Recommending Improvements to the Efficiency, Equity, and Sustainability of the Bus System in Melbourne, Australia

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Abstract

Our project goal was to provide recommendations for improving the efficiency, equity, and sustainability of Greater Melbourne's bus system. We interviewed experts, conducted a spatial analysis to supplement a satisfaction survey distributed to riders, and completed cost-benefit and life-cycle analyses of electric buses. Our findings provided Friends of the Earth Melbourne and the Public Transport Users Association with suggestions for improving the bus system's equity and efficiency, as well as statistics supporting Melbourne's switch to a fully electric fleet.

Acknowledgements

We would like to thank our partners on this project, Claudia Gallois from Friends of the Earth Melbourne and David Robertson from the Public Transport User Association. They helped us answer many questions about our project and provided us with extensive support and resources.

We also would like to thank our advisors, Professors Stephen McCauley and Esther Boucher-Yip, for their continued support on this project. Without their abundance of feedback and advice, this project would not have been nearly as successful.

Executive Summary

Although Melbourne, Australia has a well-known tram system, its current bus system has a host of problems that contribute to inefficiency, inequity, and unsustainability. In Melbourne, buses run on meandering and confusing routes, taking far too long to reach their destinations (Currie, 2017). This indirect routing is compounded by the lack of overlap between buses and other modes of transit, making transfers difficult. Additionally, long wait times at bus stops in Melbourne are a hindrance to attracting new riders. Wait times in Melbourne average 20 to 30 minutes during the week, and 30 minutes to an hour on weekends (Pandangwati & Milyanab, 2017). These wait times are excessive compared to the suggested wait times of 10 minutes during peak hours and 30 minutes during low-demand periods (Mees, 2009). Traffic congestion is another major problem in Melbourne, contributing to a slow and unreliable system. Since Melbourne's population has grown by 48% in the past 20 years, the number of cars on the road has increased tremendously, slowing down the buses (World Population Review, 2021).

These inefficiencies encourage an increase in the use of passenger vehicles. Since buses carry more passengers per trip than cars do, the emissions produced per person are significantly lower. In an attempt to reduce carbon emissions, the Victorian government has expressed an interest in shifting its bus fleet to fully electric in the coming decades. Battery-powered buses remove the effects of tailpipe emissions, which can contain a variety of greenhouse gases as well as fine particulate matter. Reducing emissions can help prevent climate change and alleviate related public health concerns. Additionally, electric buses are more attractive to users due to their smooth, quiet operation, which encourages higher ridership levels (Marshall, 2019; US EPA, n.d.).

When conducting background research on the current system's equity in terms of bus accessibility, we found a positive spatial correlation between nearby, convenient bus routes and high-income neighborhoods. There is also a lack of services in fringe suburban areas. These regions are where economically and socially disadvantaged groups typically can afford to live (Ricciardi et al., 2015). Melbourne residents are moving to the suburbs so there is an increased need to service these neighborhoods. The suburbs currently have less access to bus and rail services than the inner city populations (Currie, 2017).

This project provided recommendations to Friends of the Earth Melbourne and the Public Transport Users Association's Sustainable Cities campaign for increasing the efficiency, equity, and sustainability of the bus system throughout Melbourne's suburbs.

Case Studies of Various Bus Systems

We first investigated various bus systems to understand the factors that lead to sustainable, equitable, and efficient systems. Interviewing officials helped us develop a deeper understanding of how these successes occur and provided us with strategies that we referenced when developing recommendations for improvements to Melbourne's current system. We interviewed the following six experts from various countries:

- John Storrie, a transport and infrastructure leader in Melbourne
- Dr. John Stone, an urban planning professor at Melbourne University
- An anonymous private bus operator from Sydney
- Dr. Peter Newman, a sustainability professor at Curtin University in Perth
- Gordon Price, a former founder of TransLink in Vancouver, Canada
- Dr. Gregory Trencher, a renewable energy professor at Tohoku University in Japan

These interviews drew attention to four major areas within which reforms could be applied to Melbourne's bus system:

- Efficiency
- Equity
- Public and private relationships
- Electric bus implementation/sustainability

From these interviews, we learned that efficiency is arguably the most important aspect of a successful bus system. Increasing the frequency of buses and syncing the timetables with other modes of public transport is essential to improving ridership levels. We also learned that the bus system will satisfy more users if routes are reconsidered in underserved suburbs and urban centers are implemented to increase equitable access. Additionally, we gained a deeper understanding of the role that a strong relationship between the government and private bus operators plays in implementing reform. Finally, we discussed the importance of electric bus implementation to a more sustainable future, and learned about a number of barriers to the transition that require careful planning.

Investigation of Equity in Bus Accessibility

Next, we distributed a bus satisfaction survey to give us insight into what improvements are more important to patrons. We then conducted a spatial analysis to illustrate the bus system's coverage throughout Greater Melbourne to determine potential gaps in access to transportation.

