emission rates (Hodges and Tina, 2010). Relatedly, bus types should be analyzed more thoroughly for their emission levels.

There exist various types of city buses in use around the world such as diesel, compressed natural gas, parallel hybrid, series hybrids, plug-in hybrids, overnight full electric, opportunity full electric, and fuel cell hydrogen buses. Hybrid buses use fossil fuels and electricity for traction power. Hybrid buses which have both internal combustion engine and electric motor differ from each other in terms of their running structure. In the parallel hybrid buses, both an electric motor and an internal combustion engine are used for traction power. In the series hybrid, the electric motor uses energy in the battery for traction power and the internal combustion engine produces required electric energy and stores it in the battery. The plug-in hybrid is an extended version of the series hybrid. Plug-in hybrid buses' batteries can be charged by an external power supply. Battery electric buses are full electric buses whose traction power is supplied only by an electric motor. The battery in electric buses must be recharged by external power supply since electric engine does not provide power to the battery. Thus, the battery specifications are important in battery-electric buses. There are two types of lithium-ion batteries. The first one is high energy type batteries. High energy type batteries are used in overnight electric buses. Their energy capacity is higher, and thus they need larger batteries that increase the weight and cost of the bus. The second type of batteries is high power batteries that are used in opportunity electric buses. These batteries can recharge faster and can be charged with high rate chargers (Lajunen and Lipman, 2016). The battery in the opportunity electric bus is smaller than the overnight electric bus, so the bus range is shorter. One of the most important advantages of the opportunity electric buses is that the battery recharging time is much shorter than the overnight buses. On the other hand, overnight electric buses also have an advantage; their range is higher due to high battery capacity. Nurhadi et al. (2014) conducted a sensitivity analysis on total cost of ownership of opportunity electric buses and overnight electric buses. They found that annual travel distance, service life, and investment cost including battery are the major factors that affect the total cost of ownership of electric buses. Finally, fuel cell hydrogen buses have an electric motor to provide traction power. One difference from hybrid buses is that fuel cell hydrogen buses are powered by a combination of hydrogen and oxygen to produce electricity to the battery instead of an internal combustion engine. Fuel cells convert chemical energy from hydrogen to electric energy. Electricity is produced through the catalyst which is in a fuel cell. Catalyst is generally made by platinum which is a valuable and expensive material; therefore, the purchasing cost of fuel cell hydrogen buses is expensive. Technology is growing quickly. Therefore, costs of fuel cells and catalysts are expected to decrease in the near future, which brings forth fuel cell hydrogen buses as a viable choice.

There are some fundamental reasons for considering an electric bus as an alternative to a conventional bus. First, it is known that electric buses emit less $CO_2$. Second, electricity can be produced and provided by a multitude of methods such as nuclear energy, solar; whereas, conventional buses rely on natural resources such as oil and natural gas. Third, regenerative braking function is another advantage of electric buses. The regenerative braking function produces electricity while braking. In this process, the electric motor works as a generator and converts the mechanical energy to the electrical energy and stores it in a battery. While electric buses can be seen as a viable replacement for conventional buses, the production methods of electricity should also be examined. Because 38.5% of total electricity production is through coal in 2017 in the world, and also the most $CO_2$ emitted fuel type is coal (44.2%) (International

Energy Agency, 2019). Although integrating electric buses into public bus fleets is supposed to decrease the GHG emission rates in tank to wheel (TTW), using coal as a source of electricity generation increases GHG emission rates in well to tank (WTT). Therefore, it is more beneficial to use other electricity production methods with lower GHG emission rates.

All bus propulsion systems should be investigated in terms their outcomes and to determine which system is more environmentally and economical under various circumstances. Policymakers can make decisions more accurately about their fleet variety according to these outcomes. Transit agencies have started to modify their fleets with newer technology propulsion systems. For example, according to the Federal Transit Administration, there were 7920 gasoline, 6340 diesel, 1108 CNG, 610 hybrid diesel, 560 battery-electric, and 78 hybrid-gasoline buses in use in U.S. in 2017 (United States Department of Transportation, 2017). Ercan et al. (2015) used a multiobjective linear programming model to find the optimal bus fleet assortment by considering three different driving cycles. Their objective is to minimize life-cycle costs, GHG emission and air pollution emission damage costs. They showed that fleet should include three different bus types at most since increasing the variety of bus types escalates the infrastructure costs. Also, they found out that battery-electric and hybrid buses are the most commonly used bus types in a fleet in all different driving cycles.

Transit agencies should consider the efficiency of different types of buses on routes while adding new buses to their fleet. The efficiency of a bus can be calculated through its energy consumption, life-cycle costs and GHG emissions. Road conditions such as elevation, passenger boarding rate, frequency of stops, acceleration, deceleration and average speed on routes affect the efficiency of a bus. Two different approaches (fuel-based and vehicle activity-based) are used in the existing literature to compare fuel consumption and GHG emissions of buses on different routes (Board et al., 2010). Vehicle activity-based approach is more efficient for local transit agencies because it measures performances of buses while considering local conditions. Ercan and Tatari (2015) proposed a hybrid life-cycle assessment model to show that electric and hybrid buses are not affected by low average speeds while fuel consumption of diesel, biodiesel, CNG, LNG buses are affected negatively from low average speeds. They also showed that electric and hybrid buses are less effective than other bus types on longer-distance routes with high average speeds. Emiliano et al. (2020) proposed a multi-objective optimization model to minimize costs, $CO_2$ and other types of emissions. They investigated four different bus types (diesel, CNG, overnight electric and opportunity electric) in three different driving cycles. They showed that an electric bus is a suitable choice for driving cycles with frequent stops and low average speed characterization while diesel and

CNG buses are better choices at high average speeds. Kivekäs et al. (2018) examined the energy consumption of CNG, diesel, parallel hybrid, series hybrid, battery electric, and fuel cell hydrogen buses in different types of driving cycles. They investigated the correlation between energy consumption of buses and driving cycle parameters. They found that frequency of stops and aggressiveness parameters have the most influence on energy consumption. Diesel buses have lower consumption than CNG buses while diesel buses' energy consumption is more sensitive to aggressiveness than CNG buses. Parallel hybrid buses have lower energy consumption than series hybrid buses on suburban routes. High frequency of stops and aggressiveness affect parallel hybrid buses more than series hybrid buses because of the powertrain structure. Series hybrid buses are the most stable type and nearly suitable for all driving cycles. Fuel cell hydrogen buses have the lowest energy consumption among hybrid buses. Battery electric buses have the lowest energy consumption in all driving cycles and between all powertrains.

Operational and environmental performance comparisons of various bus types are conducted mostly through simulation studies. Correa et al. (2017) analyzed the environmental and energy performances of hybrid, CNG enriched with hydrogen, fuel cell and battery-electric buses in four different ranges and under two different driving patterns. According to this study, battery-electric buses perform better in short ranges whereas hybrid bus performs well in both short and medium ranges. The authors indicated that the fuel cell bus is suitable for longer ranges, and performs well in any range in general. Dreier et al. (2018) estimated the energy use and GHG emissions of conventional, hybrid-electric and plug-in hybrid public city buses, including two axles, articulated and bi-articulated segments. According to the study, plug-in hybrid public city bus is the best option in reducing the GHG emissions, and the two-axle plug-in hybrid bus is the most energy-efficient choice. Xu et al. (2015) compared environmental impacts of the internal combustion engine, hybrid, plug-in hybrid and electric buses in two different service types (local and longer-distance express). They used Fuel and Emission Calculator (Georgia Institute of Technology, nd), a tool developed by the Georgia Institute of Technology researchers, in order to compare different types of buses under different driving conditions (road grade, passenger load, on-road duty cycle and different geographical energy generation mix). While CNG buses offer more efficient emission reductions in longer-distance express bus operations, electric buses show greater emission reduction in local-transit bus operations. Perrotta et al. (2014) analyzed the wasted energy during braking and the energy required for one specific battery electric bus under three different driving patterns (urban, interurban and tortuous). According to this study, urban route leads to the least energy waste while braking and uses the least amount of energy.

Full electrification of a fleet may not be economically feasible since replacing the conventional buses in a fleet requires a large amount of investment, additional operating and maintenance costs due to required battery installations and replacements. Mahmoud et al. (2016) reviewed earlier studies in terms of economic, operational, environmental and energy aspects of hybrid, fuel cell, overnight and opportunity battery-electric buses. They indicated that hybrid buses are not much more beneficial in terms of reducing GHG emission rates. Nonetheless, fuel cell hydrogen buses and battery-electric buses reduce GHG emission rates substantially. Lajunen (2014) investigated energy consumption and life-cycle costs of parallel, series, plug-in hybrids and full electric buses on different routes using conventional diesel-powered buses as a reference. According to this study, life-cycle costs of full electric, series and plug-in hybrid buses are not lower than that of the diesel-powered buses because of high purchase and energy-storage-system costs. Life-cycle costs of parallel hybrid buses on a specific route is found to be lower than that of the conventional diesel-powered buses. Lajunen and Lipman (2016) compared $CO_2$ emissions and life-cycle costs of diesel, CNG, parallel hybrid, series hybrid, fuel cell hydrogen, opportunity and overnight electric buses under six different routes. They investigated $CO_2$ emissions in two parts (TTW and WTT). They used California and Finland as cases to evaluate WTT $CO_2$ emissions. Overnight electric, opportunity electric and fuel-cell hydrogen buses are found to be the best options to reduce $CO_2$ emissions. Diesel hybrid buses have lower $CO_2$ emissions than conventional buses in their life time. While diesel hybrid buses have lower life-cycle costs than conventional buses, electric buses and fuel cell hydrogen buses have the highest life-cycle costs. However, Lajunen and Lipman (2016) predicted that electric buses and fuel cell hydrogen buses can be potential options for reducing in fuel cell and battery costs in the near future.

Ribau et al. (2014) compared fuel cell hybrid and plug-in fuel cell hybrid buses with conventional buses in terms of their costs, fuel consumption, and GHG emission rates. According to this study, fuel cell buses have substantial decreased fuel consumptions and emission rates. Fuel cell hybrid buses economically have more potential when compared with plug-in fuel cell hybrid buses because the cost of the fuel cell hybrid buses is cheaper. Plug-in fuel cell hybrid buses have lower fuel consumption and GHG emission rates than the fuel cell hybrid buses. Ally and Pryor (2016) compared total ownership costs of diesel, CNG, hybrid, and fuel cell hydrogen buses. Their study showed that diesel buses are the best choice in terms of total cost of ownership (TCO). Hybrid buses' total cost of ownership is 10% higher than those of conventional diesel buses. Fuel cell hydrogen buses have the highest TCO. Finally, in 2012, Fuel Cells and Hydrogen Joint Undertaking (FCHJU) compared economic, operational and environmental performances of eight different public city bus types (diesel, CNG, parallel hybrid, series hybrid, hydrogen fuel cell, trolley, opportunity e-bus and overnight e-bus) with two different bus segments (standard and articulated length) (Fuel Cells and Hydrogen Joint Undertaking, 2012). According to FCHJU, opportunity electric buses are the best options in standard length while the hydrogen fuel cells are the best options in articulated length.

In summary, energy consumptions and GHG emissions of diesel, CNG, parallel hybrid, series hybrid, plug-in hybrid, opportunity electric, overnight electric, fuel-cell hydrogen buses are compared in relation to various route characteristics (average speed, stop frequency, route range, passenger load and road grade). Total cost of ownership analyses of these bus types are conducted. Furthermore, bus type assortment of bus fleets is studied. Under the light of these existing studies, our study aims to determine the assignment of an assortment of public city bus types to a given set of routes to minimize the total cost of ownership involving social costs of carbon emissions and turned-away passenger costs in addition to the traditional cost elements such as financing, operating and maintenance. Our study has additional benefits of expanding the total cost of ownership of bus fleet by adding social cost of carbon and turned-away passenger cost. Our model can be used by transit agencies for long-term planning. In Chapter 3, we present our research questions, data set and assumptions used in our models.

# CHAPTER 3

# RESEARCH QUESTIONS AND DATA COLLECTION

In this chapter, we first pose our research questions that are motivated by the data collection process and literature review, and then, we present details about the data collection process, data sources and how we dealt with the missing data.

## 3.1 RESEARCH QUESTIONS

In this thesis, we aim to design a bus fleet by finding an optimal assignment of different types of buses in a given set of routes that will minimize the total ownership cost. We intend to find answers to the following questions:

1. What is the total cost of assigning a particular bus type to a given route?
2. What is the optimal number of buses that should be assigned to a route in a day?
3. What is the optimal assortment of bus types in a fleet?
4. What should be the replacement and retention plan?

There are several approaches to answer the research questions we posed above, ranging from simulation optimization that requires specialized and expensive software to mathematical programming. Regardless, we note that finding the best decisions is not a simple task considering the size of the problem (service periods, variety of bus types and numbers, number of routes, etc.). The research questions we posed above can be broken down into short- and long-term decisions problems that can help with tractability of the overall fleet design problem.

- *Short term decisions:* Assignment of buses to routes can be made in a short time interval, say a day. Different bus types can be cost effective on different routes. Therefore, route-bus assignment can be optimized over a day.
- *Long term decisions:* A transit agency may make decisions on purchasing and salvaging without making a detailed assessment. Fleet replacement and retention decisions should be considered over a study period with a reasonable duration. This will help with strategic planning as well.

## 3.2 DATA COLLECTION

We contacted ESHOT, the public transportation system of İzmir, Turkey, to obtain pertinent data. ESHOT was established in 1943 to provide electricity, water, coal gas, public bus, and trolleybus services. In this thesis, we only focus on the public bus transportation system. According to the Turkish Statistical Institute (TUIK, 2021), İzmir is the third highest populated city in Turkey. It is divided into five districts for bus transportation services due to the extensive acreage and high population.

ESHOT has five different fleet hubs which serve different areas of İzmir. We chose District 4 for our numerical study since it covers a larger and higher populated downtown area compared to the other districts. We make the following assumptions when generating the missing data.

A1. Setup cost: Setup costs, which is used as a bus assignment cost, are taken same for all routes and bus types.

A2. Carbon emission and operating cost: Only straight and uphill parts of roads are considered while calculating social cost of carbon emission and operating cost. Downhill parts are ignored since we assume fuel consumption is 0 in these parts.

A3. Carbon emission and operating cost: Average vehicle speeds along routes are used as vehicle speeds in straight and uphill parts of roads.

A4. Operating cost: Electricity production while regenerative braking is not taken into account because we could not find required data.

A5. Carbon emission cost: $CO_2$ emissions of opportunity, overnight electric and fuel-cell hydrogen buses are zero.

A6. Service time: Time until start of the second leg is used as the service time of the first leg's service time.

A7. Passenger capacity: Number of alighting passengers are not taken into account.

A8. Charging infrastructure: Opportunity electric bus batteries are charged at the first stop of their assigned routes at the end of a tour.

A9. Charging infrastructure: Overnight electric buses battery capacities last a whole day, i.e., battery charging is completed in the fleet hub at the end of the day.

District 4 covers Buca and Konak counties and its hub is located in Adatepe. It has 42 roundtrip routes, i.e., 84 one-way routes (see Figure 3.1). All routes in our data set are paired and converted into round tours. Round tours consist of two routes. These two routes correspond to departure (first leg) and return trips (second leg) of round tours (see Figure 3.2). Return trips must be performed after departure trips are completed. After converting all routes to the round tours, number of periods in some paired routes were found to be not equal to each other. Thus, dummy periods are added to such routes with zero cost.

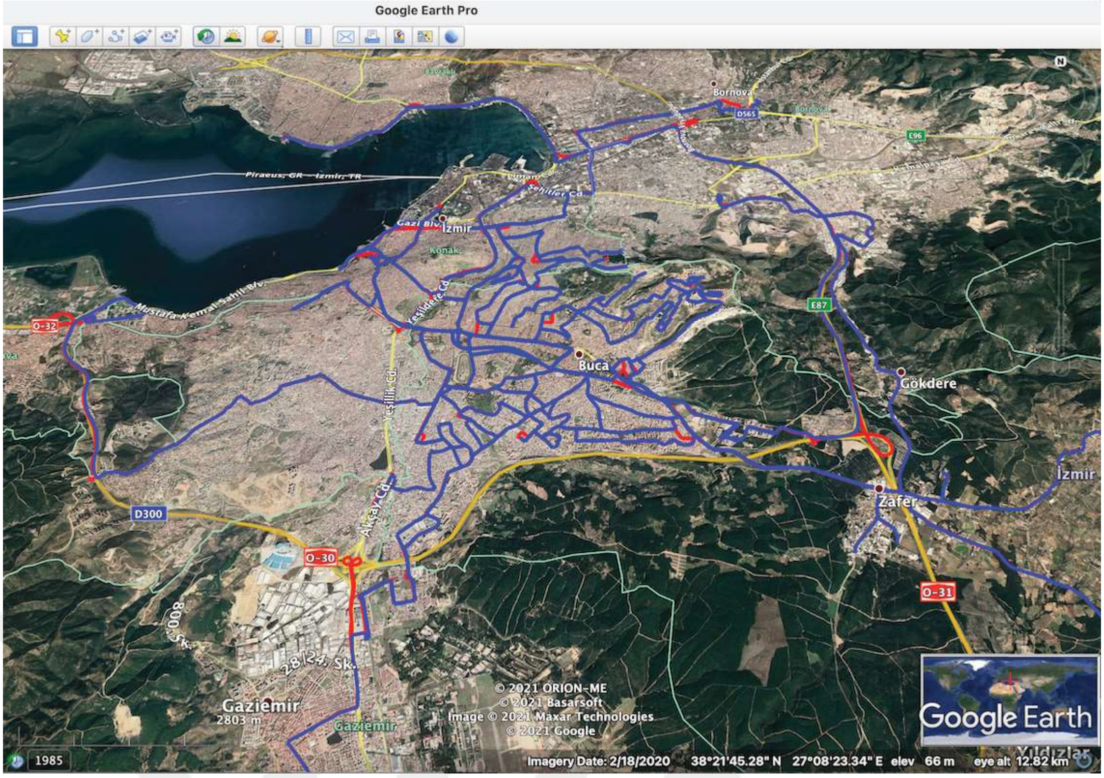
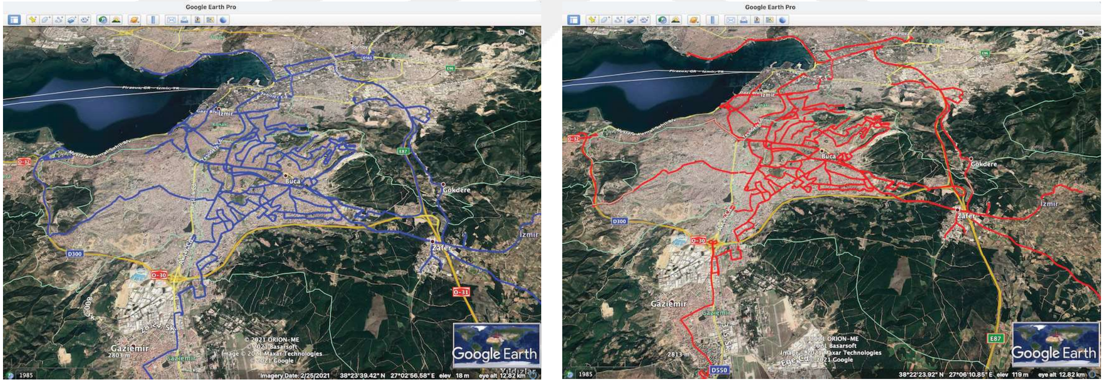


**Figure 3.1:** Routes in District 4.



(a) Departure trips.

(b) Return trips.

**Figure 3.2:** Departure and return trips for routes in District 4.

We divided the routes into 21 groups according to their service zones. Table 3.1 shows the route groups, routes included in these groups and the route IDs used by ESHOT in District 4. We labelled the first legs of trips (departure trips) by odd numbers and the second legs of trips (return trips) by even numbers. For example, departure trip of the route with ID 34 is labelled as route 1 and return trip is labelled as route 2. Figure 3.3 shows the routes included in group G1, in which the blue lines illustrate departure trips and the red lines show the return trips.

**Table 3.1:** Routes, route groups and route ID information.

| Group | Route | Route ID | Group | Route | Route ID | Group | Route | Route ID |
|---|---|---|---|---|---|---|---|---|
| G1 | 1 | 34 | G8 | 21 | 176 | G15 | 43 | 441 |
| | 2 | | | 22 | | | 44 | |
| | 5 | 39 | | 23 | 177 | | 79 | 876 |
| | 6 | | | 24 | | | 80 | |
| G2 | 3 | 36 | G9 | 25 | 277 | G16 | 45 | 465 |
| | 4 | | | 26 | | | 46 | |
| | 69 | 838 | | 29 | 290 | | 49 | 470 |
| | 70 | | | 30 | | | 50 | |
| G3 | 7 | 42 | G10 | 27 | 285 | G17 | 47 | 466 |
| | 8 | | | 28 | | | 48 | |
| | 9 | 46 | | 57 | 490 | | 53 | 484 |
| | 10 | | | 58 | | | 54 | |
| G4 | 11 | 72 | G11 | 33 | 353 | G18 | 51 | 476 |
| | 12 | | | 34 | | | 52 | |
| | 35 | 374 | | 67 | 818 | | 65 | 805 |
| | 36 | | | 68 | | | 66 | |
| G5 | 13 | 74 | G12 | 37 | 412 | G19 | 61 | 671 |
| | 14 | | | 38 | | | 62 | |
| | 55 | 485 | | 81 | 878 | | 83 | 233 |
| | 56 | | | 82 | | | 84 | |
| G6 | 15 | 104 | G13 | 39 | 417 | G20 | 71 | 866 |
| | 16 | | | 40 | | | 72 | |
| | 31 | 304 | | 63 | 676 | | 73 | 871 |
| | 32 | | | 64 | | | 74 | |
| G7 | 17 | 105 | G14 | 41 | 418 | G21 | 75 | 874 |
| | 18 | | | 42 | | | 76 | |
| | 19 | 171 | | 59 | 515 | | 77 | 875 |
| | 20 | | | 60 | | | 78 | |

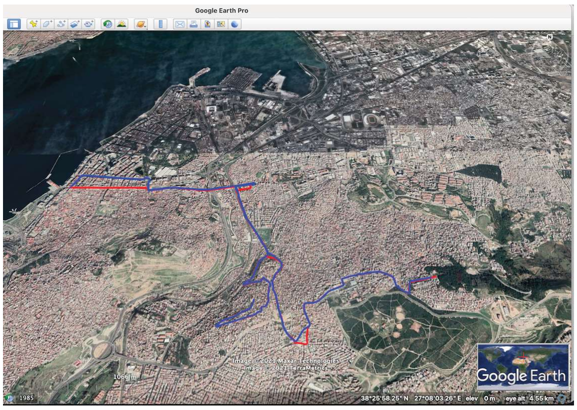


**Figure 3.3:** Routes in group G1.

We divided a day of bus operations from 5:45 A.M. until 1:00 A.M. into five-minute-long periods. As a result, there are a total of 232 periods in a day. These periods are used as departure times of the buses in these routes. The number of trips in a route varies based on the passenger demand. Table 3.2 displays service periods of routes (indicated by 1 in the table) for routes with IDs 34 and 36 from 5:45 A.M. through 7 A.M. as an example.

**Table 3.2:** Service periods of routes in groups 34 and 36.

| | | Route ID: 34 | | Route ID: 36 | |
|---|---|---|---|---|---|
| Time | Period ($p$) | Route 1 | Route 2 | Route 3 | Route 4 |
| 5:45 | 1 | | | | |
| 5:50 | 2 | | | | |
| 5:55 | 3 | | | | |
| 6:00 | 4 | | | | |
| 6:05 | 5 | | | | |
| 6:10 | 6 | 1 | | 1 | |
| 6:15 | 7 | | | | |
| 6:20 | 8 | | | | |
| 6:25 | 9 | 1 | | | |
| 6:30 | 10 | | | 1 | |
| 6:35 | 11 | | | | |
| 6:40 | 12 | 1 | | | 1 |
| 6:45 | 13 | | 1 | | |
| 6:50 | 14 | 1 | | 1 | |
| 6:55 | 15 | | | | |
| 7:00 | 16 | 1 | 1 | | 1 |

We consider 17 different types of buses as shown in Table 3.3. These bus types are classified under four main categories based on the fuel type used: diesel, CNG, hybrid, electric and hydrogen fuel-cell buses. The buses are further differentiated with respect to their engine, fuel storage system ve length. Diesel and CNG bus use diesel and compressed natural gas as fuel and their traction power is provided by an internal combustion engine (ICE). Hybrid bus, which has both internal combustion engine and electric motor (EM), uses diesel and electricity for traction power. Electric bus uses electricity as fuel and its traction power is provided by electric motor. Hydrogen fuel-cell bus uses hydrogen gas as fuel and hydrogen gas produces the required electricity to an electric motor for traction power. Bus lengths are standardized to be 12 and 18 meters where 12 corresponds to a standard-length and 18 to an articulated bus. The bus lengths are attached to the bus type labels as shown in Table 3.3. These bus types are chosen according to the available public city buses in the market.

**Table 3.3:** Specification of bus types.

| Bus Type | Fuel Type | Fuel Storage | Engine |
|---|---|---|---|
| CNG12 | CNG | Tank | ICE |
| CNG18 | CNG | Tank | ICE |
| DIESEL12 EURO2 | Diesel | Tank | ICE - Euro 2 |
| DIESEL12 EURO3 | Diesel | Tank | ICE - Euro 3 |
| DIESEL12 EURO4 | Diesel | Tank | ICE - Euro 4 |
| DIESEL12 EURO5 | Diesel | Tank | ICE - Euro 5 |
| DIESEL18 EURO2 | Diesel | Tank | ICE - Euro 2 |
| DIESEL18 EURO3 | Diesel | Tank | ICE - Euro 3 |
| DIESEL18 EURO5 | Diesel | Tank | ICE - Euro 5 |
| HYBRID12 (Series) | Diesel | Battery and Tank | ICE and EM |
| HYBRID18 (Series) | Diesel | Battery and Tank | ICE and EM |
| HYDROGEN FUEL-CELL12 | Hydrogen | Battery and Tank | EM |
| HYDROGEN FUEL-CELL18 | Hydrogen | Battery and Tank | EM |
| OPPORTUNITY ELECTRIC12 | Electric | Battery | EM |
| OPPORTUNITY ELECTRIC18 | Electric | Battery | EM |
| OVERNIGHT ELECTRIC12 | Electric | Battery | EM |
| OVERNIGHT ELECTRIC18 | Electric | Battery | EM |

Earlier studies generally classify public city bus types into two categories according to their propulsion types and length types. According to the propulsion type, ESHOT has two different buses in their fleet: diesel and overnight electric buses. In district 4, there are 282 buses that are in service. 262 of these buses are diesel buses. In particular, there are 16 DIESEL12 EURO2, 50 DIESEL12 EURO3, 36 DIESEL12 EURO4, 71 DIESEL12 EURO5, 13 DIESEL18 EURO2, 48 DIESEL18 EURO3, and 28 DIESEL18 EURO5 buses. The remaining 20 buses are OVERNIGHT ELECTRIC12 buses. However, we assume that ESHOT owns 60 buses per each bus type, which is sufficient in quantity for a one-day bus operation. We determined this number according to the number of service periods in route groups.

We note that although we were able to obtain most of the data from ESHOT authorities, we were not able to get all of the required data. We present the missing data and explain how we dealt with those in the following subsections.

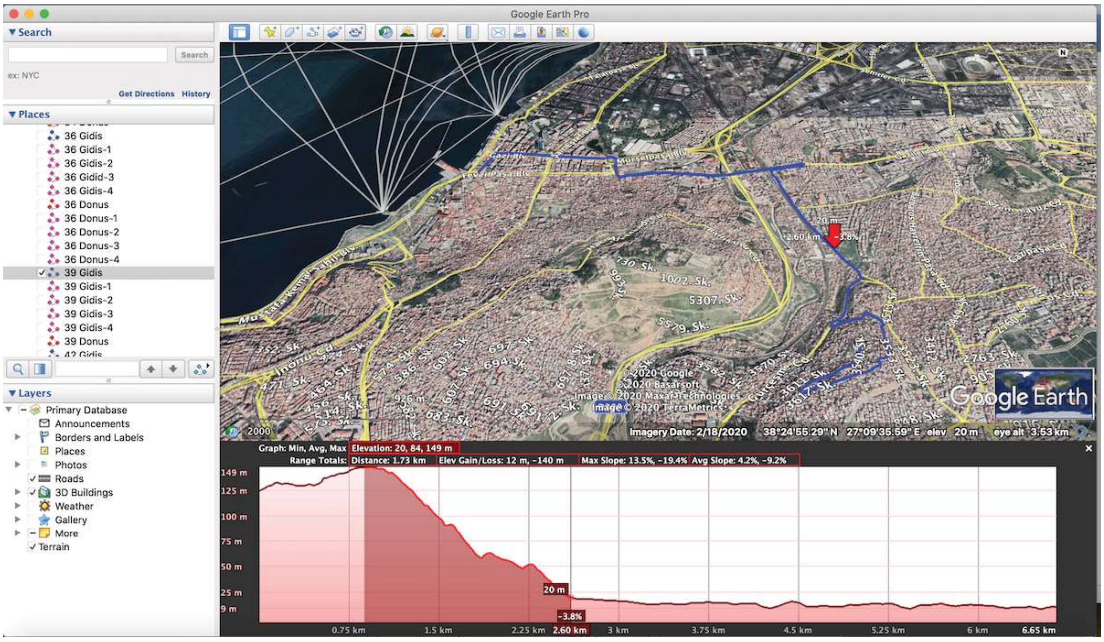
### 3.2.1 Route Topography

Route topography information is obtained using the Google Earth application (Google, 2021). All routes are drawn manually and divided into four parts through the path feature of Google Earth and the elevation information is extracted. Figures 3.4– 3.7 show the topography and parts of route group 39. The blue lines show the route. In the first part of route group 39 (see Figure 3.4), the graph below the map includes data about the elevation, distance and slope, e.g., distance is 880 meters, minimum elevation is 125 meters, maximum elevation is 148 meters, maximum positive slope is 17.2% and maximum negative slope is -5.1%, etc. Only uphill and straight parts of routes were taken into consideration while calculating the weight parameter of the road grade.

Graph: Min, Avg, Max Elevation: 125, 136, 148 m

Range Totals: Distance: 880 m Elev Gain/Loss: 29.8 m, -6.49 m Max Slope: 17.2%, -5.1% Avg Slope: 4.3%, -2.1%

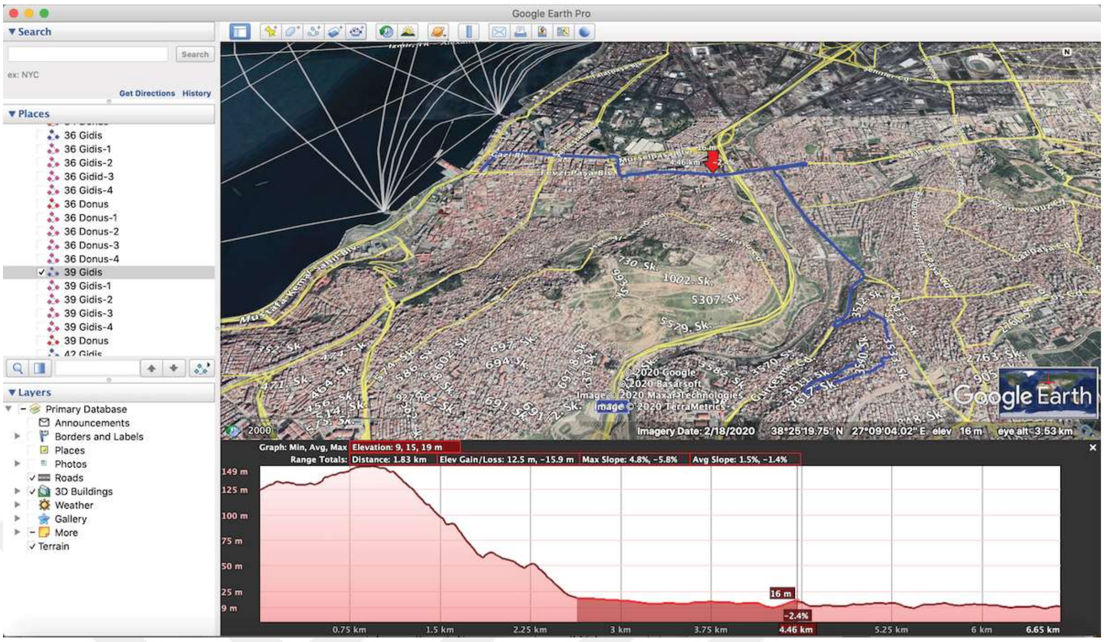
**Figure 3.4:** Topography of route group 39: First part.



Graph: Min, Avg, Max Elevation: 20, 84, 149 m

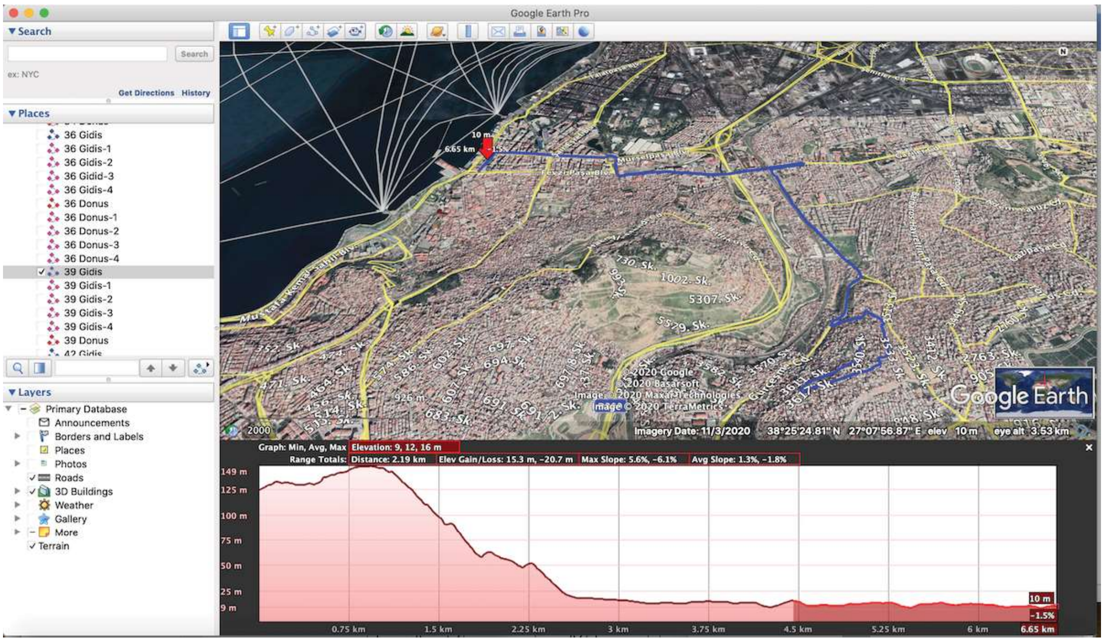
Range Totals: Distance: 1.73 km Elev Gain/Loss: 12 m, -140 m Max Slope: 13.5%, -19.4% Avg Slope: 4.2%, -9.2%

**Figure 3.5:** Topography of route group 39: Second part.



Graph: Min, Avg, Max Elevation: 9, 15, 19 m
Range Totals: Distance: 1.83 km Elev Gain/Loss: 12.5 m, -15.9 m Max Slope: 4.8%, -5.8% Avg Slope: 1.5%, -1.4%

**Figure 3.6:** Topography of route group 39: Third part.



Graph: Min, Avg, Max Elevation: 9, 12, 16 m
Range Totals: Distance: 2.19 km Elev Gain/Loss: 15.3 m, -20.7 m Max Slope: 5.6%, -6.1% Avg Slope: 1.3%, -1.8%

**Figure 3.7:** Topography of route group 39: Fourth part.

### 3.2.2 Service Times

Service times of buses were not available in the data set provided by ESHOT. Additionally, data for the start times (periods) of return trips for some routes were missing. We used the Moovit application (Moovit, 2021) that enabled us to extract service times. In order to determine the start times, i.e., periods, of return trips with no pertinent data, we used the service times of departure trips. Table 3.4 shows the service durations for routes 1–4 during the first 20 periods. In Table 3.4, time until the start of a tour's return trip (route 2 and route 4) is used as the departure trip's (route 1 and route 3) service time.

**Table 3.4:** Service durations of routes (minutes).

| Period ($p$) | Route 1 | Route 2 | Route 3 | Route 4 |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | 35 | | 30 | |
| 5 | | | | |
| 6 | | | | |
| 7 | 35 | | | |
| 8 | | | 30 | |
| 9 | | | | |
| 10 | 35 | | | 15 |
| 11 | | 20 | | |
| 12 | 35 | | 30 | |
| 13 | | | | |
| 14 | 35 | 20 | | 15 |
| 15 | 40 | | | |
| 16 | | | 30 | |
| 17 | 35 | 25 | | |
| 18 | | | | 20 |
| 19 | 35 | 25 | | |
| 20 | | | 30 | |

### 3.2.3 Passenger Capacity of Buses

We obtained the information regarding the passenger capacity of diesel buses from ESHOT. Passenger capacity of CNG buses is assumed as the same as those of the diesel buses. Passenger capacities of hybrid buses are obtained from the manufacturing companies (NovaBUS, 2021b,a) while capacities of opportunity and overnight electric buses are obtained from the manufacturers (Bozankaya, 2021a; Proterra, 2021; Newflyer, 2021; Bozankaya, 2021b). Passenger capacity data for hydrogen fuel cell buses presented in Table 3.5 are obtained from the work of Eudy and Post (2014).

**Table 3.5:** Passenger capacity of each bus type.

| Bus Type | Passenger Capacity (persons) |
|---|---|
| DIESEL12 | 80 |
| DIESEL18 | 130 |
| CNG12 | 80 |
| CNG18 | 130 |
| HYBRID12 | 80 |
| HYBRID18 | 112 |
| HYDROGEN FUEL-CELL12 | 80 |
| HYDROGEN FUEL-CELL18 | 120 |
| OPPORTUNITY ELECTRIC12 | 82 |
| OPPORTUNITY ELECTRIC18 | 125 |
| OVERNIGHT ELECTRIC12 | 90 |
| OVERNIGHT ELECTRIC18 | 130 |

### 3.2.4 Passenger Demand

Passenger demand is stochastic in reality, and it fluctuates during the day, week, month, and year. Passenger demand data in each route and each period were not available. We assumed that passenger demand follows Poisson distribution, which we believe, at least capture some randomness in the data. Below we explain how we generated the passenger demand over different periods and routes.

Considering the relative passenger density over different periods roughly, we first set an interval with minimum and maximum values for the number of passengers for each period in a given route. In general, the passenger density is high during the morning and evening rush hours (7:00-9:00 and 17:00-19:00). The minimum and maximum values are used as the bounds (i.e., the parameters) of a uniform distribution. The mean of the uniform distribution is then taken as the mean for the Poisson distribution. The related data generation is done using Python Programming Language (see Listings D.1 and D.2 in Appendix D). In Listing D.1, ‘oneday mean 6 7’ generates mean values of passenger demand hours between 6:00 and 7:00. There are 15 periods in this interval (i.e., 6:00-7:00) and 84 routes. The piece of code creates mean values for the first 15 periods of all routes. Lower and upper bounds of mean values in the time period 6:00-7:00 are taken as 20 and 70, respectively. Table 3.6 shows the passenger demand data generated using the Python codes for routes 1–4.

**Table 3.6:** Average passenger demand per period in different routes (persons).

| Period ($p$) | Route 1 | Route 2 | Route 3 | Route 4 |
|---|---|---|---|---|
| 1 | | | | |
| 2 | | | | |
| 3 | | | | |
| 4 | 49 | | 25 | |
| 5 | | | | |
| 6 | | | | |
| 7 | 20 | | | |
| 8 | | | 50 | |
| 9 | | | | |
| 10 | 39 | | | 54 |
| 11 | | 54 | | |
| 12 | 74 | | 31 | |
| 13 | | | | |
| 14 | 56 | 32 | | 37 |
| 15 | 61 | | | |
| 16 | | | 65 | |
| 17 | 92 | 78 | | |
| 18 | | | | 75 |
| 19 | 87 | 101 | | |
| 20 | | | 45 | |

### 3.2.5 Setup Cost

The setup cost is a portion of the costs of assigning a bus to route. The setup cost is incurred for every bus that is assigned to a route, and it consists of the costs related to notifying the driver and scheduling. We note that the it is incurred per bus, and it is a one-time cost per day. The setup cost also helps minimizing the number of buses that are assigned to a route, i.e., it penalizes assigning extra buses unnecessarily. The setup cost is taken as $2 per day and it is assumed to be the same for all routes and bus types.

### 3.2.6 Operating Costs

Operating cost is based on fuel consumption. The overall fuel consumption of buses was provided by ESHOT, but the fuel consumption for each route and each period were not available. In order to obtain the operating cost, first, we used the information published by Zhang et al. (2014) to calculate the fuel consumption of each bus type on different average speeds. Then, we made use of the formulas given by Yang et al. (2012) to measure the effect of road grade and mass on fuel consumption by creating weight parameters. We obtained fuel consumption amounts as summarized below.

- We used the correlation coefficients provided by Zhang et al. (2014) to calculate the fuel consumption rates for CNG12, DIESEL12 EURO2, DIESEL12 EURO3, DIESEL12 EURO4, DIESEL12 EURO5, HYBRID12 buses in each route and in each period. These coefficients relate the relative fuel consumption rates to the average bus speed (see Table 3.7). Distance-specific fuel consumptions of buses developed by the authors are obtained using Equation (3.1). Vehicle speeds along straight and uphill parts of a route were not available. Therefore, the average speed in each period is assumed to be the vehicle speed.

$$RFC_{mass\,i} = \frac{FC_{mass\,i}}{FC_{mass\,0}}. \tag{3.1}$$

  In Equation (3.1), $RFC_{mass\,i}$ is the relative fuel consumption, $FC_{mass\,i}$ is the distance-specific fuel consumption of cycle $i$ (kg/km) and $FC_{mass\,0}$ is the distance-specific fuel consumption under a baseline driving cycle (kg/km) (see Zhang et al. (2014) for further information).
- We generated the consumption rates for 12m and 18m OVERNIGHT, OPPORTUNITY, and HYDROGEN FUEL CELL buses which were not covered by Zhang et al. (2014). Therefore, we used data from manufacturers, i.e., fuel consumption per km. Fuel consumptions of OVERNIGHT ELECTRIC12 buses are obtained from Bozankaya (2021a); Proterra (2021); Newflyer (2021). Operating costs of OVERNIGHT ELECTRIC18 buses are obtained from Bozankaya (2021b); Newflyer (2021). However, the fuel consumption data varied substantially in these sources. To solve this inconsistency problem, we calculated and used the average of the fuel consumption rates reported in these sources.
- We used technical reports by Newflyer (2021) to obtain operating costs of OPPORTUNITY ELECTRIC12 and OPPORTUNITY ELECTRIC18 buses.
- Fuel consumptions of HYDROGEN FUEL CELL buses are calculated by making use of the study by Eudy and Post (2014). We note that hydrogen fuel-cell buses have recently been produced, so they are under-examined in the existing literature.