Passenger Satisfaction with Melbourne's Bus System

In addition to learning from transportation experts, we thought it would be valuable to hear from the citizens who directly interact with the buses. We distributed a Google Forms survey via email and QR code flyers to residents of Greater Melbourne to assess bus user satisfaction levels. Our survey clarified that Victorian citizens are generally dissatisfied with the buses that run throughout Greater Melbourne, mainly because of the infrequent bus scheduling and long wait times at bus stops. Our interviewees agreed that having an efficient bus system is arguably the most essential aspect of successful public transit and that frequency was an important factor to address.

Gaps in Bus Accessibility by Income

We also conducted a spatial analysis of Greater Melbourne to better visualize possible inequities in bus accessibility. We overlaid maps of the bus routes with income level and population density distributions. We confirmed that these bus routes often cater to wealthier areas. Despite some lower income areas having access to several bus routes, our interviewees discussed how these routes often do not run frequently enough to be a reliable form of transportation. We also found that bus routes are more plentiful in more densely populated areas. Overall, our two maps illustrate that although some lower income areas have a higher number of routes, they typically have a high population density, thus explaining the increased accessibility.

Implications of Electric Bus Implementation

Finally, we assessed the implications of implementing electric buses into Melbourne's existing transportation system by conducting life-cycle and cost-benefit analyses. These examinations helped us understand the overall environmental and financial savings of electric bus implementation.

Environmental Implications of Electric Bus Implementation

We first conducted a life cycle assessment to compare the lifetime carbon dioxide emissions (CO_2e) produced by diesel fuel and electric bus batteries to demonstrate the differences in their environmental impacts. For diesel buses, we quantified the CO_2e from oil extraction and tailpipe emissions, whereas for electric buses, we quantified the CO_2e from battery construction and electricity generation. We found that the fuel used to power one diesel bus throughout its lifetime produces a total of 45,819 tonnes of CO_2e, and each electric bus battery produces only 153 tonnes of CO_2e in its lifetime.

Social Savings of Electric Bus Implementation in Melbourne

The second part of our electric bus research focused on a cost-benefit analysis of all social costs and benefits related to a total implementation of electric buses. For this analysis, we accounted for all private and external costs and benefits over the lifetime of a bus. We first found that despite being a newer technology, electric buses are only slightly more expensive in terms of the direct costs. We then quantified the externalities, or costs and benefits to society as a whole. We focused on public health, sustainability, user satisfaction, national security and military efforts, job loss and creation, and insurance costs. When total social costs and benefits were combined, we found that there would be a net savings of approximately AU$222,572 for each electric bus, or a staggering AU$600,944,400 for the whole fleet.

Conclusions and Recommendations

Based on our surveys and interviews, the most recommended way to increase efficiency is to improve the frequency of buses and sync bus arrival times with other forms of public transportation. Additionally, we suggest making a bus usage guide in a physical form or an app to attract new riders and eliminate any confusion surrounding the system. We would also recommend looking into computerized signal priority, which is a software that allows buses to avoid traffic delays.

One way to improve equity is to implement urban centers throughout Greater Melbourne to ensure easy access to major modes of public transportation for all users. Additionally, the implementation of electric buses has the potential to contribute to a more equitable system, as it makes zero-emission vehicles accessible to users regardless of socioeconomic status. Finally, significantly increasing bus frequency would ensure that all routes are viable transportation options. Overall, these three components have the ability to lead to a more universally accessible bus system.

Through our examination of the feasibility of electric bus implementation, we concluded that switching Melbourne's bus fleet from diesel-powered to fully electric would be advantageous. Electric buses are generally more attractive to the public and have significant environmental benefits. In order to facilitate a smooth transition to electric buses, we suggest both implementing charging stations at existing depots and introducing electric buses gradually to avoid drastic infrastructure changes. Additionally, we recommend incentivizing reform in contract renewal, which has the potential to effectively enable a gradual transition to electric buses while simultaneously phasing out the usage of old diesel bus technology. This incentivization would also help strengthen the relationship between the government and private operators.

Authorship

The group collaborated on composing various sections of the report, including all chapter introductions and summaries, as well as the appendices related to interviews and the questionnaire. Section editing was also a group effort.

Ryan Astor: This author was the main contributor to the private costs section of the findings in research, analysis, writing, and related appendices. He also did primary research and writing related to sections about Perth and Vancouver. Next, he did primary writing for the partner organizations section and executive summary. Finally, he compiled and updated the table of contents and made graphs and other visuals for the report and presentation.

Caroline Jaeger: This author led the research, analysis, writing, and construction of related appendices of the externalities section of the findings. She also drafted the feasibility of electric bus implementation and Sydney case study methodology sections, as well as contributed to the background chapter by writing about the Sydney case study, recognized problems of the Melbourne bus network, and the sustainability of the system. She was the primary contributor to the spatial analysis, John Storrie, Dr. Peter Newman, and Dr. Gregory Trencher sections of the findings.