The fuel consumption formulations in Table 3.7 are based on the average bus speed and bus manufacturers' data only. However, route characteristics (road grade, mass) impact the fuel consumption as well. We made use of formulations provided by Yang et al. (2012) to measure the effect of road grade and mass on fuel consumption (see Equations (3.2)–(3.6)).

**Table 3.7:** Correlation between relative fuel consumption rate and average speed.

| Bus Type | Relative fuel consumption rate $y$ based on average speed $x$ |
|---|---|
| DIESEL12 EURO2 | $y = 2.8905x^{-0.3459}$ |
| DIESEL12 EURO3 | $y = 1.5630 - 3.3457 \cdot 10^{-2}x + 3.6991 \cdot 10^{-4}x^2$ |
| DIESEL12 EURO4 | $y = 4.5671x^{-0.5031}$ |
| DIESEL12 EURO5 | $y = 5.6187x^{-0.5634}$ |
| CNG12 | $y = 8.3751x^{-0.7209}$ |
| HYBRID12 | $y = 1.8818 - 3.9008 \cdot 10^{-2}x - 8.6862 \cdot 10^{-5}x^2$ |

Source: Zhang et al. (2014)

$$P = \frac{\frac{V}{3.6}[(m \cdot a) + F_R + F_W + F_D]}{1000 + AP}, \tag{3.2}$$

$$F_R = C_r \cdot m \cdot g \cdot \cos\theta, \tag{3.3}$$

$$F_W = m \cdot g \cdot \sin\theta, \tag{3.4}$$

$$F_D = 0.5 \cdot \rho \cdot C_d \cdot A_f \cdot (V + V_w)^2 \cdot (1/3.6)^2, \tag{3.5}$$

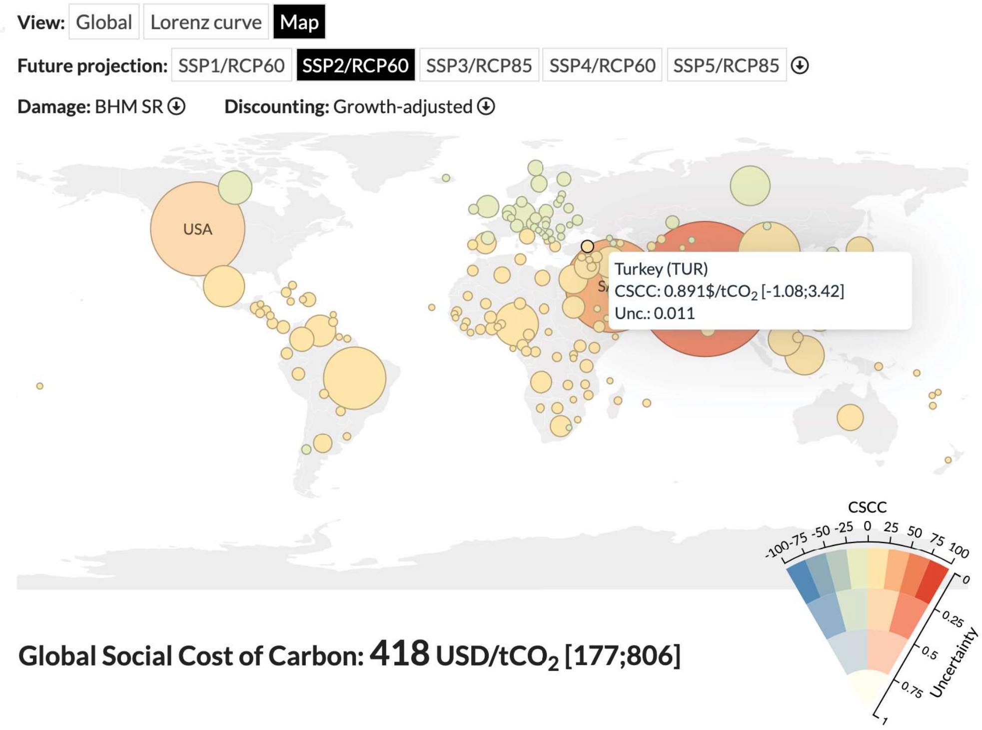
$$\text{Fuel} = P \cdot \frac{SFC}{\rho_{\text{diesel}} \cdot 1000}/DS \cdot 100. \tag{3.6}$$

In Equations (3.2)–(3.6), $P$ is total engine power demand (kW), $F_R$ is the rolling resistance force (N), $F_W$ is the gravitational weight force (N), $F_D$ is the aerodynamic drag force (N), $V$ is the vehicle speed (km/hour), $m$ is the actual vehicle mass (kg), $a$ is the vehicle acceleration (m/s$^2$), $AP$ is the auxiliary power demand (kW), $C_r$ is the rolling resistance coefficient, $g$ is the acceleration due to gravity (m/s$^2$), $\theta$ is the grade angle of the road (degree), $\rho$ is the air density (kg/m$^3$), $C_d$ is the aerodynamic drag coefficient, $A_f$ is the bus frontal area (m$^2$), $V_w$ is the head-wind speed (km/h), Fuel is the fuel consumption (liters per 100 km), $DS$ is the travel distance (km), $SFC$ is the specific fuel consumption (g/kW), $\rho_{\text{diesel}}$ is the diesel fuel density (kg/l) (see Yang et al. (2012) for further information).

To calculate the operating costs, first we determined a base route to create route-dependent weight parameters. In our setting, the average bus speed for all routes and periods is 25.63 km/hour. Fuel consumption values reported by Yang et al. (2012) and Zhang et al. (2014) are compared using this average bus speed. We observed that the lowest fuel consumption difference between these studies occurs in route 12. Thus, route 12 is selected as the base route and its weight parameter is normalized to one. Then, the weight parameters of other routes are calculated relative to that of the base route using the formulas given by Yang et al. (2012). We note that the lengths of buses (12m and 18m) are used to proportionally calculate the corresponding fuel consumptions by changing the mass input in the formulas. Fuel consumption values are then used to obtain the operating costs in each route and period (see Tables A.1 and A.2 in Appendix A).

### 3.2.7 Carbon Emission Costs

The social cost of carbon is considered as the economic damage of carbon to a country. Ricke et al. (2018) calculates the social cost of carbon with main focus on climate impacts by addressing four components: socio-economic module, climate module, damages module, and discounting module. Regarding the socio-economic module, there are five different pathways. We used the outcomes of SSP2 pathway (medium challenges to mitigation and adaptation) and SSP3 pathway (medium challenges to mitigation and adaptation). Regarding climate module, three different pathways are available. This module describes temperature increase scenarios in 2100 that are RCP4.5 is +2.5°C increase, RCP6.0 is +3°C increase and RCP8.5 is +4.5°C increase. We chose the RCP6.0 for our model. We used short-run model in damages module and growth-adjusted scenario in discounting module. Using the above relevant modules results in \$0.891 as the social cost of an additional ton of carbon to Turkey (see Figure 3.8). The reported worst case for Turkey is SSP3/RCP85 modules, long-run and growth-adjusted scenarios, in which the social cost of carbon for Turkey is \$26.6 per ton (see Figure 3.9).



**Future projection:** SSP2/RCP60

**Damage:** BHM SR

**Discounting:** Growth-adjusted

Turkey (TUR)
CSCC: 0.891\$/tCO$_2$ [-1.08;3.42]
Unc.: 0.011

**Global Social Cost of Carbon: 418 USD/tCO$_2$ [177;806]**

**Figure 3.8:** Country-level social cost of carbon considering SSP2 and RCP6.0 modules Source: Ricke et al. (2020).

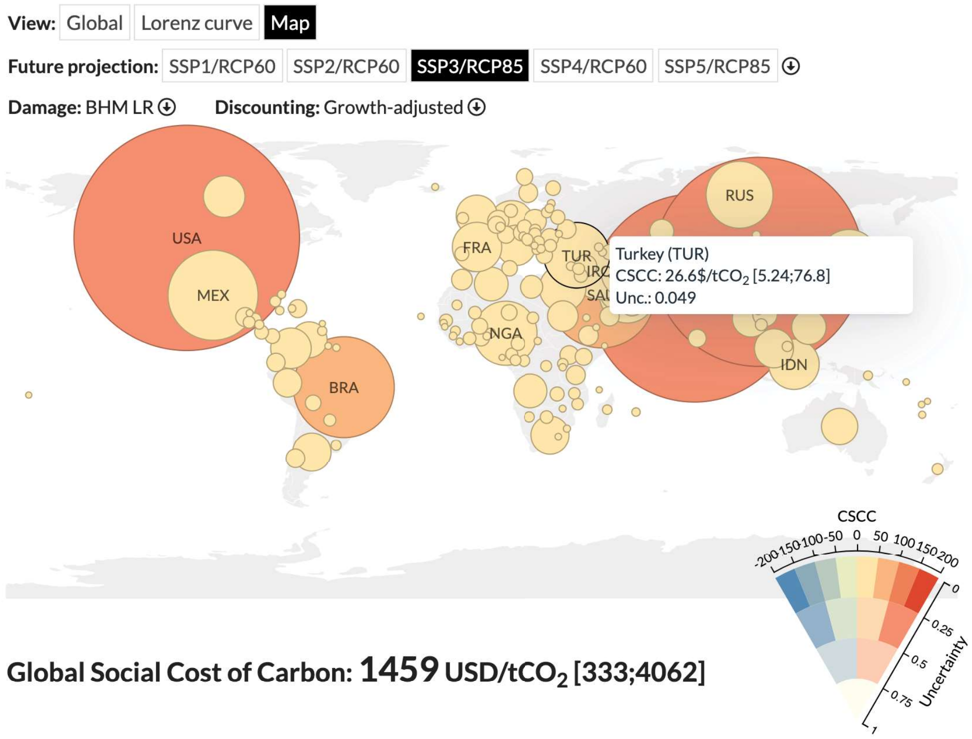


**Figure 3.9:** Country-level social cost of carbon considering SSP3 and RCP8.5 modules Source: Ricke et al. (2020).

We used the work of Zhang et al. (2014) to obtain carbon emission rates (g) of bus types in different routes and periods. We consider the tank-to-wheel (TTW) stage while calculating opportunity, overnight electric and fuel-cell hydrogen buses' $CO_2$ emissions. Emission is zero for opportunity electric, overnight electric and fuel-cell hydrogen buses. Well-to-tank (WTT) stage, which contains carbon emissions through energy production methods, storage and dispatching of energy, is ignored. We calculated the relative $CO_2$ emission factor of bus types in each route and period based on the average speed (see Table 3.8). Then, Equation (3.7) is used to calculate a distance-specific emission factor (g/km).

**Table 3.8:** Correlation between relative $CO_2$ emission rate and average speed.

| Bus Type | Relative $CO_2$ emission rate $y$ based on average speed $x$ |
|---|---|
| DIESEL12 EURO2 | $y = 2.7627x^{-0.3332}$ |
| DIESEL12 EURO3 | $y = 1.5601 - 3.3274 \cdot 10^{-2}x + 3.6855 \cdot 10^{-4}x^2$ |
| DIESEL12 EURO4 | $y = 2.5110 - 1.2544 \cdot 10^{-1}x + 2.4601 \cdot 10^{-3}x^2$ |
| DIESEL12 EURO5 | $y = 5.5949x^{-0.5618}$ |
| CNG12 | $y = 8.4604x^{-0.7249}$ |
| HYBRID12 | $y = 1.8753 - 3.8274 \cdot 10^{-2}x - 1.0516 \cdot 10^{-4}x^2$ |

Source: Zhang et al. (2014)

In Equation (3.7), $REF_{CO_2 i}$ is the relative $CO_2$ emission factor, $EF_{CO_2 i}$ is the distance-specific $CO_2$ emission factor of cycle $i$ (g/km) and $EF_{CO_2 0}$ is the distance-specific $CO_2$ emission factor under a baseline driving cycle (g/km) (see Zhang et al. (2014) for further information).

$$REF_{CO_2 i} = \frac{EF_{CO_2 i}}{EF_{CO_2 0}}. \tag{3.7}$$

A Lorenz curve is typically used to depict the income distribution versus population. Figure 3.10 shows a Lorenz curve adapted to the social cost of carbon. Share of Turkey is high which corresponds to high social cost of carbon per capita. Countries including Turkey, Iraq, Mexico, United States, United Arab Emirates, Saudi Arabia, Israel, and Kuwait are the most affected countries with additional tons of $CO_2$ emissions. We used the unit social cost of carbon ($0.891 per kg) and $CO_2$ emission rates in Table 3.8 to create carbon emissions for each bus type (see Tables B.1 and B.2 in Appendix B).

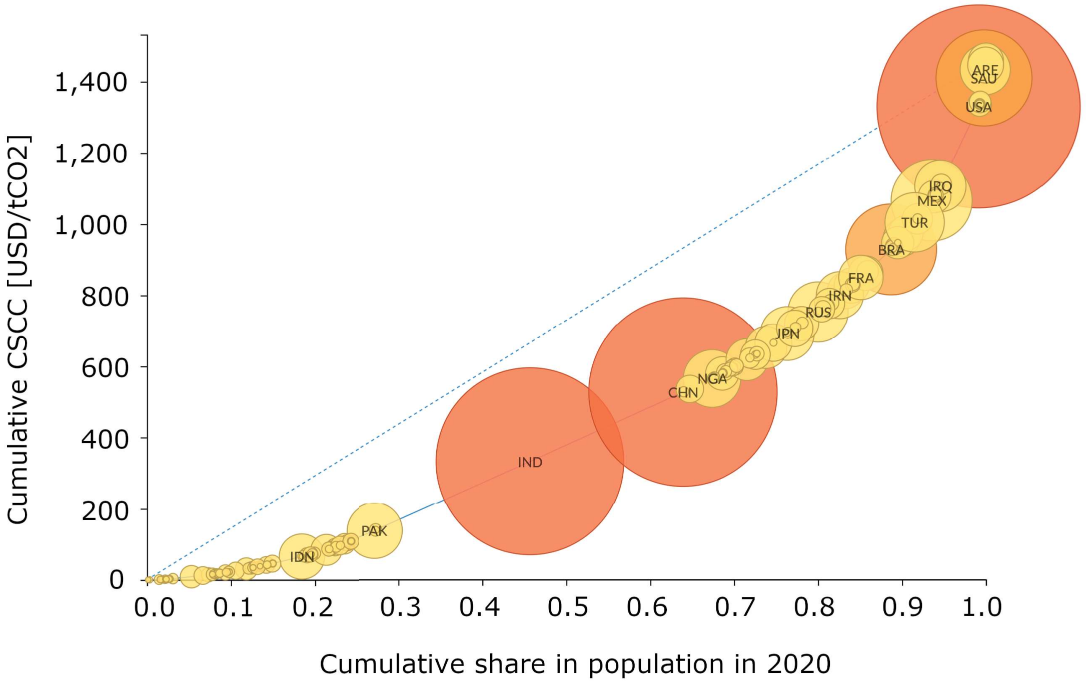


**Figure 3.10:** Cumulative country-level social cost of carbon versus country population Source: Ricke et al. (2020).

### 3.2.8 Maintenance Costs

We used the report by Worldbank (2019) to obtain maintenance costs (in $/km) for different bus types (see Tables C.1 and C.2 in Appendix C). The report includes maintenance costs in different cities such as Buenos Aires, Mexico City, etc. Hydrogen fuel-cell and 18-meter bus types are, unfortunately, not included in the report. There is no study, to our knowledge, that covers maintenance costs of different bus types in Turkey. We decided to use Mexico City data set because it covers nearly all of the bus types that we consider. In order to generate the maintenance costs for the 18-meter buses, we used the fact that 18-meter buses have more components than 12-meter buses and scaled the maintenance costs for 12-meter buses proportionally with a factor of 1.5 for the 18-meter buses. Maintenance costs for the hydrogen fuel-cell buses are obtained from the paper by Stempien and Chan (2016).

### 3.2.9 Driver Costs

Each driver is paid based on the time spent driving. We obtained the bus driver salary data from local newspapers (see, e.g., Haber 7 (2012)). Using an exchange rate of 8.68 in 3 July 2021, the monthly salary of a bus driver is calculated as \$690.14 per month. Assuming 208 hours of work in a month with 26 working days, and 8 working hours in a day results in a cost rate of \$0.0553 per minute for a driver. This rate is different for every route and period because the tour duration is different for every route and every period. Service duration in each route was multiplied by this rate to obtain driver cost per tour in every period (see Table 3.9). The omitted periods in rows and empty cells in Table 3.9 indicate that there is no service.

**Table 3.9:** Driver costs (\$/tour).

| Period ($p$) | Route 1 | Route 2 | Route 3 | Route 4 |
|---|---|---|---|---|
| 4 | 0.831 | | 1.108 | |
| 7 | 0.831 | | | |
| 8 | | | 1.108 | |
| 10 | 0.831 | | | 0.831 |
| 11 | | 1.108 | | |
| 12 | 0.831 | | 1.108 | |
| 14 | 1.108 | 1.108 | | 0.831 |
| 15 | 1.108 | | | |
| 16 | | | 1.385 | |
| 17 | 1.108 | 1.385 | | |
| 18 | | | | 1.108 |
| 19 | 1.108 | 1.385 | | |
| 20 | | | 1.385 | |

### 3.2.10 Turned-Away Passenger Cost

As we mentioned earlier, the passenger demand is stochastic in reality and it fluctuates over time. Unfortunately, passenger demand data were not disclosed by ESHOT. To ensure a predetermined level of service, we penalize the quantity of passengers turned-away due to full capacity. We assume that a passenger who is unable to board travels to her destination by a cab. This cost (see Table 3.10) is determined according to the cab rate which is based on the route length. The bus-ticket price is subtracted from this cost since the passenger will not pay for a bus ticket.

**Table 3.10:** Turned-away passenger costs ($/passenger).

| Period ($p$) | Route 1 | Route 2 | Route 3 | Route 4 |
|---|---|---|---|---|
| 4 | 4.563 | | 4.667 | |
| 7 | 4.563 | | | |
| 8 | | | 4.667 | |
| 10 | 4.563 | | | 4.197 |
| 11 | | 4.557 | | |
| 12 | 4.563 | | 4.667 | |
| 14 | 4.563 | 4.557 | | 4.197 |
| 15 | 4.563 | | | |
| 16 | | | 4.667 | |
| 17 | 4.563 | 4.557 | | |
| 18 | | | | 4.197 |
| 19 | 4.563 | 4.557 | | |
| 20 | | | 4.667 | |

### 3.2.11 First Cost and Market Values

First cost refers to the purchase cost of a bus. We obtained the first costs of buses from the works of Lajunen and Lipman (2016), Civitas (2016), Ercan et al. (2015), Ercan and Tatari (2015) and Ally and Pryor (2016). We used the average of the reported values as the estimated first cost. First costs of 12-meter diesel, CNG, hybrid, opportunity electric, overnight electric and hydrogen fuel-cell buses were determined respectively as $302,000, $340,000, $420,000, $515,000, $765,000 and $900,000. We assumed that the first cost of an 18-meter bus is 1.5 times that of a standard-length bus. In addition, we assumed that the market values decrease by 12% every year.

### 3.2.12 Bus Life

According to the Federal Transit Administration (Li and Head, 2009), the useful life of a transit bus is 12 years and 500,000 miles (804,672 km). Thus, we assumed each bus has a life of 12 years, which is also taken as the study period for the replacement and retention analysis.

# CHAPTER 4

# MATHEMATICAL MODELS

In this chapter, we present our modeling approach for designing an optimal public city bus fleet for a given set of routes by determining the quantity and assortment of different bus types that minimizes the total ownership costs over a study period. There are various modeling approaches for our decision problems. In particular, many parameters (including but not limited to passenger demand, traffic intensity, maintenance and repair-related data, etc.) are stochastic in reality. Therefore, simulation-optimization is a worthwhile approach to determine bus-type-specific performances under various conditions. Unfortunately, general-use simulation software may capture only a portion of the involved stochasticity, and transportation activities that depend on vehicle characteristics require using expensive and specialized proprietary simulation software and applications. Additionally, many parameters specific to a bus type are not disclosed by the manufacturers, and even if we had access to specialized simulation software, the corresponding missing data would have hindered the accuracy and usefulness of the simulation approach. Consequently, we decided to use a deterministic approach via mathematical programming.

Recall that İzmir ESHOT's public city bus regional service area (i.e., district 4) is selected for the numerical study. Decision problems pertaining to the assignment, quantity of bus types and replacement/retention create a large-scale mathematical model that cannot be solved within a reasonable amount of time. Therefore, we decided to create a "daily model" to capture the first set of decisions, i.e., excluding replacement and retention decisions. Note that, purchasing, salvaging and other replacement/retention related costs are not considered in the cost objective of the daily model. In particular, we formulated a mixed-integer linear program (MIP). The daily model has 2,264,000 binary variables, 4,444 real variables and 3,571,028 constraints. In other words, the resulting daily model is still large scale and cannot be solved within a reasonable amount of time. Therefore, we broke down these decision problems into two stages:

- *Stage 1.* Determine the daily cost-minimizing quantity of buses to operate in a route group given a particular type of bus. Obtain the optimal daily quantities and costs for each bus type and route group. This stage is modeled using mixed-integer linear program, whose details are given in Section 4.1.
- *Stage 2.* Scale the optimal daily costs obtained from Stage 1 to annual costs,

include first cost and market values to determine the optimal replacement and retention decisions over a study period of 12 years. This stage is modeled using shortest path formulation, whose details are given in Section 4.2.

In what follows, we first state our model-specific assumptions additional to those stated in relation to the data (see Section 4.2), and then continue with the mathematical programming formulations.

A1. Only one type of bus can be operated on a route.
A2. All passengers are boarded at the first stop of routes.
A3. The charging infrastructure deployment cost of opportunity, overnight and hydrogen fuel cell buses are not included in the total cost.

## 4.1 FLEET SIZE OPTIMIZATION FOR ROUTE GROUPS

We formulate an MIP model to calculate the optimal daily costs and quantities for each bus type and route group. Table 4.1 lists our indices, sets and parameters.

**Table 4.1:** Indices, sets and parameters used in the MIP model.

| | | |
|---|---|---|
| **Indices** | | |
| $i$ | Bus indices (based on unique license plates) | $i = 1, 2, \ldots, 60$ |
| $p, p'$ | Periods | $p, p' = 1, 2, \ldots, 232$ |
| $r$ | Routes | $r = 1, 2, \ldots, 84$ |
| $b$ | Bus types | $b = 1, 2, \ldots, 17$ |
| **Sets** | | |
| $R1$ | Set of first leg of round tours | $R1 = \{1, 3, 5, \ldots, 83\}$ |
| $R2$ | Set of second leg of round tours | $R2 = \{2, 4, 6, \ldots, 84\}$ |
| $PP_r$ | $\{(p, p') : (p, p')$ are starting period index tuples for round trips on route $r$, $r \in R1\}$ | |
| **Infrastructure and Route Related Parameters** | | |
| $\Delta$ | Period length between consecutive services (5 minutes) | |
| $L_r$ | Total length of route $r$ (km) | $r = 1, 2, \ldots, R$ |
| $P_r$ | Number of periods in route $r$ | $r = 1, 2, \ldots, R$ |
| $G_r$ | Road grade weight parameter of route $r$ | $r = 1, 2, \ldots, R$ |
| $V_{rp}$ | Average speed within speed limits on route $r$ starting in period $p$ (km/hr) | $r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |
| $N_{rp}$ | Service duration of route $r$ starting in period $p$, $N_{rp} \geq 60 \cdot L_r / (\Delta \cdot V_{rp})$ | $r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |
| $D_{rp}$ | Passenger demand in route $r$ and period $p$ | $r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |

**Table 4.1:** Indices, sets and parameters used in MIP (continued).

| | | |
|---|---|---|
| **Passenger Related Parameters** | | |
| $\alpha$ | Upper bound on percentage of passengers turned back (0.10) | |
| $C_i$ | Passenger capacity of bus $i$ | $i = 1, 2, \ldots, I$ |
| **Operating and Maintenance Costs** | | |
| $MC_{ir}$ | Maintenance cost during the tour serviced by bus $i$ at route $r$ (\$/tour) | $i = 1, 2, \ldots, I$;<br>$r = 1, 2, \ldots, R$ |
| $DC_{rp}$ | Driver cost of route $r$ in period $p$ (\$/tour) | $r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |
| $OC_{irp}$ | Operating cost during the tour serviced by bus $i$ at route $r$ that starts at period $p$ (\$/tour) | $i = 1, 2, \ldots, I$;<br>$r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |
| $EC_{irp}$ | Carbon emission cost during the tour serviced by bus $i$ at route $r$ that starts at period $p$ (\$/tour) | $i = 1, 2, \ldots, I$;<br>$r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |
| $AC$ | Setup cost of assigning a bus to a route group per day (\$2) | |
| **Passenger Related Costs** | | |
| $PC_{rp}$ | Unit penalty cost per turned-away passenger at route $r$ in period $p$ | $r = 1, 2, \ldots, R$;<br>$p = 1, 2, \ldots, P$ |

Our decision variables are as follows:

$\delta_{rp}$ = Number of passengers turned-away on route $r$ in period $p$

$$x_{irp} = \begin{cases} 1 & \text{if bus } i \text{ is assigned to route } r \text{ in period } p \\ 0 & \text{otherwise} \end{cases}$$

$$w_{ir} = \begin{cases} 1 & \text{if bus } i \text{ is assigned to route } r \\ 0 & \text{otherwise} \end{cases}$$

The objective in (4.1) minimizes the setup, operating, emission, maintenance, driver and turned-away passenger costs. Constraints are given in (4.2) through (4.15) with explanations before them.

$$\text{Minimize} \quad \left\{ \sum_{i=1}^{I} \sum_{r=1}^{R} AC \cdot w_{ir} \; + \; \sum_{i=1}^{I} \sum_{r=1}^{R} \sum_{p=1}^{P} (OC_{irp} + EC_{irp} + MC_{ir} + DC_{rp}) \cdot x_{irp} + \sum_{r=1}^{R} \sum_{p=1}^{P} PC_{rp} \cdot \delta_{rp} \right\}. \tag{4.1}$$

Each bus can be assigned to at most one route in each period.

$$\sum_{r=1}^{R} x_{irp} \leq 1 \qquad \forall i, p \tag{4.2}$$

Each bus can be assigned to at most one route except for the round tours.

$$w_{ir} + \sum_{r' \in R2 : r' \neq r+1} w_{ir'} \leq 1 \qquad \forall i, r \in R1 \tag{4.3}$$

$$w_{ir} + \sum_{r' \in R1 : r' \neq r-1} w_{ir'} \leq 1 \qquad \forall i, r \in R2 \tag{4.4}$$

$$\sum_{r \in R1} w_{ir} \leq 1 \qquad \forall i \tag{4.5}$$

$$\sum_{r \in R2} w_{ir} \leq 1 \qquad \forall i \tag{4.6}$$

Number of assignments for each bus cannot exceed the number of periods on a route.

$$\sum_{p=1}^{P} x_{irp} \leq P_r \cdot w_{ir} \qquad \forall i, r \tag{4.7}$$

$$w_{ir} \leq \sum_{p=1}^{P} x_{irp} \qquad \forall i, r \tag{4.8}$$

If bus $i$ is assigned to route $r$ starting in period $p$, this bus cannot be assigned to any period $p'$ until its service ends.

$$x_{irp} + \sum_{p''=p+1}^{p'-1} x_{irp''} + \sum_{p''=p+1}^{p'-1} x_{i,r+1,p''} \leq 1 \qquad \forall i, r : r \in R1, p, p' : p' \in PP_r \tag{4.9}$$

$$x_{irp} + \sum_{p''=p+1}^{p+N_{rp}-1} x_{irp''} + \sum_{p''=p+1}^{p+N_{rp}-1} x_{i,r-1,p''} \leq 1 \qquad \forall i, r : r \in R2, p \tag{4.10}$$

If bus $i$ is assigned to the first leg $r$ in period $p$, it must also be assigned to the second leg of the same round tour. Hence, this constrain set ensures round-trip connections.

$$x_{irp} = x_{i,r+1,p'} \qquad \forall i, \;\; r \in R1, \;\; (p, p') \in PP_r \tag{4.11}$$

Passengers boarding at route $r$ in period $p$ cannot exceed the assigned bus $i$'s capacity.

$$D_{rp} - \delta_{rp} \leq \sum_{i=1}^{I} C_i \cdot x_{irp}, \qquad \forall r, p \tag{4.12}$$

Number of turned-away passengers must not exceed a predefined bound on a route.

$$\sum_{p=1}^{P} \delta_{rp} \leq \alpha \cdot \sum_{p=1}^{P} D_{rp} \qquad \forall r \qquad (4.13)$$

Sign and type restrictions.

$$x_{irp}, w_{ir} \in \{0, 1\} \qquad \forall i, r, p \qquad (4.14)$$

$$\delta_{rp} \in \mathbb{R}^{+} \qquad \forall r, p \qquad (4.15)$$

## 4.2 REPLACEMENT AND RETENTION DECISIONS

We use a shortest path formulation in order to determine the optimal replacement and retention decisions over a 12-year study period. Recall that the optimal daily costs and bus quantities are obtained from the solution to the MIP model in Section 4.1. These optimal daily values are used, upon scaling, as part of the inputs for the shortest path model.

We annualize the daily costs (multiplied by 365) and include the first costs and market values of buses in the shortest path model formulation. Optimal bus quantities are also multiplied by the unit first cost to obtain total initial cost. A network representation of the shortest path problem is depicted in Figure 4.1.

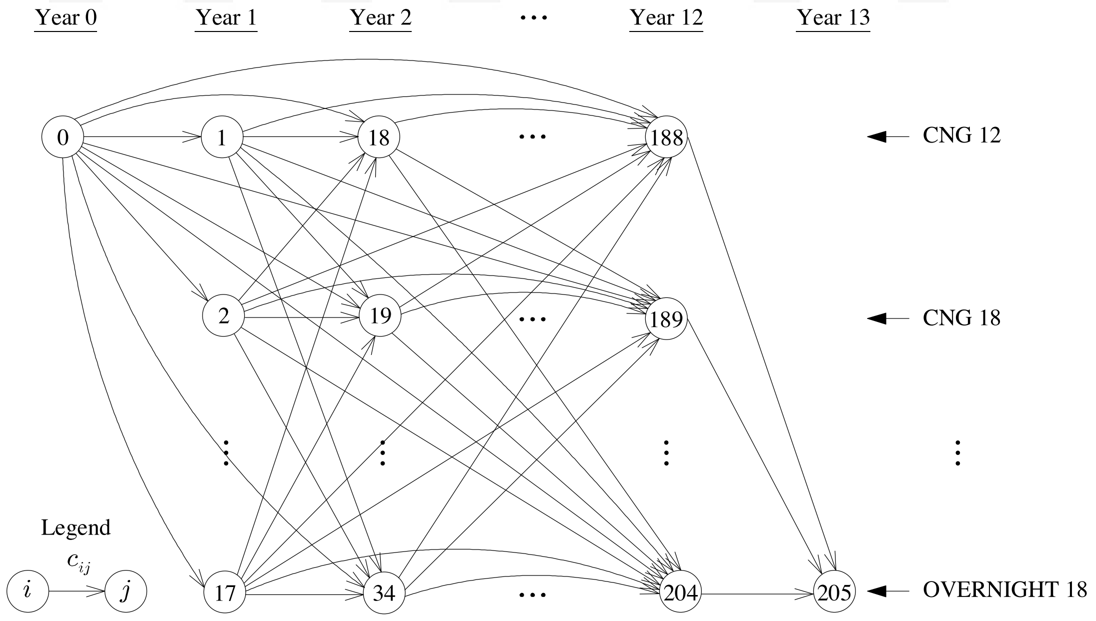


**Figure 4.1:** Shortest path network representation over a study period of 12 years.

An arc $(i, j)$ indicates that a set of particular type of buses is purchased at the beginning of year $i$ and kept until the beginning of year $j$. In Figure 4.1, the nodes in a row correspond to bus types, whereas the nodes in a column correspond to years.

The cost $(c_{ij})$ on an arc $(i, j)$ is the corresponding cost in net present value (NPV). For example, $\mathrm{c}_{01}$ is the cost of purchasing CNG12 at the beginning of year 0 and keeping it until the beginning of year 1. $\mathrm{c}_{0,18}$ is the cost of purchasing CNG 12 at the beginning of year 0 and keeping it until beginning of year 2. Equations (4.16) and (4.17) show the corresponding economic elements for calculating these arc costs:

$$c_{0,1} = FC_0 + OM_1 - SV_1, \tag{4.16}$$

$$c_{0,18} = FC_0 + OM_1 + OM_2 - SV_2, \tag{4.17}$$

where, $FC_0$ is the first cost at the beginning of year 0, $OM_1$ is the operating cost in year one, $OM_2$ is the operating costs in year two, $SV_1$ and $SV_2$ are the salvage values at the end of years one and two, respectively.

Recall that the time value of money is taken into account using NPV as the basis in the shortest path formulation. An annual interest rate of 5% is used to calculate the NPV of operating costs $(OM)$, first cost $(FC)$ and salvage value $(SV)$. Arc cost calculation examples over a four-year study period are provided in Table E.1 in Appendix E.

We now explain how various costs are estimated. First, we converted the daily $OM$ costs into annual values for year one. Then, we used the Consumer Price Index (CPI) from the U.S. Bureau of Labor Statistics (2021) to estimate $FC$, $OM$ and $SV$ values in the remaining years of the study period. In particular, we calculated the average of increase in the CPI for a 20-year period, that is between the years of 2000 and 2020, to obtain more accurate forecasts (see Table 4.2). This average is applied over a study period of 12 years (see Table 4.3). For the operating and bus assignment cost, we used fuel CPI. For the maintenance cost, we used the maintenance CPI. For the first cost, we used the new vehicle CPI, and for the emission, driver, and turned-away passenger costs, we used the relevant CPI values from the U.S. Bureau of Labor Statistics (2021).

**Table 4.2:** Consumer price indexes of the U.S. between years of 2000 and 2020.

| Year | All Items | Electricity | New Vehicles | Motor Fuel | Maintenance |
|---|---|---|---|---|---|
| 2000 | 172.20 | 128.50 | 142.80 | 129.30 | 177.30 |
| 2001 | 177.10 | 137.80 | 142.10 | 124.70 | 183.50 |
| 2002 | 179.90 | 136.20 | 140.00 | 116.60 | 190.20 |
| 2003 | 184.00 | 139.50 | 137.90 | 135.80 | 195.60 |
| 2004 | 188.90 | 142.10 | 137.10 | 160.40 | 200.20 |
| 2005 | 195.30 | 150.80 | 137.90 | 195.70 | 206.90 |
| 2006 | 201.60 | 169.20 | 137.60 | 221.00 | 215.60 |
| 2007 | 207.34 | 175.83 | 136.25 | 239.07 | 222.96 |
| 2008 | 215.30 | 187.15 | 134.19 | 279.65 | 233.86 |
| 2009 | 214.54 | 192.71 | 135.62 | 201.98 | 243.34 |
| 2010 | 218.06 | 193.10 | 138.01 | 239.18 | 247.95 |
| 2011 | 224.94 | 196.74 | 141.88 | 302.62 | 253.10 |
| 2012 | 229.59 | 196.63 | 144.23 | 312.66 | 257.58 |
| 2013 | 232.96 | 200.75 | 145.78 | 303.85 | 261.64 |
| 2014 | 236.74 | 208.02 | 146.28 | 292.44 | 266.03 |
| 2015 | 237.02 | 209.19 | 147.14 | 213.06 | 270.72 |
| 2016 | 240.01 | 206.98 | 147.36 | 188.39 | 275.35 |
| 2017 | 245.12 | 211.44 | 146.99 | 212.72 | 280.83 |
| 2018 | 251.11 | 212.93 | 146.29 | 241.86 | 286.36 |
| 2019 | 255.66 | 213.36 | 146.83 | 233.23 | 296.00 |
| 2020 | 258.81 | 214.62 | 147.60 | 195.24 | 305.99 |
| Average Change | 4.33 | 4.31 | 0.24 | 3.30 | 6.43 |

**Table 4.3:** Forecasts of consumer price indexes in U.S. in 2021 through 2031.

| | | All Items | | Electricity | | New Vehicles | | Motor Fuel | | Maintenance | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Node | CPI | Ratio | CPI | Ratio | CPI | Ratio | CPI | Ratio | CPI | Ratio |
| 2021 | 2 | 263.14 | 1.0167 | 218.92 | 1.0201 | 147.84 | 1.0016 | 198.54 | 1.0169 | 312.42 | 1.0210 |
| 2022 | 3 | 267.47 | 1.0335 | 223.23 | 1.0401 | 148.08 | 1.0033 | 201.84 | 1.0338 | 318.86 | 1.0421 |
| 2023 | 4 | 271.80 | 1.0502 | 227.53 | 1.0602 | 148.32 | 1.0049 | 205.13 | 1.0507 | 325.29 | 1.0631 |
| 2024 | 5 | 276.13 | 1.0669 | 231.84 | 1.0803 | 148.56 | 1.0065 | 208.43 | 1.0675 | 331.73 | 1.0841 |
| 2025 | 6 | 280.46 | 1.0837 | 236.14 | 1.1003 | 148.80 | 1.0081 | 211.73 | 1.0844 | 338.16 | 1.1051 |
| 2026 | 7 | 284.79 | 1.1004 | 240.45 | 1.1204 | 149.04 | 1.0098 | 215.02 | 1.1013 | 344.60 | 1.1262 |
| 2027 | 8 | 289.12 | 1.1171 | 244.76 | 1.1404 | 149.28 | 1.0114 | 218.32 | 1.1182 | 351.03 | 1.1472 |
| 2028 | 9 | 293.46 | 1.1339 | 249.06 | 1.1605 | 149.52 | 1.0130 | 221.62 | 1.1351 | 357.47 | 1.1682 |
| 2029 | 10 | 297.79 | 1.1506 | 253.37 | 1.1806 | 149.76 | 1.0146 | 224.92 | 1.1520 | 363.90 | 1.1893 |
| 2030 | 11 | 302.12 | 1.1673 | 257.67 | 1.2006 | 150.00 | 1.0163 | 228.21 | 1.1689 | 370.34 | 1.2103 |
| 2031 | 12 | 306.45 | 1.1841 | 261.98 | 1.2207 | 150.24 | 1.0179 | 231.51 | 1.1858 | 376.77 | 1.2313 |

Indices, sets, and parameters of the shortest path formulation are given in Table 4.4.

**Table 4.4:** Indices, sets and parameters of the shortest path formulation.

| | | |
|---|---|---|
| **Indices** | | |
| $i$ | Initial node | $i = 0, 1, \ldots, 205$ |
| $j$ | Terminal node | $j = 0, 1, \ldots, 205$ |
| **Sets** | | |
| $A$ | Set of arcs $(i, j)$ | $(i, j) = \{(0, 0), (0, 1), \ldots, (205, 205)\}$ |
| **Parameters** | | |
| $c_{ij}$ | Total cost from node $i$ to node $j$ (\$) | $i, j = 0, 1, \ldots, 205$ |
| $a_{ij}$ | 1 if there is an arc from node $i$ to node $j$, zero otherwise | $i, j = 0, 1, \ldots, 205$ |

For the shortest path formulation, we use the typical binary decision variable definitions as given below. However, due to the special structure of the shortest path formulation, we use linear programming for the solution of the model.

$$y_{ij} = \begin{cases} 1 & \text{if bus type is used on arc } (i, j) \\ 0 & \text{otherwise} \end{cases}$$

The shortest path model is as follows:

$$\text{Minimize} \sum_{(i,j) \in A} c_{ij} \cdot y_{ij} \tag{4.18}$$

Subject to

$$\sum_{i=0}^{205} a_{ji} \cdot y_{ji} - \sum_{i=0}^{205} a_{ij} \cdot y_{ij} = 1, \qquad j = 0 \tag{4.19}$$

$$\sum_{i=0}^{205} a_{ji} \cdot y_{ji} - \sum_{i=0}^{205} a_{ij} \cdot y_{ij} = 0, \qquad j = 1, 2, \ldots, 204 \tag{4.20}$$

$$\sum_{i=0}^{205} a_{ji} \cdot y_{ji} - \sum_{i=0}^{205} a_{ij} \cdot y_{ij} = -1, \qquad j = 205 \tag{4.21}$$

$$y_{ij} \geq 0, \qquad \forall (i, j) \in A \tag{4.22}$$

The objective in (4.18) minimizes total cost of bus fleet ownership during the study period of 12 years. Constraints of the model are given in (4.19) through (4.22). Constraint (4.19) is the flow balance at node 0. Constraint set (4.20) presents the flow balance at nodes 1–204. Constraint (4.21) is the flow balance at the terminal node 205. Constraint set (4.22) shows the sign and type restrictions on the decision variables. The solutions to both mathematical programming formulations will be discussed in Chapter 5.

# CHAPTER 5

# DISCUSSION OF THE MODEL SOLUTIONS

The solutions and their discussions for the two models, i.e., the MIP model given in Section 4.1 and the shortest path model given in Section 4.2, will be provided in this chapter. All models are solved on a computer equipped with Intel(R) Xeon(R) CPU E5-2620 2.0GHz processor and 88GB RAM.

We used CPLEX to solve the MIP model discussed in Section 4.1. We note that we have 357 models considering the 21 route groups and 17 bus types. Model sizes and solution times are given in Table F.1 in Appendix F. Equations (5.1)–(5.10) below provide the explanations and formulations of the outputs obtained from the CPLEX solver.