Jenny Lewitzky: This author led the research, analysis, and writing of the life-cycle assessment of diesel fuel, as well as the related appendices. She also produced the Dr. John Stone interview findings and composed the questionnaire methodology and findings. Additionally, she researched and worked on the renewable energy sections of the background and collaborated on the project conclusion and recommendations. Finally, this author designed the two supplemental infographics.

Anthony LoPresti: This author led the writing and research for the life cycle assessment of the electric bus section, the case studies of bus reforms in different cities, specifically the Perth, Sydney, and Shenzhen sections, the interview sections, and the executive summary. Additionally, he contributed to research in regards to the problem section and research throughout the methodology section of the report.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

Melbourne is one Australia's most populous cities, with a growing need for accessible mass transit. Although the city has a well-known tram system, the buses suffer from low ridership levels, resulting in cost-inefficiency in many areas throughout Greater Melbourne (Mallis, 2020). There is a negative correlation between transit usage and the number of individual cars on the road, meaning that increased transit usage leads to fewer people driving cars (*Public transit ridership increases*, 2018). Lower individual car usage leads to higher overall sustainability levels (Zheng et al., 2011). Since the greenhouse gas emissions produced by individual vehicles contribute substantially to the current climate crisis, Melbourne is encouraging citizens to utilize public buses to reduce the number of cars on the road (Climate Council, 2017).

According to our partner organizations, Victoria is facing an economic recession due to the onset of the COVID-19 pandemic, resulting in fewer monetary allocations for infrastructure projects. Bus system reform is likely to be seen as more achievable for the Victorian government than reform of other modes of transportation because the bus system is smaller scale and less expensive. Buses play a crucial role across metropolitan, regional and rural areas by providing connectivity that is essential to a high-functioning transport network. In metropolitan areas, buses provide mass transit into urban centers, serve as feeder services to the broader public transport network (trains, trams, and ferries), and link outer suburban centers. In regional and rural areas where population densities do not justify higher-cost and less-flexible options such as heavy rail and light rail, buses are the backbone of the public transport system (Tourism & Transport Forum Australia, 2016). The fundamental nature of the bus system has motivated our partner organizations to advocate for minimizing the inefficient, inequitable, and unsustainable practices within Melbourne's bus system. Melbourne's bus routes are known to be meandering and slow, and this infrequency leads to long trips and waiting times at bus stops, making this mode of transportation seem unappealing. These low ridership levels lead to unnecessarily high levels of greenhouse gas emissions (Mallis, 2020). The Victorian government has expressed an interest in implementing a fully electric fleet of buses throughout Melbourne, which could considerably reduce these emissions. Greenhouse gas emissions are also directly correlated to air pollution, and they significantly endanger public health (World Health Organization, n.d.).

Additionally, there is a disparity in transit accessibility between income brackets; it is less common for citizens with lower economic statuses to have convenient access to bus stops (Ricciardi et al., 2015).

Our goal for this project was to provide recommendations for increasing the efficiency, equity, and sustainability of the bus system throughout Melbourne’s suburbs. To do this, we investigated various bus systems via interviews conducted with experts in the transportation sector. This helped us gain insight into factors that Melbourne can implement into its bus system to become more successful. We also studied the state of the current bus system throughout Melbourne’s suburbs to determine potential gaps in access to transportation. This helped us form a comprehensive visual of where inequities exist. Lastly, we assessed the effects of electric bus integration into Melbourne’s existing mass transit through use of cost-benefit and life-cycle analyses.

2.0 Background

This chapter presents an overview of the current bus system in Melbourne, Australia. The city has a history of low bus use that resulted from inefficient and ineffective design. There is also a disparity in accessibility between income brackets. To better understand the low patronage of the Melbourne bus system, we discuss routing that could contribute to the lack of ridership as well as how these issues hinder the city's sustainability and equity efforts. We also introduce case studies of other bus and public transportation systems worldwide.

2.1 Partner Organizations

Our team worked with Friends of the Earth Melbourne and the Public Transport Users Association to complete this project. We hoped to aid them in making their goals of a more efficient, equitable, and sustainable bus system a reality. Due to the onset of the COVID-19 pandemic, Victoria is facing an economic recession. This has resulted in less money being allocated for infrastructure projects. Our partners suggested this project on bus reform instead of reform of other modes of public transit because bus system reform is likely to be seen as more achievable for the Victorian government.

2.1.1 Friends of the Earth (FoE)

Friends of the Earth, FoE, is a global organization with chapters in more than 70 countries. They are a non-profit organization advocating for social and environmental justice, which they view as one and the same. They also look to build a more equitable and viable future for communities all around the world. We are working locally with FoE Melbourne, one of the eight chapters in FoE Australia (Friends of the Earth Melbourne, n.d.). This chapter participates in food co-ops, climate action, economic justice, nuclear-free collectives, and numerous environmental campaigns to preserve ecosystems and biodiversity.