*Daily operating cost:*
$$\text{opcost} = \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{p=1}^{P} OC_{irp} \cdot x_{irp} \tag{5.1}$$

*Daily emission cost:*
$$\text{emcost} = \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{p=1}^{P} EC_{irp} \cdot x_{irp} \tag{5.2}$$

*Daily maintenance cost:*
$$\text{macost} = \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{p=1}^{P} MC_{ir} \cdot x_{irp} \tag{5.3}$$

*Daily driver cost:*
$$\text{dricost} = \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{p=1}^{P} DC_{rp} \cdot x_{irp} \tag{5.4}$$

*Daily turned-away passenger cost:*
$$\text{tapcost} = \sum_{r=1}^{R}\sum_{p=1}^{P} PC_{rp} \cdot \delta_{rp} \tag{5.5}$$

*Daily total distance travelled:*
$$\text{tmil} = \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{p=1}^{P} L_{r} \cdot x_{irp} \tag{5.6}$$

*Time spent in service per day:*
$$\text{ttime} = \Delta \sum_{i=1}^{I}\sum_{r=1}^{R}\sum_{p=1}^{P} N_{rp} \cdot x_{irp} \tag{5.7}$$

*Daily number of passengers transported:*
$$\text{tboar} = \sum_{r=1}^{R}\sum_{p=1}^{P} (D_{rp} - \delta_{rp}) \tag{5.8}$$

*Daily number of passengers turned-away:*
$$\text{ttap} = \sum_{r=1}^{R}\sum_{p=1}^{P} \delta_{rp} \tag{5.9}$$

*Daily number of buses operated:*

$$\text{nbus} = \sum_{i=1}^{I} \sum_{r=1}^{R} w_{ir} \tag{5.10}$$

Table 5.1 summarizes the daily MIP model results for route groups G1–G4 using CNG 12 buses and the corresponding annualized values.

**Table 5.1:** Summary of MIP results and solution statistics for route groups G1–G4 using CNG 12 (first cost: $340,000.00).

| | G1 | G2 | G3 | G4 |
|---|---|---|---|---|
| **Daily Model** | | | | |
| Solution time (seconds) | 99.61 | 156.75 | 653.89 | 52.22 |
| Deterministic time (seconds) | 35,720.29 | 51,467.15 | 208,794.08 | 17,909.09 |
| Objective ($/day) | 1,140.16 | 1,795.46 | 2,739.37 | 2,186.89 |
| opcost (OC, $/day) | 242.02 | 370.23 | 595.09 | 664.77 |
| emcost (EC, $/day) | 0.68 | 1.03 | 1.66 | 1.86 |
| macost (MC, $/day) | 599.54 | 925.63 | 1,430.17 | 1,028.47 |
| dricost (DC, $/day) | 263.92 | 411.26 | 602.34 | 437.01 |
| tapcost (PC, $/day) | 0 | 33.31 | 18.10 | 22.79 |
| tmil (km/day) | 1,809.42 | 2,747.66 | 4,328.73 | 3,024.91 |
| ttime (min/day) | 4,765 | 7,425 | 10,875 | 7,890 |
| tboar (passengers/day) | 10,275 | 14,492 | 24,416 | 12,129 |
| ttap (passengers/day) | 0 | 7 | 4 | 3 |
| nbus (units/day) | 17 | 27 | 46 | 16 |
| Number of periods per day | 101 | 136 | 226 | 115 |
| | | | | |
| **Annualized Values** | | | | |
| Objective ($/year) | 416,156.61 | 655,344.24 | 999,871.26 | 798,215.42 |
| opcost (OC, $/year) | 88,337.04 | 135,135.14 | 217,209.02 | 242,639.38 |
| emcost (EC, $/year) | 246.88 | 377.64 | 607.10 | 678.01 |
| macost (MC, $/year) | 218,830.49 | 337,854.80 | 522,013.00 | 375,391.33 |
| dricost (DC, $/year) | 96,332.19 | 150,108.40 | 219,855.74 | 159,509.13 |
| tapcost (PC, $/year) | 0 | 12,158.25 | 6,606.40 | 8,317.56 |
| tmil (km/year) | 660,438.30 | 1,002,895.90 | 1,579,986.45 | 1,104,092.15 |
| ttime (min/year) | 1,739,225 | 2,710,125 | 3,969,375 | 2,879,850 |
| tboar (passengers/year) | 3,750,375 | 5,289,580 | 8,911,840 | 4,427,085 |
| ttap (passengers/year) | 0 | 2,555 | 1,460 | 1,095 |
| nbus (units/year) | 17 | 27 | 46 | 16 |
| Number of periods per year | 36,865 | 49,640 | 82,490 | 41,975 |
| First Cost (FC, $/year) | 5,780,000 | 9,180,000 | 15,640,000 | 5,440,000 |

The results obtained from the MIP models, first costs and salvage values of bus types are used as inputs for the shortest path model. There are 206 nodes and 19,295 arcs in the shortest path model for each route group. We solved the shortest path model using CPLEX solver in GAMS. The solution time for a single model is between 0.109 and 0.344 seconds. Table 5.2 summarizes the solutions for the shortest path model.

**Table 5.2:** Shortest path model solution summary.

| Route Group | Bus Type Assigned | Total Cost ($) | Solution Time (sec) | Selected Arcs |
|---|---|---|---|---|
| G1 | DIESEL18 EURO5 | 7,675,755.89 | 0.109 | (0,196), (196,205) |
| G2 | DIESEL12 EURO5 | 13,097,010.00 | 0.125 | (0,193), (193,205) |
| G3 | DIESEL12 EURO5 | 21,245,500.00 | 0.110 | (0,193), (193,205) |
| G4 | DIESEL12 EURO5 | 11,617,980.00 | 0.125 | (0,193), (193,205) |
| G5 | DIESEL12 EURO5 | 7,165,712.14 | 0.109 | (0,193), (193,205) |
| G6 | DIESEL18 EURO5 | 14,793,570.00 | 0.109 | (0,196), (196,205) |
| G7 | DIESEL18 EURO5 | 20,556,960.00 | 0.125 | (0,196), (196,205) |
| G8 | OPPORTUNITY18 | 8,577,090.39 | 0.109 | (0,202), (202,205) |
| G9 | HYBRID12 | 9,044,408.63 | 0.125 | (0,197), (197,205) |
| G10 | DIESEL12 EURO5 | 16,067,740.00 | 0.344 | (0,193), (193,205) |
| G11 | DIESEL12 EURO5 | 7,690,122.32 | 0.109 | (0,193), (193,205) |
| G12 | DIESEL18 EURO5 | 5,034,954.18 | 0.109 | (0,196), (196,205) |
| G13 | DIESEL12 EURO5 | 7,980,947.81 | 0.156 | (0,193), (193,205) |
| G14 | DIESEL12 EURO5 | 10,981,030.00 | 0.141 | (0,193), (193,205) |
| G15 | HYBRID12 | 6,373,788.33 | 0.109 | (0,197), (197,205) |
| G16 | DIESEL12 EURO5 | 14,454,700.00 | 0.109 | (0,193), (193,205) |
| G17 | DIESEL18 EURO5 | 11,391,730.00 | 0.109 | (0,196), (196,205) |
| G18 | DIESEL12 EURO5 | 12,117,340.00 | 0.125 | (0,193), (193,205) |
| G19 | HYBRID12 | 21,466,330.00 | 0.109 | (0,197), (197,205) |
| G20 | DIESEL18 EURO5 | 11,237,150.00 | 0.109 | (0,196), (196,205) |
| G21 | DIESEL12 EURO5 | 8,900,493.54 | 0.110 | (0,193), (193,205) |

According to the results, each bus is purchased at the beginning of the first year and used for the 12 years of its service life, after which it is salvaged. Table 5.3 shows the bus types and quantities (see also Figures 5.1 and 5.2 for distributions) in the fleet as well as the total ownership costs. Accordingly, DIESEL12 EURO5 is assigned to 11 route groups out of 21 route groups. DIESEL18 EURO5 is assigned to six route groups. HYBRID12 is assigned to three route groups and OPPORTUNITY ELECTRIC18 is assigned to one route group. The fleet consists of 232 DIESEL12 EURO5, 77 DIESEL18 EURO5, 45 HYBRID12 and 6 OPPORTUNITY ELECTRIC18 buses.

Overall, CNG (12,18) DIESEL12 (EURO2, EURO3, EURO4), DIESEL18 (EURO2, EURO3), HYBRID18, OPPORTUNITY12, OVERNIGHT (12, 18), HYDROGEN FUEL CELL (12, 18) buses are not assigned to any of the 21 route groups. Due to the cost and limit placed on the turned-away passengers, 18-meter buses are assigned to the routes that have sufficiently high passenger demand. We also investigated the solutions based on the route characteristics (see Tables 5.4 and 5.5).

**Table 5.3:** Bus types, quantities and total ownership costs in route groups G1–G21.

| Route | DIESEL12 EURO5 | | DIESEL18 EURO5 | | HYBRID12 | | OPPORTUNITY18 | |
|---|---|---|---|---|---|---|---|---|
| Group | Quantity | TCO ($) | Quantity | TCO ($) | Quantity | TCO ($) | Quantity | TCO ($) |
| G1 | | | 9 | 7, 675, 755.89 | | | | |
| G2 | 27 | 13, 097, 010.00 | | | | | | |
| G3 | 46 | 21, 245, 500.00 | | | | | | |
| G4 | 16 | 11, 617, 980.00 | | | | | | |
| G5 | 15 | 7, 165, 712.14 | | | | | | |
| G6 | | | 17 | 14, 793, 570.00 | | | | |
| G7 | | | 20 | 20, 556, 960.00 | | | | |
| G8 | | | | | | | 6 | 8, 577, 090.39 |
| G9 | | | | | 11 | 9, 044, 408.63 | | |
| G10 | 23 | 16, 067, 740.00 | | | | | | |
| G11 | 13 | 7, 690, 122.32 | | | | | | |
| G12 | | | 5 | 5, 034, 954.18 | | | | |
| G13 | 18 | 7, 980, 947.81 | | | | | | |
| G14 | 15 | 10, 981, 030.00 | | | | | | |
| G15 | | | | | 8 | 6, 373, 788.33 | | |
| G16 | 19 | 14, 454, 700.00 | | | | | | |
| G17 | | | 13 | 11, 391, 730.00 | | | | |
| G18 | 24 | 12, 117, 340.00 | | | | | | |
| G19 | | | | | 26 | 21, 466, 330.00 | | |
| G20 | | | 13 | 11, 237, 150.00 | | | | |
| G21 | 16 | 8, 900, 493.54 | | | | | | |
| Total | 232 | 131, 318, 575.81 | 77 | 70, 690, 120.07 | 45 | 36, 884, 526.96 | 6 | 8, 577, 090.39 |

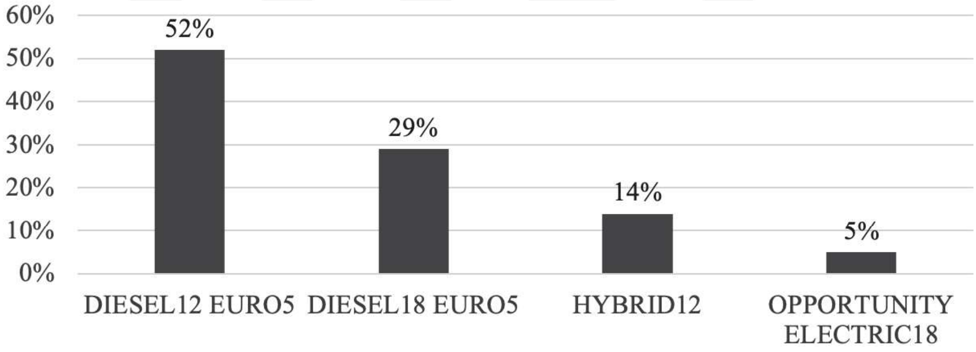


**Figure 5.1:** Distribution of bus types in the fleet using the base model.

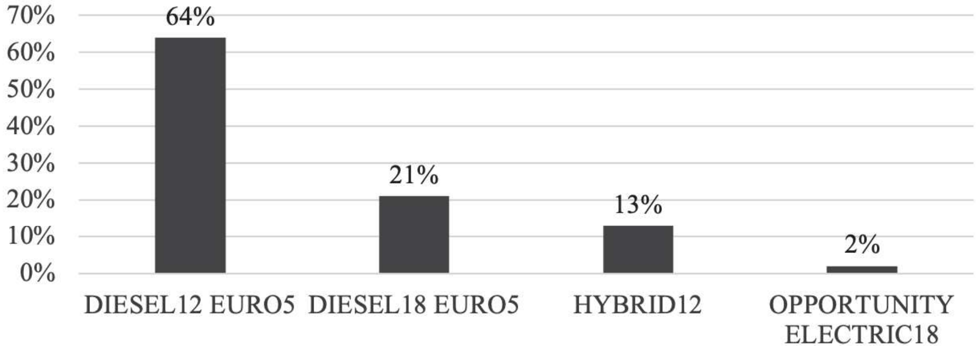


**Figure 5.2:** Distribution of bus quantities in the fleet using the base model.

**Table 5.4:** Solutions based on characteristics of route groups G1–G10.

| Route Group | Route | Bus Type Assigned | Weight Parameter | Group Average | Average Speed | Group Average | Route Length | Group Average |
|---|---|---|---|---|---|---|---|---|
| G1 | 1 | DIESEL18 EURO5 | 0.33 | 0.53 | 24.96 | 26.15 | 7.68 | 7.04 |
| | 2 | | 0.85 | | 24.66 | | 7.67 | |
| | 5 | | 0.32 | | 28.13 | | 6.65 | |
| | 6 | | 0.61 | | 26.86 | | 6.16 | |
| G2 | 3 | DIESEL12 EURO5 | 0.31 | 0.51 | 23.78 | 25.41 | 7.86 | 7.95 |
| | 4 | | 0.51 | | 26.65 | | 7.05 | |
| | 69 | | 0.52 | | 25.65 | | 8.68 | |
| | 70 | | 0.72 | | 25.56 | | 8.22 | |
| G3 | 7 | DIESEL12 EURO5 | 0.27 | 0.57 | 23.49 | 24.48 | 7.62 | 7.54 |
| | 8 | | 0.95 | | 24.28 | | 7.39 | |
| | 9 | | 0.33 | | 25.20 | | 7.69 | |
| | 10 | | 0.71 | | 24.95 | | 7.46 | |
| G4 | 11 | DIESEL12 EURO5 | 0.69 | 0.90 | 23.39 | 25.77 | 8.79 | 10.77 |
| | 12 | | 1.00 | | 28.28 | | 10.60 | |
| | 35 | | 0.48 | | 23.41 | | 10.80 | |
| | 36 | | 1.42 | | 27.99 | | 12.90 | |
| G5 | 13 | DIESEL12 EURO5 | 0.41 | 0.40 | 25.17 | 25.08 | 9.90 | 9.00 |
| | 14 | | 0.42 | | 25.86 | | 9.75 | |
| | 55 | | 0.36 | | 23.23 | | 8.12 | |
| | 56 | | 0.43 | | 26.08 | | 8.21 | |
| G6 | 15 | DIESEL18 EURO5 | 0.50 | 0.67 | 24.97 | 28.49 | 10.10 | 10.18 |
| | 16 | | 0.97 | | 29.42 | | 11.90 | |
| | 31 | | 0.42 | | 30.72 | | 9.49 | |
| | 32 | | 0.79 | | 28.84 | | 9.23 | |
| G7 | 17 | DIESEL18 EURO5 | 0.52 | 0.75 | 23.48 | 25.54 | 10.80 | 12.83 |
| | 18 | | 0.82 | | 27.51 | | 12.70 | |
| | 19 | | 0.62 | | 23.53 | | 12.80 | |
| | 20 | | 1.05 | | 27.64 | | 15.00 | |
| G8 | 21 | OPPORTUNITY18 | 2.20 | 1.74 | 22.53 | 23.43 | 33.60 | 26.20 |
| | 22 | | 2.65 | | 22.29 | | 34.10 | |
| | 23 | | 0.75 | | 26.30 | | 18.30 | |
| | 24 | | 1.34 | | 22.61 | | 18.80 | |
| G9 | 25 | HYBRID12 | 1.35 | 1.33 | 21.19 | 32.06 | 18.90 | 24.43 |
| | 26 | | 1.05 | | 20.88 | | 18.40 | |
| | 29 | | 1.60 | | 45.96 | | 28.90 | |
| | 30 | | 1.32 | | 40.23 | | 31.50 | |
| G10 | 27 | DIESEL12 EURO5 | 0.86 | 0.92 | 23.55 | 24.43 | 14.20 | 13.04 |
| | 28 | | 1.67 | | 27.11 | | 16.30 | |
| | 57 | | 0.55 | | 23.46 | | 11.80 | |
| | 58 | | 0.59 | | 23.60 | | 9.87 | |

**Table 5.5:** Solutions based on characteristics of route groups G11–G20.

| Route Group | Route | Bus Type Assigned | Weight Parameter | Group Average | Average Speed | Group Average | Route Length | Group Average |
|---|---|---|---|---|---|---|---|---|
| G11 | 33 | DIESEL12 EURO5 | 0.99 | 0.84 | 20.42 | 22.15 | 17.90 | 15.58 |
| | 34 | | 1.13 | | 25.11 | | 21.20 | |
| | 67 | | 0.54 | | 22.00 | | 11.80 | |
| | 68 | | 0.69 | | 21.08 | | 11.40 | |
| G12 | 37 | DIESEL18 EURO5 | 0.40 | 0.37 | 19.80 | 20.45 | 3.30 | 5.52 |
| | 38 | | 0.11 | | 15.96 | | 2.66 | |
| | 81 | | 0.22 | | 22.72 | | 8.12 | |
| | 82 | | 0.77 | | 23.31 | | 8.00 | |
| G13 | 39 | DIESEL12 EURO5 | 0.33 | 0.50 | 7.66 | 17.79 | 7.85 | 9.06 |
| | 40 | | 0.53 | | 15.51 | | 8.23 | |
| | 63 | | 0.48 | | 23.87 | | 9.95 | |
| | 64 | | 0.68 | | 24.09 | | 10.20 | |
| G14 | 41 | DIESEL12 EURO5 | 0.31 | 0.72 | 21.77 | 22.78 | 7.98 | 15.37 |
| | 42 | | 0.48 | | 19.96 | | 7.00 | |
| | 59 | | 0.91 | | 25.25 | | 23.30 | |
| | 60 | | 1.16 | | 24.12 | | 23.20 | |
| G15 | 43 | HYBRID12 | 0.23 | 4.63 | 21.10 | 23.45 | 5.78 | 5.95 |
| | 44 | | 0.83 | | 23.82 | | 5.64 | |
| | 79 | | 0.22 | | 24.84 | | 6.39 | |
| | 80 | | 17.23 | | 24.03 | | 5.98 | |
| G16 | 45 | DIESEL12 EURO5 | 0.52 | 0.75 | 24.53 | 24.57 | 10.60 | 11.63 |
| | 46 | | 0.98 | | 28.58 | | 12.40 | |
| | 49 | | 0.55 | | 22.12 | | 11.50 | |
| | 50 | | 0.96 | | 23.05 | | 12.00 | |
| G17 | 47 | DIESEL18 EURO5 | 0.39 | 0.55 | 28.30 | 27.17 | 10.70 | 10.29 |
| | 48 | | 0.55 | | 25.38 | | 8.48 | |
| | 53 | | 0.52 | | 25.04 | | 9.98 | |
| | 54 | | 0.76 | | 29.96 | | 12.00 | |
| G18 | 51 | DIESEL12 EURO5 | 0.59 | 0.55 | 22.03 | 23.02 | 12.40 | 10.12 |
| | 52 | | 0.77 | | 22.66 | | 12.30 | |
| | 65 | | 0.39 | | 23.29 | | 7.95 | |
| | 66 | | 0.44 | | 24.09 | | 7.81 | |
| G19 | 61 | HYBRID12 | 1.22 | 1.07 | 29.67 | 26.80 | 18.50 | 15.70 |
| | 62 | | 1.34 | | 29.11 | | 17.20 | |
| | 83 | | 0.69 | | 23.18 | | 13.60 | |
| | 84 | | 1.03 | | 25.25 | | 13.50 | |
| G20 | 71 | DIESEL18 EURO5 | 0.47 | 0.64 | 23.65 | 23.44 | 10.40 | 7.55 |
| | 72 | | 1.17 | | 23.89 | | 9.86 | |
| | 73 | | 0.41 | | 23.12 | | 5.17 | |
| | 74 | | 0.49 | | 23.11 | | 4.78 | |
| G21 | 75 | DIESEL12 EURO5 | 0.31 | 0.84 | 25.33 | 24.67 | 7.80 | 9.23 |
| | 76 | | 1.01 | | 24.47 | | 7.50 | |
| | 77 | | 0.76 | | 24.53 | | 11.20 | |
| | 78 | | 1.27 | | 24.35 | | 10.40 | |

Tables 5.4 and 5.5 show route characteristics (i.e., weight parameters in relation to the route grade, average speed and the route length) and the solutions obtained from the shortest path model. Opportunity electric buses and hybrid buses are assigned to the route groups having high weight parameters. The weight parameters of these four groups (G8, G9, G15, G19) are above one. Since the influence of average speed of bus to the fuel consumption for opportunity electric, overnight electric and hydrogen fuel cell are not included in the model, we cannot discuss the effect of the average speed on the bus assignment. Considering the average tour distance, it can be observed that the opportunity electric 18 and hybrid 12 buses are assigned to the two groups which have a length above a 20-kilometer average.

In Chapter 6, we discuss the impacts of changes in social cost of carbon and first costs on the results.

# CHAPTER 6

# FURTHER ANALYSIS OF REPLACEMENT AND RETENTION DECISIONS

In the previous chapter, we discussed the results of the MIP and the shortest path models. Regarding the shortest path model results, weight parameter (road grade) of route groups and route length are observed to have significant effects on the replacement decisions. In particular, hybrid buses are assigned to routes with weight parameters which are above one, while opportunity electric buses are assigned to routes with high weight parameter and route length. We can state that the replacement of conventional buses (DIESEL and CNG) with HYBRID, OPPORTUNITY and OVERNIGHT buses is highly dependent on the route characteristics. We now provide further analyses on the replacement and retention decisions considering changes in the social cost of carbon and the first cost, and provide a summary of our observations.