In 2017, FoE Melbourne started a campaign called "Sustainable Cities." The goal of the campaign is to make the city of Melbourne more livable for the average citizen. FoE aims to do this by advocating for more investment in public transport instead of new roads. They believe the campaign will benefit jobs, education, healthcare, shopping, and more (Friends of the Earth Melbourne, n.d.).

2.1.2 Public Transport Users Association (PTUA)

FoE Melbourne has partnered with the Public Transport Users Association, PTUA, to promote their Sustainable Cities campaign. They are a non-profit organization representing public transportation users. The PTUA operates solely in Victoria and advocates for use of public transportation to minimize the production of carbon emissions from individual cars. They provide people who have limited resources access to various parts of the city and lobby the government to make public transport a higher priority. Some of their major accomplishments include reversing a ban on bicycles on trams, increasing rail and tram frequency on busy days, and increasing bus service routes (Public Transport Users Association, n.d.).

2.2 Problems Identified Within the Melbourne Bus System

The population of the Greater Melbourne Area is currently almost 5 million (World Population Review, 2021). Melbourne is the fastest growing city in Australia, with a population growth of over 2% every year since 2007 (Melbourne, n.d.). Over 50% of the working population drives to work, and bus ridership levels are inconsistent (Jacks, 2019). While some routes have no trouble pulling in plenty of passengers, three separate bus routes carried less than 100 passengers during the entirety of the 2016-17 financial year (Jacks, 2019). In Melbourne, the tram is the most common form of public transportation, followed by the commuter railway, and the bus in third place with over 137 million passenger trips in 2015–16 (Australian Bureau of Statistics, n.d.).

2.2.1 Poor Routing

Although public transit is becoming more emphasized throughout the world, Melbourne's bus system suffers from low ridership levels. Some of the buses carry fewer than ten passengers a day (Jacks, 2019). This can be partially attributed to the routing system of the city's buses. These buses run on indirect, slow, and confusing routes that take far too long to reach their destinations (Currie, 2017).