## 6.1 EFFECTS OF THE SOCIAL COST OF CARBON

In the MIP model, social cost of carbon, or emission cost, is taken as \$0.891 per ton (low level). In order to observe its effect on the bus fleet formation, we varied the social cost of carbon emissions from its low value to \$26.6 per ton (medium level), and then to \$50 per ton (high level).

After solving the models with modified carbon emission costs, we obtained the results shown in Tables 6.1 and 6.2. The solutions indicate that the emission cost in this range does not affect the types of buses assigned to route groups. In particular, even a factor of more than 50 from the low level leaves the overall social cost of carbon insignificant as compared to the levels of the other cost elements. In particular, the first costs constitute the largest of all cost elements. Therefore, this result is not surprising but hints that regulations should take pricing and valuation of carbon emissions very seriously into consideration.

Table 6.1: Effect of social cost of carbon on results for route groups G1–G11.

| Route Group | Carbon Cost Level | Bus Type Assigned | Total Cost ($) | Selected Arcs |
|---|---|---|---|---|
| G1 | Low | DIESEL18 EURO5 | 7,675,755.89 | (0,196), (196,205) |
| | Medium | DIESEL18 EURO5 | 7,751,427.51 | (0,196), (196,205) |
| | High | DIESEL18 EURO5 | 7,820,302.84 | (0,196), (196,205) |
| G2 | Low | DIESEL12 EURO5 | 13,097,010.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 13,197,330.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 13,288,640.00 | (0,193), (193,205) |
| G3 | Low | DIESEL12 EURO5 | 21,245,500.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 21,404,460.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 21,549,150.00 | (0,193), (193,205) |
| G4 | Low | DIESEL12 EURO5 | 11,617,980.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 11,796,670.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 11,959,310.00 | (0,193), (193,205) |
| G5 | Low | DIESEL12 EURO5 | 7,165,712.14 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 7,209,038.14 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 7,248,472.90 | (0,193), (193,205) |
| G6 | Low | DIESEL18 EURO5 | 14,793,570.00 | (0,196), (196,205) |
| | Medium | DIESEL18 EURO5 | 14,953,180.00 | (0,196), (196,205) |
| | High | DIESEL18 EURO5 | 15,098,450.00 | (0,196), (196,205) |
| G7 | Low | DIESEL18 EURO5 | 20,556,960.00 | (0,196), (196,205) |
| | Medium | DIESEL18 EURO5 | 20,854,790.00 | (0,196), (196,205) |
| | High | DIESEL18 EURO5 | 21,125,880.00 | (0,196), (196,205) |
| G8 | Low | OPPORTUNITY18 | 8,577,090.39 | (0,202), (202,205) |
| | Medium | OPPORTUNITY18 | 8,577,090.39 | (0,202), (202,205) |
| | High | OPPORTUNITY18 | 8,577,090.39 | (0,202), (202,205) |
| G9 | Low | HYBRID12 | 9,044,408.63 | (0,197), (197,205) |
| | Medium | HYBRID12 | 9,165,987.65 | (0,197), (197,205) |
| | High | HYBRID12 | 9,276,647.30 | (0,197), (197,205) |
| G10 | Low | DIESEL12 EURO5 | 16,067,740.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 16,315,170.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 16,540,370.00 | (0,193), (193,205) |
| G11 | Low | DIESEL12 EURO5 | 7,690,122.32 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 7,784,192.26 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 7,869,813.51 | (0,193), (193,205) |

**Table 6.2:** Effect of social cost of carbon on results for route groups G12–G21.

| Route Group | Carbon Cost Level | Bus Type Assigned | Total Cost ($) | Selected Arcs |
|---|---|---|---|---|
| G12 | Low | DIESEL18 EURO5 | 5,034,954.18 | (0,196), (196,205) |
| | Medium | DIESEL18 EURO5 | 5,085,653.67 | (0,196), (196,205) |
| | High | DIESEL18 EURO5 | 5,131,799.69 | (0,196), (196,205) |
| G13 | Low | DIESEL12 EURO5 | 7,980,947.81 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 8,037,089.44 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 8,088,188.83 | (0,193), (193,205) |
| G14 | Low | DIESEL12 EURO5 | 10,981,030.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 11,138,220.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 11,281,300.00 | (0,193), (193,205) |
| G15 | Low | HYBRID12 | 6,373,788.33 | (0,197), (197,205) |
| | Medium | HYBRID12 | 6,545,725.54 | (0,197), (197,205) |
| | High | HYBRID12 | 6,702,220.57 | (0,197), (197,205) |
| G16 | Low | DIESEL12 EURO5 | 14,454,700.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 14,658,070.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 14,843,170.00 | (0,193), (193,205) |
| G17 | Low | DIESEL18 EURO5 | 11,391,730.00 | (0,196), (196,205) |
| | Medium | DIESEL18 EURO5 | 11,505,110.00 | (0,196), (196,205) |
| | High | DIESEL18 EURO5 | 11,608,300.00 | (0,196), (196,205) |
| G18 | Low | DIESEL12 EURO5 | 12,117,340.00 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 12,221,300.00 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 12,315,920.00 | (0,193), (193,205) |
| G19 | Low | HYBRID12 | 21,466,330.00 | (0,197), (197,205) |
| | Medium | HYBRID12 | 21,700,400.00 | (0,197), (197,205) |
| | High | HYBRID12 | 21,913,440.00 | (0,197), (197,205) |
| G20 | Low | DIESEL18 EURO5 | 11,237,150.00 | (0,196), (196,205) |
| | Medium | DIESEL18 EURO5 | 11,374,320.00 | (0,196), (196,205) |
| | High | DIESEL18 EURO5 | 11,499,170.00 | (0,196), (196,205) |
| G21 | Low | DIESEL12 EURO5 | 8,900,493.54 | (0,193), (193,205) |
| | Medium | DIESEL12 EURO5 | 9,010,564.08 | (0,193), (193,205) |
| | High | DIESEL12 EURO5 | 9,110,748.87 | (0,193), (193,205) |

## 6.2 EFFECTS OF THE FIRST COST

As we mentioned earlier, the first costs have the largest magnitude in the overall total ownership costs. A considerable portion of the first cost for electric buses is the cost of batteries. Future advancements in the battery technologies may lead to a decrease in their cost which will also reduce the first costs.

We investigated the effect of a decrease in the first costs of OPPORTUNITY ELECTRIC, OVERNIGHT ELECTRIC, and HYDROGEN FUEL-CELL buses. We looked into two plausible cases. First, we decreased the first cost by 25% after the sixth year. Then, we assumed a decrease in the first cost by 25% only at the beginning of the study period. The results of the corresponding experiments shown in Tables 6.3 and 6.4 indicates that there are no changes in the bus assignments if the first cost decreases in the sixth year of the study period. Another analysis which explores the 25% decrease in the first year results in changes in the bus type assignments. In route groups G9, G15, and G19, opportunity electric buses are preferred instead of the hybrid buses. In route groups G4, G7, G10, G11, G12, G14, G16, G20, and G21, opportunity electric buses are used instead of DIESEL12 EURO5 and DIESEL18 EURO5 buses.

To summarize, a 25% decrease in the first costs of opportunity electric, overnight electric and hydrogen fuel-cell buses at the beginning of study period shows that OPPORTUNITY ELECTRIC12 buses are assigned to nine route groups, OPPORTUNITY ELECTRIC18 buses are assigned to three route groups, DIESEL12 EURO5 buses are assigned to six route groups and DIESEL18 EURO5 buses are assigned to three route groups (see Table 6.5). The fleet consists of 146 DIESEL12 EURO5, 39 DIESEL18 EURO5, 167 OPPORTUNITY ELECTRIC12 and 24 OPPORTUNITY ELECTRIC18 buses.

Figures 6.1 and 6.2 show the distribution of bus types and quantities in the fleet, respectively. It can be seen in Tables 6.6 and 6.7 that OPPORTUNITY ELECTRIC buses are assigned to the route groups of which weight parameters are above 0.7. Additionally, HYBRID buses are replaced with OPPORTUNITY ELECTRIC buses due to the decrease in the first cost of OPPORTUNITY ELECTRIC buses which is applied at the beginning of the 12-year study period. Traditional buses (diesel and CNG) are more cost effective than other bus types on relatively flat roads. On the other hand, electric and hybrid buses are better choices than other bus types on rough and high-grade roads. Finally, electric buses are more cost effective than hybrid buses on high-grade roads if their first cost decreases by 25%.

**Table 6.3:** Influence of the first cost on results for route groups G1–G11.

| Route Group | First Cost Level | Bus Type Assigned | Total Cost ($) | Selected Arcs |
|---|---|---|---|---|
| G1 | Base | DIESEL18 EURO5 | 7,675,755.89 | (0,196), (196,205) |
| | -25% at year 6 | DIESEL18 EURO5 | 7,675,755.89 | (0,196), (196,205) |
| | -25% at year 0 | DIESEL18 EURO5 | 7,675,755.89 | (0,196), (196,205) |
| G2 | Base | DIESEL12 EURO5 | 13,097,010.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 13,097,010.00 | (0,193), (193,205) |
| | -25% at year 0 | DIESEL12 EURO5 | 13,097,010.00 | (0,193), (193,205) |
| G3 | Base | DIESEL12 EURO5 | 21,245,500.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 21,245,500.00 | (0,193), (193,205) |
| | -25% at year 0 | DIESEL12 EURO5 | 21,245,500.00 | (0,193), (193,205) |
| G4 | Base | DIESEL12 EURO5 | 11,617,980.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 11,617,980.00 | (0,193), (193,205) |
| | -25% at year 0 | OPPORTUNITY12 | 10,619,540.00 | (0,201), (201,205) |
| G5 | Base | DIESEL12 EURO5 | 7,165,712.14 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 7,165,712.14 | (0,193), (193,205) |
| | -25% at year 0 | DIESEL12 EURO5 | 7,165,712.14 | (0,193), (193,205) |
| G6 | Base | DIESEL18 EURO5 | 14,793,570.00 | (0,196), (196,205) |
| | -25% at year 6 | DIESEL18 EURO5 | 14,793,570.00 | (0,196), (196,205) |
| | -25% at year 0 | DIESEL18 EURO5 | 14,793,570.00 | (0,196), (196,205) |
| G7 | Base | DIESEL18 EURO5 | 20,556,960.00 | (0,196), (196,205) |
| | -25% at year 6 | DIESEL18 EURO5 | 20,556,960.00 | (0,196), (196,205) |
| | -25% at year 0 | OPPORTUNITY12 | 19,503,110.00 | (0,201), (201,205) |
| G8 | Base | OPPORTUNITY18 | 8,577,090.39 | (0,202), (202,205) |
| | -25% at year 6 | OPPORTUNITY18 | 8,577,090.39 | (0,202), (202,205) |
| | -25% at year 0 | OPPORTUNITY18 | 7,558,158.98 | (0,202), (202,205) |
| G9 | Base | HYBRID12 | 9,044,408.63 | (0,197), (197,205) |
| | -25% at year 6 | HYBRID12 | 9,044,408.63 | (0,197), (197,205) |
| | -25% at year 0 | OPPORTUNITY12 | 8,147,376.28 | (0,201), (201,205) |
| G10 | Base | DIESEL12 EURO5 | 16,067,740.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 16,067,740.00 | (0,193), (193,205) |
| | -25% at year 0 | OPPORTUNITY12 | 14,431,500.00 | (0,201), (201,205) |
| G11 | Base | DIESEL12 EURO5 | 7,690,122.32 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 7,690,122.32 | (0,193), (193,205) |
| | -25% at year 0 | OPPORTUNITY12 | 7,114,848.45 | (0,201), (201,205) |

**Table 6.4:** Influence of the first cost on results for route groups G12–G21.

| Route Group | First Cost Level | Bus Type Assigned | Total Cost ($) | Selected Arcs |
|---|---|---|---|---|
| G12 | Base | DIESEL18 EURO5 | 5,034,954.18 | (0,196), (196,205) |
| | -25% at year 6 | DIESEL18 EURO5 | 5,034,954.18 | (0,196), (196,205) |
| | -25% at year 0 | OPPORTUNITY18 | 4,874,018.70 | (0,202), (202,205) |
| G13 | Base | DIESEL12 EURO5 | 7,980,947.81 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 7,980,947.81 | (0,193), (193,205) |
| | -25% at year 0 | DIESEL12 EURO5 | 7,980,947.81 | (0,193), (193,205) |
| G14 | Base | DIESEL12 EURO5 | 10,981,030.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 10,981,030.00 | (0,193), (193,205) |
| | -25% at year 0 | OPPORTUNITY12 | 9,758,292.79 | (0,201), (201,205) |
| G15 | Base | HYBRID12 | 6,373,788.33 | (0,197), (197,205) |
| | -25% at year 6 | HYBRID12 | 6,373,788.33 | (0,197), (197,205) |
| | -25% at year 0 | OPPORTUNITY12 | 5,685,620.08 | (0,201), (201,205) |
| G16 | Base | DIESEL12 EURO5 | 14,454,700.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 14,454,700.00 | (0,193), (193,205) |
| | -25% at year 0 | OPPORTUNITY12 | 13,128,380.00 | (0,201), (201,205) |
| G17 | Base | DIESEL18 EURO5 | 11,391,730.00 | (0,196), (196,205) |
| | -25% at year 6 | DIESEL18 EURO5 | 11,391,730.00 | (0,196), (196,205) |
| | -25% at year 0 | DIESEL18 EURO5 | 11,391,730.00 | (0,196), (196,205) |
| G18 | Base | DIESEL12 EURO5 | 12,117,340.00 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 12,117,340.00 | (0,193), (193,205) |
| | -25% at year 0 | DIESEL12 EURO5 | 12,117,340.00 | (0,193), (193,205) |
| G19 | Base | HYBRID12 | 21,466,330.00 | (0,197), (197,205) |
| | -25% at year 6 | HYBRID12 | 21,466,330.00 | (0,197), (197,205) |
| | -25% at year 0 | OPPORTUNITY12 | 19,825,810.00 | (0,201), (201,205) |
| G20 | Base | DIESEL18 EURO5 | 11,237,150.00 | (0,196), (196,205) |
| | -25% at year 6 | DIESEL18 EURO5 | 11,237,150.00 | (0,196), (196,205) |
| | -25% at year 0 | OPPORTUNITY18 | 11,098,850.00 | (0,202), (202,205) |
| G21 | Base | DIESEL12 EURO5 | 8,900,493.54 | (0,193), (193,205) |
| | -25% at year 6 | DIESEL12 EURO5 | 8,900,493.54 | (0,193), (193,205) |
| | -25% at year 0 | OPPORTUNITY12 | 8,694,188.51 | (0,201), (201,205) |

**Table 6.5:** Effects of reducing both the first and the carbon emission costs.

| Route | DIESEL12 EURO5 | | DIESEL18 EURO5 | | OPPORTUNITY12 | | OPPORTUNITY18 | |
|---|---|---|---|---|---|---|---|---|
| Group | Quantity | TCO($) | Quantity | TCO ($) | Quantity | TCO ($) | Quantity | TCO ($) |
| G1 | | | 9 | 7,675,755.89 | | | | |
| G2 | 27 | 13,097,010.00 | | | | | | |
| G3 | 46 | 21,245,500.00 | | | | | | |
| G4 | | | | | 16 | 10,619,540.00 | | |
| G5 | 15 | 7,165,712.14 | | | | | | |
| G6 | | | 17 | 14,793,570.00 | | | | |
| G7 | | | | | 33 | 19,503,110.00 | | |
| G8 | | | | | | | 6 | 7,558,158.98 |
| G9 | | | | | 12 | 8,147,376.28 | | |
| G10 | | | | | 22 | 14,431,500.00 | | |
| G11 | | | | | 12 | 7,114,848.45 | | |
| G12 | | | | | | | 5 | 4,874,018.70 |
| G13 | 18 | 7,980,947.81 | | | | | | |
| G14 | | | | | 15 | 9,758,292.79 | | |
| G15 | | | | | 9 | 5,685,620.08 | | |
| G16 | | | | | 19 | 13,128,380.00 | | |
| G17 | | | 13 | 11,391,730.00 | | | | |
| G18 | 24 | 12,117,340.00 | | | | | | |
| G19 | | | | | 29 | 19,825,810.00 | | |
| G20 | | | | | | | 13 | 11,098,850.00 |
| G21 | 16 | 8,694,188.51 | | | | | | |
| Total | 146 | 70,300,698.46 | 39 | 33,861,055.89 | 167 | 108,214,477.59 | 24 | 23,531,027.67 |

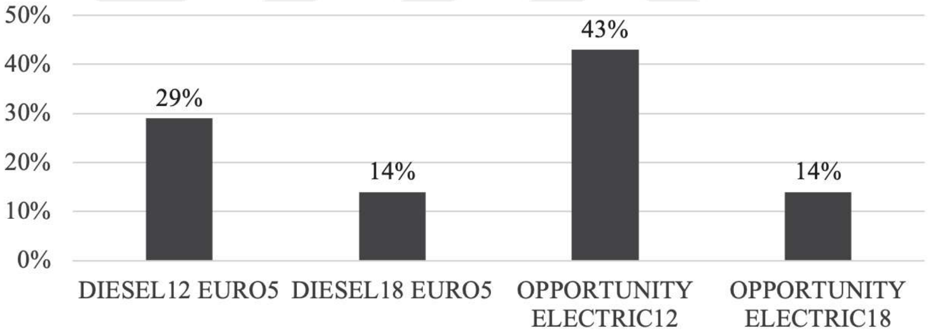


**Figure 6.1:** Distribution of bus types in the fleet when the first cost is reduced by 25% at the beginning of the study period.

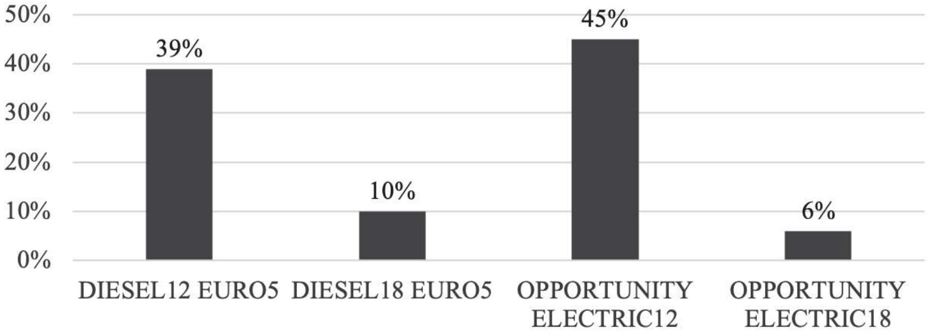


**Figure 6.2:** Distribution of bus quantities in the fleet when the first cost is reduced by 25% at the beginning of the study period.

**Table 6.6:** Characteristics of route groups G1–G10 and impact of reducing the first cost by 25% at the beginning of the study period.

| Route Group | Route | Bus Type Assigned | Weight Parameter | Group Average | Average Speed | Group Average | Route Length | Group Average |
|---|---|---|---|---|---|---|---|---|
| G1 | 1 | DIESEL18 EURO5 | 0.33 | 0.53 | 24.96 | 26.15 | 7.68 | 7.04 |
| | 2 | | 0.85 | | 24.66 | | 7.67 | |
| | 5 | | 0.32 | | 28.13 | | 6.65 | |
| | 6 | | 0.61 | | 26.86 | | 6.16 | |
| G2 | 3 | DIESEL12 EURO5 | 0.31 | 0.51 | 23.78 | 25.41 | 7.86 | 7.95 |
| | 4 | | 0.51 | | 26.65 | | 7.05 | |
| | 69 | | 0.52 | | 25.65 | | 8.68 | |
| | 70 | | 0.72 | | 25.56 | | 8.22 | |
| G3 | 7 | DIESEL12 EURO5 | 0.27 | 0.57 | 23.49 | 24.48 | 7.62 | 7.54 |
| | 8 | | 0.95 | | 24.28 | | 7.39 | |
| | 9 | | 0.33 | | 25.20 | | 7.69 | |
| | 10 | | 0.71 | | 24.95 | | 7.46 | |
| G4 | 11 | OPPORTUNITY12 | 0.69 | 0.90 | 23.39 | 25.77 | 8.79 | 10.77 |
| | 12 | | 1.00 | | 28.28 | | 10.60 | |
| | 35 | | 0.48 | | 23.41 | | 10.80 | |
| | 36 | | 1.42 | | 27.99 | | 12.90 | |
| G5 | 13 | DIESEL12 EURO5 | 0.41 | 0.40 | 25.17 | 25.08 | 9.90 | 9.00 |
| | 14 | | 0.42 | | 25.86 | | 9.75 | |
| | 55 | | 0.36 | | 23.23 | | 8.12 | |
| | 56 | | 0.43 | | 26.08 | | 8.21 | |
| G6 | 15 | DIESEL18 EURO5 | 0.50 | 0.67 | 24.97 | 28.49 | 10.10 | 10.18 |
| | 16 | | 0.97 | | 29.42 | | 11.90 | |
| | 31 | | 0.42 | | 30.72 | | 9.49 | |
| | 32 | | 0.79 | | 28.84 | | 9.23 | |
| G7 | 17 | OPPORTUNITY12 | 0.52 | 0.75 | 23.48 | 25.54 | 10.80 | 12.83 |
| | 18 | | 0.82 | | 27.51 | | 12.70 | |
| | 19 | | 0.62 | | 23.53 | | 12.80 | |
| | 20 | | 1.05 | | 27.64 | | 15.00 | |
| G8 | 21 | OPPORTUNITY18 | 2.20 | 1.74 | 22.53 | 23.43 | 33.60 | 26.20 |
| | 22 | | 2.65 | | 22.29 | | 34.10 | |
| | 23 | | 0.75 | | 26.30 | | 18.30 | |
| | 24 | | 1.34 | | 22.61 | | 18.80 | |
| G9 | 25 | OPPORTUNITY12 | 1.35 | 1.33 | 21.19 | 32.06 | 18.90 | 24.43 |
| | 26 | | 1.05 | | 20.88 | | 18.40 | |
| | 29 | | 1.60 | | 45.96 | | 28.90 | |
| | 30 | | 1.32 | | 40.23 | | 31.50 | |
| G10 | 27 | OPPORTUNITY12 | 0.86 | 0.92 | 23.55 | 24.43 | 14.20 | 13.04 |
| | 28 | | 1.67 | | 27.11 | | 16.30 | |
| | 57 | | 0.55 | | 23.46 | | 11.80 | |
| | 58 | | 0.59 | | 23.60 | | 9.87 | |

**Table 6.7:** Characteristics of route groups G11–G21 and impact of reducing the first cost by 25% at the beginning of the study period.

| Route Group | Route | Bus Type Assigned | Weight Parameter | Group Average | Average Speed | Group Average | Route Length | Group Average |
|---|---|---|---|---|---|---|---|---|
| G11 | 33 | OPPORTUNITY12 | 0.99 | 0.84 | 20.42 | 22.15 | 17.90 | 15.58 |
| | 34 | | 1.13 | | 25.11 | | 21.20 | |
| | 67 | | 0.54 | | 22.00 | | 11.80 | |
| | 68 | | 0.69 | | 21.08 | | 11.40 | |
| G12 | 37 | OPPORTUNITY18 | 0.40 | 0.37 | 19.80 | 20.45 | 3.30 | 5.52 |
| | 38 | | 0.11 | | 15.96 | | 2.66 | |
| | 81 | | 0.22 | | 22.72 | | 8.12 | |
| | 82 | | 0.77 | | 23.31 | | 8.00 | |
| G13 | 39 | DIESEL12 EURO5 | 0.33 | 0.50 | 7.66 | 17.79 | 7.85 | 9.06 |
| | 40 | | 0.53 | | 15.51 | | 8.23 | |
| | 63 | | 0.48 | | 23.87 | | 9.95 | |
| | 64 | | 0.68 | | 24.09 | | 10.20 | |
| G14 | 41 | OPPORTUNITY12 | 0.31 | 0.72 | 21.77 | 22.78 | 7.98 | 15.37 |
| | 42 | | 0.48 | | 19.96 | | 7.00 | |
| | 59 | | 0.91 | | 25.25 | | 23.30 | |
| | 60 | | 1.16 | | 24.12 | | 23.20 | |
| G15 | 43 | OPPORTUNITY12 | 0.23 | 4.63 | 21.10 | 23.45 | 5.78 | 5.95 |
| | 44 | | 0.83 | | 23.82 | | 5.64 | |
| | 79 | | 0.22 | | 24.84 | | 6.39 | |
| | 80 | | 17.23 | | 24.03 | | 5.98 | |
| G16 | 45 | OPPORTUNITY12 | 0.52 | 0.75 | 24.53 | 24.57 | 10.60 | 11.63 |
| | 46 | | 0.98 | | 28.58 | | 12.40 | |
| | 49 | | 0.55 | | 22.12 | | 11.50 | |
| | 50 | | 0.96 | | 23.05 | | 12.00 | |
| G17 | 47 | DIESEL18 EURO5 | 0.39 | 0.55 | 28.30 | 27.17 | 10.70 | 10.29 |
| | 48 | | 0.55 | | 25.38 | | 8.48 | |
| | 53 | | 0.52 | | 25.04 | | 9.98 | |
| | 54 | | 0.76 | | 29.96 | | 12.00 | |
| G18 | 51 | DIESEL12 EURO5 | 0.59 | 0.55 | 22.03 | 23.02 | 12.40 | 10.12 |
| | 52 | | 0.77 | | 22.66 | | 12.30 | |
| | 65 | | 0.39 | | 23.29 | | 7.95 | |
| | 66 | | 0.44 | | 24.09 | | 7.81 | |
| G19 | 61 | OPPORTUNITY12 | 1.22 | 1.07 | 29.67 | 26.80 | 18.50 | 15.70 |
| | 62 | | 1.34 | | 29.11 | | 17.20 | |
| | 83 | | 0.69 | | 23.18 | | 13.60 | |
| | 84 | | 1.03 | | 25.25 | | 13.50 | |
| G20 | 71 | OPPORTUNITY18 | 0.47 | 0.64 | 23.65 | 23.44 | 10.40 | 7.55 |
| | 72 | | 1.17 | | 23.89 | | 9.86 | |
| | 73 | | 0.41 | | 23.12 | | 5.17 | |
| | 74 | | 0.49 | | 23.11 | | 4.78 | |
| G21 | 75 | OPPORTUNITY12 | 0.31 | 0.84 | 25.33 | 24.67 | 7.80 | 9.23 |
| | 76 | | 1.01 | | 24.47 | | 7.50 | |
| | 77 | | 0.76 | | 24.53 | | 11.20 | |
| | 78 | | 1.27 | | 24.35 | | 10.40 | |

## 6.3 SUMMARY OF OBSERVATIONS

The results of our study led to the following observations. First, in the routes which have more challenging topographies with higher grades, HYBRID and OPPORTUNITY ELECTRIC buses are the best choices. In other routes, DIESEL EURO5 buses are the best choices due to their lower first cost. The impact of the social cost of carbon seems to be insignificant. Increasing the social cost of carbon about 50 times had no effect on the optimal assortment of buses over the study period. This shows that the social cost of carbon, or the emission cost, does not have any impacts on the bus route assignments, since it is too small compared to the first cost.

CNG bus, a conventional bus type, is not assigned to any of the route groups. This could be due to various reasons. The first cost, maintenance and emission costs are higher for CNG buses than those for DIESEL buses in most route groups. Even though CNG buses are frequently used in the bus fleets in real life, their efficiency is lower than the other bus types. Similar to CNG buses, DIESEL EURO2, DIESEL EURO3 and DIESEL EURO4 buses are not assigned to any route groups. DIESEL EURO5 consume less fuel and releases less emission than its diesel counterparts.

When compared with ELECTRIC buses, HYBRID buses are assigned to topographically-challenging routes more frequently due to their low first costs. After decreasing the first cost of the all types of OPPORTUNITY ELECTRIC, OVERNIGHT ELECTRIC AND FUEL-CELL HYDROGEN buses by 25%, the assignment of OPPORTUNITY ELECTRIC buses increases from 1 to 12. This result indicates that hybrid buses are suitable in current bus purchase prices. However, in the future with the help of the technological advancements, the cost of electric buses may decrease and they can be preferred choices in the long-term plans replacing both diesel and hybrid buses.

The shortest path model does not assign OVERNIGHT ELECTRIC buses to any route groups because of the high cost of their large size batteries. When compared with OPPORTUNITY ELECTRIC buses, OVERNIGHT ELECTRIC buses hold much larger battery sizes and this increases their first cost. In reality, electric buses' travel distance range is limited to their battery size. For instance, OPPORTUNITY ELECTRIC buses' range is shorter than OVERNIGHT ELECTRIC buses as they include smaller batteries. Thus, in our model, we assume that the OPPORTUNITY ELECTRIC buses are charged at the first stop of their appointed routes. This assumption removes the travel range disadvantage between the OPPORTUNITY ELECTRIC buses and OVERNIGHT ELECTRIC buses. In addition, since the first cost of the OPPORTUNITY ELECTRIC buses are lower, the model considers them mainly as optimal choices over the OVERNIGHT ELECTRIC buses.

Total ownership cost of a HYDROGEN FUEL-CELL bus is more than those of other bus types due to high purchase costs. In addition, its fuel consumption rate is higher and thus it is not appointed to any route group. Hydrogen buses, similar to electric buses, have zero carbon emission rates. In addition, unlike full electric buses HYDROGEN FUEL-CELL buses do not have the range limit. Since the energy that is needed by the electric engine is provided by the hydrogen tank, HYDROGEN FUEL-CELL buses can serve with zero carbon emission rate and without travel range limit. Due to these advantages, HYDROGEN FUEL-CELL buses can be used as ecological alternatives in the future if their first costs decrease substantially.

Passenger demand exceeds the capacity of a 12-meter bus in some periods. Our model applies a penalty cost and a limit to the turned-away passengers. In order to avoid the penalty cost and stay below the limit, the model assigns two 12-meter buses to the same period when the number of passengers exceeds the capacity. This situation increases both the minimum number of buses assigned to some route groups and the total purchasing costs. Since the passenger capacity of a 18-meter bus is higher, the model assigns the 18-meter buses to route groups with even higher passenger demands. The first cost of a 18-meter bus is higher than that of a 12-meter bus. Due to their large passenger capacity, they reduce the total number of buses needed in route groups when compared with 12-meter buses. This also reduces the total purchasing cost. For these reasons, the model uses 18-meter buses in route groups with sufficiently high passenger demands.

# CHAPTER 7

# DISCUSSION AND CONCLUSION

This thesis aimed to design a city bus fleet by finding an optimal assignment of different types of buses for a given set of routes that will minimize the total ownership cost. In practice, bus-route assignments and fleet renewal decisions are generally made using heuristic approaches. The approaches and the results that are obtained from this thesis might help transit agencies make better long-term decisions in forming their city bus fleets. Our analyses shed a light on how the social cost of carbon as well as purchasing costs affect replacement and retention decisions in the long-term plans for these agencies. We note, however, that these impacts vary based on the attitude of the decision makers as well as the regulations concerning the useful life of vehicles.

Our major observations can be summarized as follows. First, the road grade has a significant impact on the type of bus that is preferred from an economical point of view. Diesel buses with euro 5 engine are assigned to routes that are fairly level. Other conventional bus types are not assigned to any of the route groups with fairly flat road characteristics. This result could be due to various reasons. The first cost, maintenance and emission costs are higher for CNG buses than those for diesel buses for most route groups. Even though CNG buses are frequently used in city bus fleets in real life, their efficiency is lower than those of the other bus types. Additionally, euro 5 engine consumes less fuel and releases less emission than other diesel bus types. On the other hand, electric and hybrid buses are assigned to topographically challenging routes more frequently than other types of buses. We observed that a 25% decrease in the first cost of electric buses results in a significant increase in the number of this type of buses that are assigned to routes. Without a decrease in the purchase price of the electric buses, hybrid buses are naturally preferred to the electric ones.

However, with the ongoing concerns about the environmental pollution and the climate change issues, governments may impose additional restrictions, regulations, and taxes to limit impacts from using fossil based fuels. Additionally, there has been an increasing interest in designing more efficient and more economic electric vehicles. Therefore, we believe that, in the future, electric buses will probably be preferred and will replace both diesel and hybrid buses, which may be accelerated through technological advancements and reduction of their purchase costs. When compared with opportunity electric buses, overnight electric buses hold much larger battery sizes and this increases their first cost. Therefore overnight electric buses are not assigned to any route groups. Total ownership cost of a hydrogen fuel-cell bus is more than those of other bus types due to high purchase costs. In addition, its fuel consumption rate is higher and thus it is not assigned to any route group. Hydrogen fuel-cell buses have zero carbon emission rate and no limitation on travel range. Due to these advantages, they can be used as ecological alternatives in the future if their first costs decrease substantially.

Second, larger-capacity buses are preferred to smaller-capacity buses for routes with a sufficiently large passenger demand. This is expected since the cost of two smaller buses is larger than the cost of larger-size bus of the same type. We note that we enforce serving a pre-determined level of passengers and penalize turning away passengers.

Third, existing literature generally investigates the effects of average speed and distance. In contrast, this thesis specially focuses on road grade and distance. Ercan and Tatari (2015) indicate that hybrid and electric buses are not affected by low average speed, while diesel and CNG are negatively affected from low average speeds. The authors also report that hybrid and electric buses are less affected by longer distance and high average speeds. Emiliano et al. (2020) state that an electric bus is a suitable choice for driving cycles with frequent stops and low average speeds whereas diesel and CNG buses are better choices at high average speeds. According to Correa et al. (2017), electric buses perform better in short ranges; whereas, hybrid bus performs well in both short and medium ranges. The results of our study have indicated the following conclusions. In the routes which have more challenging topographies with higher grades, hybrid and opportunity electric buses are the best choices. In other routes, diesel buses are the best choices due to their lower first cost. The impact of the social cost of carbon seems to be insignificant. Increasing the social cost of carbon about 50 times had no effect on the optimal assortment of buses over the study period. This shows that the social cost of carbon, or the emission cost, does not have any impacts on the bus route assignments, since it is significantly lower than the first cost. However, as we mentioned before, the unit costs of emissions may increase or additional carbon regulations may be imposed in the future, which may change the results drastically in the future.

We used earlier studies and manufacturers' data to obtain fuel consumptions of different bus types. Future studies can use real world data sets in which the fuel consumption rate of a bus is included. The potential influences of passenger weights on fuel consumption rates of different bus types can be examined. Since climate change might worsen ahead, future studies can investigate the effects of higher social costs of carbon and different carbon emission regulations such as cap-and-trade, carbon tax and tax incentives. In this thesis, we had to divide a district into groups and assumed that only one bus type can be assigned to each route to make sure that the mathematical model can be solved within a reasonable amount of time. Future studies can reduce the model size by expanding the period intervals, thereby reducing the number of periods in a day. Consequently, it may be worthwhile to investigate if a reduction in the number of periods will result in acceptable solution times for models in which multiple bus types can be assigned to a route.

# REFERENCES

Ally, J. and Pryor, T. (2016). Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study. *Energy Policy*, 94:285–294.

Board, T. R., National Academies of Sciences, E., and Medicine (2010). *Assessing Mechanisms for Integrating Transportation-Related Greenhouse Gas Reduction Objectives into Transportation Decision Making*. The National Academies Press, Washington, DC.

Bozankaya (2021a). Sileo S12. Technical report, Bozankaya. `https://www.bozankaya.com.tr/wp-content/uploads/Sileo_Katalog_S12_TR.pdf`.

Bozankaya (2021b). Sileo S18. Technical report, Bozankaya. `https://www.bozankaya.com.tr/wp-content/uploads/Sileo_Katalog_S18_TR.pdf`.

Britannica, The Editors of Encyclopaedia (2021). Paris Agreement. Encyclopedia Britannica. `https://www.britannica.com/topic/Paris-Agreement-2015`.

Civitas (2016). Smart Choices for Cities: Alternative Fuel Buses. Technical report, Civitas. `https://civitas.eu/sites/default/files/civ_pol-08_m_web.pdf`.

Correa, G., Muñoz, P., Falaguerra, T., and Rodriguez, C. (2017). Performance comparison of conventional, hybrid, hydrogen and electric urban buses using well to wheel analysis. *Energy*, 141:537–549.

Dreier, D., Silveira, S., Khatiwada, D., Fonseca, K. V., Nieweglowski, R., and Schepanski, R. (2018). Well-to-wheel analysis of fossil energy use and greenhouse gas emissions for conventional, hybrid-electric and plug-in hybrid-electric city buses in the BRT system in Curitiba, Brazil. *Transportation Research Part D: Transport and Environment*, 58:122–138.

Emiliano, M. W., Costa, L., Carvalho, S. M., Telhada, J., and Lanzer, E. A. (2020). Multiobjective optimization of transit bus fleets with alternative fuel options: The case of Joinville, Brazil. *International Journal of Sustainable Transportation*, 14(1):14–24.

EPA (2019). Inventory of U.S. greenhouse gas emissions and sinks. Annual Report EPA 430-R-19-001, Environmental Protection Agency.

Ercan, T. and Tatari, O. (2015). A hybrid life cycle assessment of public transportation buses with alternative fuel options. *The International Journal of Life Cycle Assessment*, 20(9):1213–1231.

Ercan, T., Zhao, Y., Tatari, O., and Pazour, J. A. (2015). Optimization of transit bus fleet's life cycle assessment impacts with alternative fuel options. *Energy*, 93:323–334.

Eudy, L. and Post, M. (September 2014). Bc transit fuel cell bus project evaluation results: Second report. Technical Report NREL/TP-5400-62317, National Renewable Energy Laboratory.

European Commission (2012). Energy Roadmap 2050. Luxembourg: Publications Office of the European Union. https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf.

European Commission (2019). Emissions Database for Global Atmospheric Research. https://edgar.jrc.ec.europa.eu/.

Fuel Cells and Hydrogen Joint Undertaking (2012). Urban Buses: Alternative Powertrains for Europe. https://www.fch.europa.eu/sites/default/files/20121029%20Urban%20buses%2C%20alternative%20powertrains%20for%20Europe%20-%20Final%20report_0_0.pdf.

Georgia Institute of Technology (n.d.). Fuel Emission Online Calculator. http://fec.ce.gatech.edu/bus/.

Google (2021). Google Earth. https://www.google.com/intl/tr/earth/.

Haber 7 (2012). 2021 Belediye Otobüsü Şoför Maaşları Ne Kadar? https://www.haber7.com/memur/haber/3076470-2021-belediye-otobusu-sofor-maaslari-ne-kadar-devlette-derecelere-gore-sofor-maaslari-tablosu.

Hodges and Tina (2010). Public transportation's role in responding to climate change.

International Energy Agency (2019). World Energy Statistics 2019. IEA, Paris. https://www.iea.org/reports/world-energy-statistics-2019.

International Energy Agency (2020). Data and Statistics. https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energy%20supply&indicator=TPESbySource.

Kivekäs, K., Lajunen, A., Vepsäläinen, J., and Tammi, K. (2018). City bus powertrain comparison: Driving cycle variation and passenger load sensitivity analysis. *Energies*, 11(7):1755.

Lajunen, A. (2014). Energy consumption and cost-benefit analysis of hybrid and electric city buses. *Transportation Research Part C: Emerging Technologies*, 38:1–15.

Lajunen, A. and Lipman, T. (2016). Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. *Energy*, 106:329–342.

Li, J.-Q. and Head, K. L. (2009). Sustainability provisions in the bus-scheduling problem. *Transportation Research Part D: Transport and Environment*, 14(1):50–60.

Mahmoud, M., Garnett, R., Ferguson, M., and Kanaroglou, P. (2016). Electric buses: A review of alternative powertrains. *Renewable and Sustainable Energy Reviews*, 62:673–684.

Moovit (2021). Maas Solutions and the #1 Urban Mobility App. `https://moovit.com/`.

Newflyer (2021). Newflyer Xcelsior Charge NG. Technical report, Newflyer. `https://www.newflyer.com/site-content/uploads/2021/03/Xcelsior-CHARGE-NG-Brochure-1.pdf`.

NovaBUS (2021a). Nova LFS Artic. `https://novabus.com/blog/bus/lfs_artic/`.

NovaBUS (2021b). Nova LFS HEV. `https://novabus.com/blog/bus/lfs_hev/`.

Nurhadi, L., Borén, S., and Ny, H. (2014). A sensitivity analysis of total cost of ownership for electric public bus transport systems in swedish medium sized cities. *Transportation Research Procedia*, 3:818–827. 17th Meeting of the EURO Working Group on Transportation, EWGT2014, 2-4 July 2014, Sevilla, Spain.

Perrotta, D., Macedo, J. L., Rossetti, R. J., de Sousa, J. F., Kokkinogenis, Z., Ribeiro, B., and Afonso, J. L. (2014). Route planning for electric buses: A case study in Oporto. *Procedia - Social and Behavioral Sciences*, 111:1004–1014. Transportation: Can we do more with less resources? – 16th Meeting of the Euro Working Group on Transportation – Porto 2013.

Proterra (2021). Proterra ZX5 Spec Sheet. Technical report, Proterra. `https://www.proterra.com/wp-content/uploads/2021/01/Proterra-ZX5-Spec-Sheet-40-Foot-Bus-Canada.pdf`.

Ribau, J. P., Silva, C. M., and Sousa, J. M. (2014). Efficiency, cost and life cycle co2 optimization of fuel cell hybrid and plug-in hybrid urban buses. *Applied Energy*, 129:320–335.

Ricke, K., Drouet, L., Caldeira, K., and Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, 8(10):895–900.

Ricke, K., Drouet, L., Caldeira, K., and Tavoni, M. (2020). Country-level Social Cost of Carbon. European Institute on Economics and the Environment. `https://country-level-scc.github.io/explorer/`.

Saeidizand, P. (2019). Global Bus Survey. International Association of Public Transport. `https://www.sustainable-bus.com/wp-content/uploads/2019/07/Statistics-Brief_Global-bus-survey-003.pdf`.

Song, Q., Wang, Z., Wu, Y., Li, J., Yu, D., Duan, H., and Yuan, W. (2018). Could urban electric public bus really reduce the ghg emissions: A case study in macau? *Journal of Cleaner Production*, 172:2133–2142.

Stempien, J. and Chan, S. (2016). Comparative study of fuel cell, battery and hybrid buses for renewable energy constrained areas. *Journal of Power Sources*, 340:347.

TUIK (2021). Adrese dayalı nüfus kayıt sistemi sonuçları, 2020. Technical report, Turkish Statistical Institute.

UITP (2017). Urban public transport in the 21st century. Statistics brief, Union Internationale des Transports Publics.