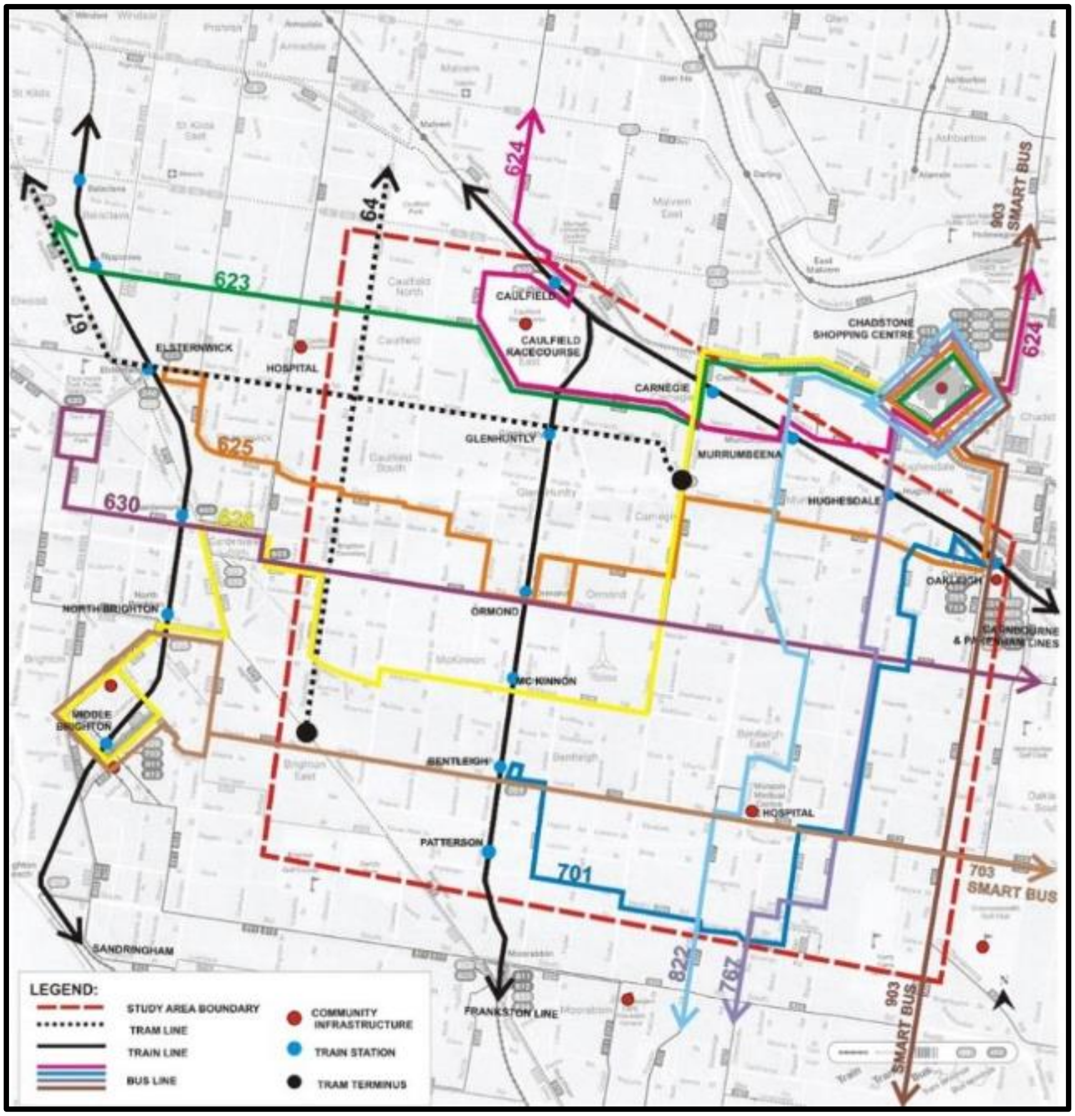

Figure 1: Current Bus Routes in Melbourne (Pandangwati & Milyanab, 2017)

Currently, Melbourne's bus routes overlap significantly, as shown in Figure 1. The colored routes represent the bus lines, and the black solid and dashed lines are the train and tram routes, respectively. Different routes, such as 623 (green) and 624 (pink), service the same neighborhoods, leaving some areas underserved and others overserved. Without access to buses, people without passenger vehicles such as cars do not have a mode of transportation to the inner city. Additionally, if the routes are inaccessible, ridership is limited to those who live close by.

Over two-thirds of Melbourne can be reached only by bus; the train and tram systems are reserved for the inner city, making them inaccessible to passengers in the suburbs (Currie, 2017).

As buses are the main mode of public transport in the suburbs, addressing the lack of accessible routing is necessary to ensure reliable public transportation for the majority of the population.

Additionally, the system's indirect routing can lead to longer travel times. Figure 1 shows that some bus routes are meandering with unnecessary overlap with other routes (Pandangwati & Milyanab, 2017). This indirect routing is compounded by the lack of overlap between bus stops and train stations, making transfer difficult from bus to rail and bus to bus. The blue dots in Figure 1 along the tram line are train stations; none of the current bus routes stop at any of these stations, despite the intersection and opportunity for transfers (Pandangwati & Milyanab, 2017).

2.2.2 Long Trip Durations and Wait Times

The long trip durations and wait times of Melbourne's bus routes also contribute to the system's inefficiency. On average, the duration of a full one-way trip on the bus takes roughly an hour (Transdev Melbourne, n.d.). These long wait times at bus stops in Melbourne result from infrequent scheduling and poor network planning. Based on data collected from Melbourne's inner southeast suburbs, the average time between bus arrivals was 20 to 30 minutes during the week, and on the weekends 30 minutes to an hour (Pandangwati & Milyanab, 2017). According to former Public Transport Users Association president and transportation expert Paul Mees, an acceptable time to wait for a bus should be no longer than 10 minutes during peak transportation hours and only up to 30 minutes during slower times (Mees, 2009). Therefore, Melbourne's buses have excessively long wait times. Additionally, transfers are often inevitable, since arriving at a destination generally requires multiple services. However, the bus and train schedules are not always coordinated effectively. In some cases, trains regularly depart just before buses arrive. For example, on Wednesdays, it was observed that the 9:26 am Sandringham line leaves Gardenvale Station for the city one minute before the bus arrives, forcing commuters to wait an additional 14 minutes for the next train (Metro, n.d.; Transdev Melbourne, n.d.). To make transfers convenient and efficient, the network must have a careful timetable coordination or more frequent services.

2.2.3 Traffic Congestion

One of the biggest roadblocks for the Melbourne bus system is traffic congestion. With a population that has grown by 48% in the past 20 years, the amount of cars on the road has increased tremendously (World Population Review, 2021). As a vehicle sits idling in traffic, unnecessary fuel is being consumed and time and money are being wasted. In a study conducted by Infrastructure Australia, it was observed that congestion is exacerbated during morning peak hours on the western and eastern suburb roads that provide access to the inner city. Another finding in this study was that a commute from the airport to the city via the Tullamarine Freeway, a mere 17 km trip, experienced a delay of 24 minutes during peak morning hours. This route between Melbourne Airport and the city is the busiest and most congested route and is the worst performing in both peak periods (Australian Infrastructure, 2016). Not only is addressing traffic congestion in Melbourne significant to daily commuters, but it greatly affects the overall bus system. Buses get caught in this traffic due to a lack of bus lanes and effective signal priority. To avoid the unreliable buses, commuters may choose to take their own cars, leading to low levels of bus ridership.