United Nations Framework Convention on Climate Change (n.d.a). The Paris Agreement. `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`.

United Nations Framework Convention on Climate Change (n.d.b). What is the Kyoto Protocol? `https://unfccc.int/kyoto_protocol`.

United States Department of Transportation (2017). 2017 Annual Database Revenue Vehicle Inventory. Federal Transit Administration. `https://www.transit.dot.gov/ntd/data-product/2017-annual-database-revenue-vehicle-inventory`.

U.S. Bureau of Labor Statistics (2021). Consumer Price Index (CPI). `https://www.bls.gov/cpi/data.htm`.

Worldbank (2019). Green Your Bus Ride: Clean buses in Latin America. Technical report, Worldbank. `https://documents1.worldbank.org/curated/en/410331548180859451/pdf/133929-WP-PUBLIC-P164403-Summary-Report-Green-Your-Bus-Ride.pdf`.

Xu, Y., Gbologah, F. E., Lee, D.-Y., Liu, H., Rodgers, M. O., and Guensler, R. L. (2015). Assessment of alternative fuel and powertrain transit bus options using real-world operations data: Life-cycle fuel and emissions modeling. *Applied Energy*, 154:143–159.

Yang, C. X., Bibeau, E., and Molinski, T. (2012). Fuel consumption model for diesel and electric buses considering bus route and passenger load variation.

Zhang, S., Wu, Y., Liu, H., Huang, R., Yang, L., Li, Z., Fu, L., and Hao, J. (2014). Real-world fuel consumption and CO2 emissions of urban public buses in Beijing. *Applied Energy*, 113:1645–1655.

# APPENDIX A

# OPERATING COSTS

**Table A.1:** Operating costs of diesel and CNG buses in the first 30 periods of route 1.

| $r\backslash p$ | DIESEL12 E2 | DIESEL12 E3 | DIESEL12 E4 | DIESEL12 E5 | DIESEL18 E2 | DIESEL18 E3 | DIESEL18 E5 | CNG12 | CNG18 |
|---|---|---|---|---|---|---|---|---|---|
| 1\1 | | | | | | | | | |
| 1\2 | | | | | | | | | |
| 1\3 | | | | | | | | | |
| 1\4 | 0.6937 | 0.7188 | 0.7146 | 0.6179 | 0.9956 | 1.3179 | 0.8857 | 0.5347 | 0.7676 |
| 1\5 | | | | | | | | | |
| 1\6 | | | | | | | | | |
| 1\7 | 0.6937 | 0.7188 | 0.7146 | 0.6179 | 0.9956 | 1.3179 | 0.8857 | 0.5347 | 0.7676 |
| 1\8 | | | | | | | | | |
| 1\9 | | | | | | | | | |
| 1\10 | 0.6937 | 0.7188 | 0.7146 | 0.6179 | 0.9956 | 1.3179 | 0.8857 | 0.5347 | 0.7676 |
| 1\11 | | | | | | | | | |
| 1\12 | 0.6937 | 0.7188 | 0.7146 | 0.6179 | 0.9956 | 1.3179 | 0.8857 | 0.5347 | 0.7676 |
| 1\13 | | | | | | | | | |
| 1\14 | 0.7931 | 0.7367 | 0.7382 | 0.6399 | 1.1897 | 1.5742 | 0.9185 | 0.5619 | 0.8462 |
| 1\15 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\16 | | | | | | | | | |
| 1\17 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\18 | | | | | | | | | |
| 1\19 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\20 | | | | | | | | | |
| 1\21 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\22 | | | | | | | | | |
| 1\23 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\24 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\25 | | | | | | | | | |
| 1\26 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\27 | | | | | | | | | |
| 1\28 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |
| 1\29 | | | | | | | | | |
| 1\30 | 0.7528 | 0.7878 | 0.8489 | 0.7532 | 1.8450 | 1.1388 | 1.1191 | 0.6348 | 0.9118 |

**Table A.2:** Operating costs of hybrid, hydrogen fuel-cell, opportunity electric and overnight electric buses in the first 30 periods of route 1.

| $r\backslash p$ | HYBRID12 | HYBRID18 | HYDROGEN12 | HYDROGEN18 | OPPORTUNITY12 | OPPORTUNITY18 | OVERNIGHT12 | OVERNIGHT18 |
|---|---|---|---|---|---|---|---|---|
| 1\1 | | | | | | | | |
| 1\2 | | | | | | | | |
| 1\3 | | | | | | | | |
| 1\4 | 0.3143 | 0.4511 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\5 | | | | | | | | |
| 1\6 | | | | | | | | |
| 1\7 | 0.3143 | 0.4511 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\8 | | | | | | | | |
| 1\9 | | | | | | | | |
| 1\10 | 0.3143 | 0.4511 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\11 | | | | | | | | |
| 1\12 | 0.3143 | 0.4511 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\13 | | | | | | | | |
| 1\14 | 0.3586 | 0.5147 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\15 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\16 | | | | | | | | |
| 1\17 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\18 | | | | | | | | |
| 1\19 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\20 | | | | | | | | |
| 1\21 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\22 | | | | | | | | |
| 1\23 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\24 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\25 | | | | | | | | |
| 1\26 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\27 | | | | | | | | |
| 1\28 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |
| 1\29 | | | | | | | | |
| 1\30 | 0.4623 | 0.6635 | 2.8425 | 2.8828 | 0.3489 | 0.5389 | 0.2576 | 0.3765 |

# APPENDIX B

# SOCIAL COSTS OF CARBON EMISSIONS

**Table B.1:** Social costs of carbon emissions of diesel and CNG buses in the first 30 periods of route 1.

| $r \backslash p$ | DIESEL12 E2 | DIESEL12 E3 | DIESEL12 E4 | DIESEL12 E5 | DIESEL18 E2 | DIESEL18 E3 | DIESEL18 E5 | CNG12 | CNG18 |
|---|---|---|---|---|---|---|---|---|---|
| 1\1 | | | | | | | | | |
| 1\2 | | | | | | | | | |
| 1\3 | | | | | | | | | |
| 1\4 | 0.0016 | 0.0017 | 0.0020 | 0.0015 | 0.0023 | 0.0024 | 0.0021 | 0.0015 | 0.0021 |
| 1\5 | | | | | | | | | |
| 1\6 | | | | | | | | | |
| 1\7 | 0.0016 | 0.0017 | 0.0020 | 0.0015 | 0.0023 | 0.0024 | 0.0021 | 0.0015 | 0.0021 |
| 1\8 | | | | | | | | | |
| 1\9 | | | | | | | | | |
| 1\10 | 0.0016 | 0.0017 | 0.0020 | 0.0015 | 0.0023 | 0.0024 | 0.0021 | 0.0015 | 0.0021 |
| 1\11 | | | | | | | | | |
| 1\12 | 0.0016 | 0.0017 | 0.0020 | 0.0015 | 0.0023 | 0.0024 | 0.0021 | 0.0015 | 0.0021 |
| 1\13 | | | | | | | | | |
| 1\14 | 0.0017 | 0.0017 | 0.0019 | 0.0015 | 0.0024 | 0.0025 | 0.0022 | 0.0016 | 0.0022 |
| 1\15 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\16 | | | | | | | | | |
| 1\17 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\18 | | | | | | | | | |
| 1\19 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\20 | | | | | | | | | |
| 1\21 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\22 | | | | | | | | | |
| 1\23 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\24 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\25 | | | | | | | | | |
| 1\26 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\27 | | | | | | | | | |
| 1\28 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |
| 1\29 | | | | | | | | | |
| 1\30 | 0.0018 | 0.0019 | 0.0019 | 0.0017 | 0.0025 | 0.0027 | 0.0024 | 0.0018 | 0.0025 |

**Table B.2:** Social costs of carbon emissions of hybrid, hydrogen fuel-cell, opportunity electric and overnight electric buses in the first 30 periods of route 1.

| $r\backslash p$ | HYBRID12 | HYBRID18 | HYDROGEN12 | HYDROGEN18 | OPPORTUNITY12 | OPPORTUNITY18 | OVERNIGHT12 | OVERNIGHT18 |
|---|---|---|---|---|---|---|---|---|
| 1\1 | | | | | | | | |
| 1\2 | | | | | | | | |
| 1\3 | | | | | | | | |
| 1\4 | 0.0009 | 0.0013 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\5 | | | | | | | | |
| 1\6 | | | | | | | | |
| 1\7 | 0.0009 | 0.0013 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\8 | | | | | | | | |
| 1\9 | | | | | | | | |
| 1\10 | 0.0009 | 0.0013 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\11 | | | | | | | | |
| 1\12 | 0.0009 | 0.0013 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\13 | | | | | | | | |
| 1\14 | 0.0010 | 0.0014 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\15 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\16 | | | | | | | | |
| 1\17 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\18 | | | | | | | | |
| 1\19 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\20 | | | | | | | | |
| 1\21 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\22 | | | | | | | | |
| 1\23 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\24 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\25 | | | | | | | | |
| 1\26 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\27 | | | | | | | | |
| 1\28 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1\29 | | | | | | | | |
| 1\30 | 0.0013 | 0.0019 | 0 | 0 | 0 | 0 | 0 | 0 |

# APPENDIX C

# MAINTENANCE COSTS

**Table C.1:** Maintenance costs of diesel and CNG buses in the first 30 periods of route 1.

| $r\backslash p$ | DIESEL12 E2 | DIESEL12 E3 | DIESEL12 E4 | DIESEL12 E5 | DIESEL18 E2 | DIESEL18 E3 | DIESEL18 E5 | CNG12 | CNG18 |
|---|---|---|---|---|---|---|---|---|---|
| 1\1 | | | | | | | | | |
| 1\2 | | | | | | | | | |
| 1\3 | | | | | | | | | |
| 1\4 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\5 | | | | | | | | | |
| 1\6 | | | | | | | | | |
| 1\7 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\8 | | | | | | | | | |
| 1\9 | | | | | | | | | |
| 1\10 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\11 | | | | | | | | | |
| 1\12 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\13 | | | | | | | | | |
| 1\14 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\15 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\16 | | | | | | | | | |
| 1\17 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\18 | | | | | | | | | |
| 1\19 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\20 | | | | | | | | | |
| 1\21 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\22 | | | | | | | | | |
| 1\23 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\24 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\25 | | | | | | | | | |
| 1\26 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\27 | | | | | | | | | |
| 1\28 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |
| 1\29 | | | | | | | | | |
| 1\30 | 2.1504 | 2.1504 | 2.1504 | 2.1504 | 3.2256 | 3.2256 | 3.2256 | 2.6112 | 3.9168 |

**Table C.2:** Maintenance costs of hybrid, hydrogen fuel-cell, opportunity electric and overnight electric buses in the first 30 periods of route 1.

| $r\backslash p$ | HYBRID12 | HYBRID18 | HYDROGEN12 | HYDROGEN18 | OPPORTUNITY12 | OPPORTUNITY18 | OVERNIGHT12 | OVERNIGHT18 |
|---|---|---|---|---|---|---|---|---|
| 1\1 | | | | | | | | |
| 1\2 | | | | | | | | |
| 1\3 | | | | | | | | |
| 1\4 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\5 | | | | | | | | |
| 1\6 | | | | | | | | |
| 1\7 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\8 | | | | | | | | |
| 1\9 | | | | | | | | |
| 1\10 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\11 | | | | | | | | |
| 1\12 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\13 | | | | | | | | |
| 1\14 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\15 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\16 | | | | | | | | |
| 1\17 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\18 | | | | | | | | |
| 1\19 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\20 | | | | | | | | |
| 1\21 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\22 | | | | | | | | |
| 1\23 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\24 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\25 | | | | | | | | |
| 1\26 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\27 | | | | | | | | |
| 1\28 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |
| 1\29 | | | | | | | | |
| 1\30 | 2.5344 | 3.8400 | 4.7616 | 7.1424 | 1.6896 | 2.5344 | 1.6896 | 2.5344 |

# APPENDIX D

## PYTHON CODE FOR GENERATING PASSENGER DEMAND

**Listing D.1:** Python source code to obtain mean values of passenger demands in each route and period.

```
# generating uniform mean values for each period and route

import pandas as pd
import numpy as np

oneday_mean_6_7 = pd.DataFrame(np.random.uniform(20, 70, size
    =(15,84)))
oneday_mean_7_9 = pd.DataFrame(np.random.uniform(30, 120, size
    =(24,84)))
oneday_mean_9_10 = pd.DataFrame(np.random.uniform(30, 80, size
    =(12,84)))
oneday_mean_10_16 = pd.DataFrame(np.random.uniform(10, 80, size
    =(72,84)))
oneday_mean_16_17 = pd.DataFrame(np.random.uniform(30, 80, size
    =(12,84)))
oneday_mean_17_19 = pd.DataFrame(np.random.uniform(30, 120, size
    =(24,84)))
oneday_mean_19_20 = pd.DataFrame(np.random.uniform(20, 80, size
    =(12,84)))
oneday_mean_20_22 = pd.DataFrame(np.random.uniform(10, 60, size
    =(24,84)))
oneday_mean_22_01 = pd.DataFrame(np.random.uniform(10, 30, size
    =(37,84)))

oneday_mean = [oneday_mean_6_7, oneday_mean_7_9, oneday_mean_9_10,
    oneday_mean_10_16, oneday_mean_16_17, oneday_mean_17_19,
    oneday_mean_19_20, oneday_mean_20_22, oneday_mean_22_01]

oneday_mean = pd.concat(oneday_mean, ignore_index=True)
oneday_mean.columns += 1
```

**Listing D.2:** Python code to generate passenger demands in each route and period.

```
# generating boarding passengers according to the Poisson
    distribution using uniform mean values

import itertools

pr_set = pd.read_excel("210526_sets.xlsx", sheet_name="pr_for_Drp",
    usecols="C:CH", skiprows=3, nrows=232)
pr_set = pr_set.fillna(0)
pr_set = pr_set.astype(int)

oneday_mean_valid = oneday_mean * pr_set

oneday_mean_last = oneday_mean_valid.values.tolist()
oneday_mean_last = list(itertools.chain.from_iterable(
    oneday_mean_last))

day = []
for x in oneday_mean_last:
    d = np.random.poisson(lam = x)
    day.append(d)

d_rp = np.reshape(day, (232,84))
d_rp = pd.DataFrame(d_rp)
```

# APPENDIX E

# EXAMPLE ARC COST CALCULATIONS FOR THE SHORTEST PATH MODEL

**Table E.1:** Arc costs for CNG12, CNG18 and DIESEL12 EURO2 buses.

|  |  |  | Year |  |  |
|---|---|---|---|---|---|
| Element | 0 | 1 | 2 | 3 | 4 |
| **CNG12** |  |  |  |  |  |
| Operating Cost (OC) |  | 88,337.04 | 89,828.81 | 91,320.58 | 92,812.35 |
| Maintenance Cost (MC) |  | 218,830.49 | 223,432.16 | 228,033.83 | 232,635.50 |
| Emission Cost (EC) |  | 246.88 | 251.01 | 255.14 | 259.27 |
| Driver Cost (DC) |  | 96,332.19 | 97,944.07 | 99,555.95 | 101,167.82 |
| Turned-Away Passenger Cost (PC) |  | N/A | N/A | N/A | N/A |
| Bus Route Assignment Cost (AC) |  | 12,410.00 | 12,619.57 | 12,829.14 | 13,038.71 |
| OM Cost (OC+MC+EC+DC+PC+AC) |  | 416,156.61 | 424,075.63 | 431,994.64 | 439,913.66 |
| NPV(OM) |  | 396,339.63 | 384,649.09 | 373,173.22 | 361,918.06 |
| First Cost (FC) | 5,780,000.00 | 5,789,398.37 | 5,798,796.75 | 5,808,195.12 | 5,817,593.50 |
| NPV(FC) | 5,780,000.00 | 5,513,712.74 | 5,259,679.59 | 5,017,337.33 | 4,786,148.57 |
| Salvage Value (SV) |  | 5,086,400.00 | 4,476,032.00 | 3,938,908.16 | 3,466,239.18 |
| NPV(SV) |  | 4,844,190.48 | 4,059,892.97 | 3,402,576.97 | 2,851,683.55 |
| **CNG18** |  |  |  |  |  |
| Operating Cost (OC) |  | 103,095.32 | 104,836.32 | 106,577.32 | 108,318.31 |
| Maintenance Cost (MC) |  | 266,792.04 | 272,402.27 | 278,012.50 | 283,622.72 |
| Emission Cost (EC) |  | 288.11 | 292.93 | 297.75 | 302.57 |
| Driver Cost (DC) |  | 77,227.49 | 78,519.70 | 79,811.90 | 81,104.11 |
| Turned-Away Passenger Cost (PC) |  | 2,686.01 | 2,730.95 | 2,775.89 | 2,820.84 |
| Bus Route Assignment Cost (AC) |  | 6,570.00 | 6,680.95 | 6,791.90 | 6,902.85 |
| OM Cost (OC+MC+EC+DC+PC+AC) |  | 456,658.96 | 465,463.11 | 474,267.25 | 483,071.40 |
| NPV(OM) |  | 434,913.30 | 422,188.76 | 409,689.89 | 397,424.03 |
| First Cost (FC) | 4,590,000.00 | 4,597,463.41 | 4,604,926.83 | 4,612,390.24 | 4,619,853.66 |
| NPV(FC) | 4,590,000.00 | 4,378,536.59 | 4,176,804.38 | 3,984,356.11 | 3,800,765.04 |
| Salvage Value (SV) |  | 4,039,200.00 | 3,554,496.00 | 3,127,956.48 | 2,752,601.70 |
| NPV(SV) |  | 3,846,857.14 | 3,224,032.65 | 2,702,046.41 | 2,264,572.23 |
| **DIESEL12 EURO2** |  |  |  |  |  |
| Operating Cost (OC) |  | 105,762.00 | 107,548.03 | 109,334.06 | 111,120.09 |
| Maintenance Cost (MC) |  | 180,213.35 | 184,002.96 | 187,792.57 | 191,582.18 |
| Emission Cost (EC) |  | 248.90 | 253.07 | 257.23 | 261.40 |
| Driver Cost (DC) |  | 96,332.19 | 97,944.07 | 99,555.95 | 101,167.82 |
| Turned-Away Passenger Cost (PC) |  | N/A | N/A | N/A | N/A |
| Bus Route Assignment Cost (AC) |  | 12,410.00 | 12,619.57 | 12,829.14 | 13,038.71 |
| OM Cost (OC+MC+EC+DC+PC+AC) |  | 394,966.45 | 402,367.70 | 409,768.95 | 417,170.20 |
| NPV(OM) |  | 376,158.52 | 364,959.36 | 353,973.83 | 343,206.96 |
| First Cost (FC) | 5,134,000.00 | 5,142,347.97 | 5,150,695.93 | 5,159,043.90 | 5,167,391.87 |
| NPV(FC) | 5,134,000.00 | 4,897,474.25 | 4,671,833.05 | 4,456,576.10 | 4,251,226.08 |
| Salvage Value (SV) |  | 4,517,920.00 | 3,975,769.60 | 3,498,677.25 | 3,078,835.98 |
| NPV(SV) |  | 4,302,780.95 | 3,606,140.23 | 3,022,288.95 | 2,532,965.98 |

# APPENDIX F

## STATISTICS OF THE MIP MODEL

**Table F.1:** Statistics of the MIP model for all route groups.

| Route | Binary | Real | | Solution Time (seconds) | | |
|---|---|---|---|---|---|---|
| Group | Variables | Variables | Constraints | min | average | max |
| G1 | 12,360 | 202 | 25,886 | 34.81 | 87.45 | 263.39 |
| G2 | 16,560 | 272 | 25,886 | 30.94 | 184.07 | 367.56 |
| G3 | 27,360 | 452 | 51,036 | 487.00 | 949.70 | 1554.89 |
| G4 | 14,040 | 230 | 30,834 | 31.72 | 46.89 | 68.84 |
| G5 | 8,280 | 134 | 18,858 | 18.33 | 30.13 | 46.16 |
| G6 | 17,760 | 292 | 36,956 | 127.27 | 292.49 | 601.43 |
| G7 | 18,960 | 312 | 39,376 | 34.49 | 395.88 | 2150.72 |
| G8 | 3,360 | 52 | 7,796 | 3.07 | 4.68 | 6.45 |
| G9 | 5,760 | 92 | 12,576 | 7.33 | 12.87 | 52.11 |
| G10 | 16,560 | 272 | 35,676 | 52.86 | 147.65 | 438.36 |
| G11 | 7,320 | 118 | 16,442 | 7.42 | 9.23 | 11.31 |
| G12 | 10,320 | 168 | 22,012 | 12.19 | 30.13 | 58.66 |
| G13 | 8,520 | 138 | 19,702 | 23.58 | 29.27 | 37.05 |
| G14 | 10,200 | 166 | 23,390 | 52.57 | 168.75 | 453.94 |
| G15 | 6,120 | 98 | 13,002 | 9.71 | 18.48 | 29.52 |
| G16 | 18,120 | 298 | 37,922 | 163.59 | 1415.01 | 6453.03 |
| G17 | 13,440 | 220 | 29,084 | 26.00 | 68.30 | 175.63 |
| G18 | 12,360 | 202 | 27,086 | 31.99 | 58.25 | 91.79 |
| G19 | 19,080 | 314 | 38,958 | 28.25 | 219.23 | 534.57 |
| G20 | 14,760 | 242 | 31,866 | 52.16 | 370.45 | 3104.81 |
| G21 | 10,440 | 170 | 21,954 | 21.12 | 101.75 | 199.18 |