2.3 Improving the Network's Equity and Sustainability

2.3.1 Equity Considerations

There is a positive spatial correlation between accessible, convenient bus routes and high-income neighborhoods, with a lack of services in fringe suburban areas. These suburban areas are where economically and socially disadvantaged groups are most likely to reside (Ricciardi et al., 2015). Residents within 20% of Melbourne's most financially stable households tend to be within walking distance of a bus stop, whereas lower income groups tend to live farther away (Scheurer et al., 2017). When analyzing inequity in public transportation, researchers concluded that the three most vulnerable populations to inconsistent transportation access are low-income households, no-car households, and the elderly (Ricciardi et al., 2015).

A recently published report examining the disparity in transportation accessibility in Greater Melbourne utilized these factors to calculate and compare Perth's and Melbourne's Gini coefficients (Ricciardi et al., 2015). These coefficients are widely accepted measures of access to public services based on income in the field of statistics, and can be thought of as the expected ratio of equitably distributed access to public transit (Rogerson, 2013). The authors that conducted this study concluded that Perth has a Gini coefficient of 0.52 while Melbourne's is 0.68, from which we can see that Perth's system is considerably more equitable than

Melbourne's (Ricciardi et al., 2015). According to a similar study focusing on Sydney, Australia, Sydney's Gini coefficient is 0.62 (Xia et al., 2016). Although this value signifies that Sydney is not as equitable as Perth, we can still conclude that Melbourne has the highest level of inequity among the cities.

2.3.2 Sustainability of Melbourne's Bus System

As a whole, Australia's transportation system is ranked very poorly in terms of environmental performance, which was determined to be due to a high rate of automobile usage (Henriques-Gomes, 2018). The number of cars on the road correlates to bus ridership. In 2017, the Utah Transit Authority demonstrated this after allowing free bus rides all day for one Friday, providing an incentive to increase bus users; as a result, the association calculated that 17,560 fewer individual vehicles were driven that day, which significantly reduced greenhouse gas emissions (Utah Transit Authority, 2018). Since buses transport greater numbers of passengers per trip than cars, the emissions produced per person are significantly lower in modes of mass transit relative to cars. Figure 2 shows the average carbon emissions per kilometer for various forms of transportation (Climate Council, 2017).

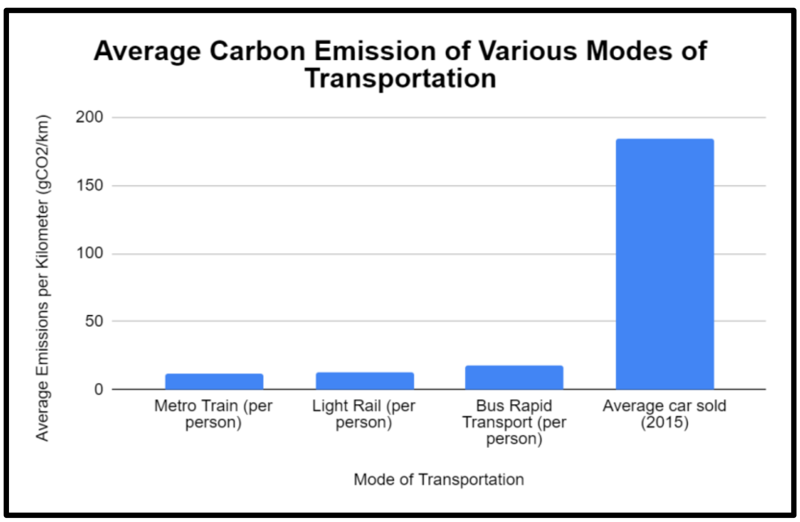

Figure 2: Carbon emissions of various modes of transportation (Climate Council, 2017)

Besides simplifying bus routes, another sustainable strategy would be to replace diesel buses with electric buses. While diesel buses emit greenhouse gases through tailpipe emissions, electric buses are sustainable during vehicle operation. Melbourne's bus fleet produces around 78,300 tonnes of carbon dioxide emissions (CO_2e) each year through tailpipe emissions alone

(MacKechnie, 2019; Chang et al., 2019). This is equivalent to cutting down roughly 3,195 trees a year (Alter, 2018). These emissions lead to global warming and other extreme weather events that affect the makeup of ecosystems and contribute to rising sea levels, amongst other impacts (Nunez, 2019). Additionally, the direct tailpipe emissions from diesel buses contain fine particulate matter that contributes to local air pollution. These particles can be carried over long distances and settle on the ground or in the water, which can change the pH levels of bodies of water, deplete nutrients, damage crops, contribute to acid rain effects, and lower biodiversity in these ecosystems (US EPA, 2016b). However, although electric buses do not produce CO_2e while running, it is crucial to also take into account other processes during their lifetimes, such as the manufacturing of the buses' batteries. These processes release CO_2e into the atmosphere.

Electric buses can also encourage higher ridership numbers since they ride more smoothly and quietly than diesel buses (Marshall, 2019; US EPA, n.d.). They produce far less noise pollution and can provide various amenities, including onboard internet, charging, and air conditioning (Nunno, 2018). All of these factors have the opportunity to contribute to an increase in ridership (Currie et al., 2018). The reduction in noise pollution is especially important, as environmental noise pollution has health implications for the local population exposed to it. For example, studies suggest a relationship between exposure and hypertension, as well as sleep disruption and noise induced hearing loss (Hammer et al., 2014). There are also a variety of psychological effects, including stress and annoyance (Stansfeld & Matheson, 2003).

Additionally, other major public health improvements are to be gained through the switch from diesel to electric buses. Battery powered buses remove the effects of tailpipe emissions, which can contain fine particulate matter in addition to a variety of greenhouse gases. According to the United States Environmental Protection Agency (US EPA), exposure to particulate matter can cause earlier death, cardiovascular and respiratory harm, cancer, and reproductive and developmental harm, among other things (US EPA, 2016b). The greenhouse gases, including CO_2, methane, and nitrous oxide, have environmental and health impacts related to exposure such as asthma, cancer, and cardiovascular diseases, as well as any subsequent health effects from climate change (National Institute of Environmental Health Sciences, n.d.).

The Victorian government has begun to work towards electric buses in the past few years. Currently, Melbourne has only one fully electric bus integrated into the public transportation system, which is still in a trial phase (Hope, 2020). Additionally, 50 hybrid buses were introduced earlier that year (Sustainable Bus, 2019). Although Melbourne has recently begun this integration of hybrid and battery-powered electric buses, most buses are still powered by fuel.

2.4 Case Studies of Bus Reform in Different Cities

2.4.1 Bus Reform in Sydney

As Australia's two largest cities, Sydney and Melbourne have a historic rivalry that is alive and well today (McGilvray, 2016). Our partner organizations subsequently suggested that we look into how Sydney plans on implementing their future bus reforms to provide further incentive for the Melbourne government to consider our future recommendations.

As of December 2, 2020, Sydney has proposed switching over to fully electric buses by 2030. Although the city only has five electric buses that are all in trial phases, the government plans to replace the entire fleet of 8,000 diesel-powered buses in the next decade (Rabe, 2020).

Sydney's public transportation system is privately operated, with the exception of the State Transit Authority (NSW Government: Transport, n.d.). The State Transit Authority is a publicly owned bus operator controlled by the New South Wales government (NSW Government: Transport for NSW, n.d.). They operate on the same level as the other private operators in Sydney. This differs from Melbourne's bus system which is run by exclusively private bus operators (Grigorovitch, 2017). Our partner organizations are interested in exploring how to improve the relationship between the government and private bus operators in Melbourne, so this topic was especially important for us to pursue.

2.4.2 Bus Reform in Perth

Generally speaking, Perth has a highly regarded public transportation system. Our partner organizations specifically suggested that we look into Perth because of the cohesive relationship that Perth's bus companies have with their government. Melbourne also currently has private buses, but they have poor communication between one another and the government, so the system has not had the same success (Tourism & Transport Forum Australia, 2016). In 1993, Perth made one of the largest bus reform changes in its history by privatizing a large portion of its bus fleet. This privatization reduced operational costs of the bus system and improved user satisfaction. Transperth, the city's transportation department, set out to save money on the current system while keeping the same or better quality of service. In a study done a few years after this change was enacted, the researchers found that costs were reduced by a factor of 20% (Auditor General, 1997). Many local bus providers competed in this privatization of the previously government run routes. Because of the competition, bus companies were incentivised to run the lines cheaper than the government used to. At the same time, it was found that the reliability of the buses, based on customer complaint data, did not see any significant change from before and after the shift in bus management (Auditor General, 1997). The system was eventually fully privatized in 1998. The prices to tender today's bus routes in Perth continue to drop as companies must compete over operating one of the twelve sectors of routes in the city. This has made the bus system very cost-effective (Wallis & Bray, 2014). Even with reduced spending, satisfaction rates have gone up. From 1996 to 2013, overall satisfaction increased by 6% and ridership increased by 87% (Wallis & Bray, 2014). Beyond cost benefits, the Perth system is also considerably more equitable than other Australian cities. As referenced earlier, Transperth has a better equity coefficient than Melbourne's bus system (Ricciardi et al., 2015). Like with Sydney, it is crucial to study other cities' successful public and private relationships so we can develop suggestions for more successful communication within Melbourne's system.

2.4.3 The Bus System of Vancouver

Vancouver, Canada's transportation network provides us with a valuable outsider perspective on transportation while still being a very relevant comparison. Our partner organizations noted that Melbourne and Vancouver have a similar layout and population density, making such an analysis very valuable. Founded in 1999, TransLink is a company in Vancouver that is responsible for all public transportation services. Under their management, the city's transit system has flourished, with public ridership more than doubling in the past 20 years (BC Transit, n.d.).

TransLink has been discussing the possibility of switching to electric buses for a few years and has even implemented a few into the bus system already. In fact, Vancouver's trolleybus system is powered by overhead electric wires, with routes that mainly run in downtown Vancouver. Their 70 year history shows that Vancouver has been pushing towards electrified buses for decades (William-Ross, 2018). TransLink is now starting to push into electrifying their conventional buses as well. On January 26, 2021, TransLink announced a CA$16 million expansion of their electric bus network with the purchase of 15 new electric buses to be rolled out in the next few years. They hope to cut the fleet's greenhouse gas emissions by 45% by 2030 and be fully electric by 2050 (TransLink, 2021).

2.4.4 Shenzhen Electric Bus Implementation

One of the most effective integrations of electric buses occurred in Shenzhen, China. Between 1980 and the present, the city has been experiencing rapid population growth, which has led to significant environmental challenges due to the expansion of the transportation sector (Macrotrends, n.d.). Shenzhen has become one of China's first pilot cities for alternative fuel vehicles, with the world's first 100% electric bus fleet (Keegan, 2018). During the shift, bus ridership in Shenzhen remained proportional to public transport availability as the overall population increased (Dong et al., 2018).

In a study published in 2018, researchers conducted a general life cycle assessment of vehicles powered by different fuels. Researchers found that larger electric buses contributed the most to carbon emission reductions; out of all of the reductions due to alternative fuel buses, they accounted for 73% (Dong et al., 2018). This shift has resulted in an expected 48% reduction in carbon emissions, with substantial cuts in pollutants like nitrogen oxides and other particulate matter (Keegan, 2018).

2.5 Summary

Our research aimed to develop solutions that address the issues of Melbourne's current bus transportation system. Our background research focused on the system's efficiency, equity, and sustainability. With help from our partner organizations, we aimed to minimize the CO_2e produced by Melbourne's bus network and advocate for more convenient and equitable routes throughout Greater Melbourne. It is crucial to understand both the costs and emissions related to diesel and electric buses. Numerous metropolitan areas have recently made significant reforms to their bus systems, and researching these reforms is valuable to understand how to support similar transitions in Melbourne. Similarly, in terms of accessibility, it is essential to collect current demographic data related to income in various communities throughout Melbourne to fully understand how to effectively optimize bus routing.

3.0 Methodology

Our project goal was to provide recommendations for increasing the efficiency, equity, sustainability of the bus system throughout Melbourne's suburbs. In this chapter, we explore three main objectives through which we develop a related methodology. First, we investigate various bus systems from around the world to understand the aspects that led to a successful bus system. Interviewing officials helped us develop a deeper understanding of how these successes occurred and provided us with strategies that we referenced when proposing refinements to Melbourne's current system. Our second objective is to determine the coverage of the existing bus system throughout Greater Melbourne to determine potential gaps in access to transportation. By examining current access to public transportation in these suburbs using satisfaction surveys and a spatial analysis, we gained a better understanding of how to optimize routes for increased equity. Our final objective is to assess the effects of integrating electric buses into Melbourne's existing transportation system by conducting life-cycle and cost-benefit analyses. These examinations helped us understand how bus implementation costs might compare between diesel and electric buses, as well as how electric buses could improve the city's CO_2e levels.

3.1 An Analysis of Bus Systems

Our first objective was to investigate various bus networks throughout the world to inform our proposal for bus reform in Melbourne. We also aimed to better understand the Melbourne bus system to identify effective and ineffective components. To achieve this objective, we conducted interviews with representatives from Melbourne, Sydney, Perth, and Vancouver. We also spoke with a professor at Tohoku University in Japan about the logistics of alternative energy bus systems. These interviews helped us learn about possible methods of bus reform implementation.

3.1.1 Melbourne, Australia

In addition to our background research on Melbourne's current bus system, we decided that it would be valuable to interview some experts to gain first-hand insight on how the network is struggling. Our first Melbourne interviewee, Dr. John Stone, is a professor at Melbourne University who specializes in transport and urban planning. He has extensive experience researching Melbourne's transportation system and how it can be improved, so he is familiar with our partner organizations' work as well. We focused our interview questions on the state of Melbourne's current bus system and the main issues Dr. Stone has found within the network.

We also interviewed John Storrie about the state of Melbourne's bus system. He currently works as a Transport and Infrastructure Leader at Smedley Technical and Strategic in Melbourne, a company that aims to develop more equitable infrastructure throughout the city (Smedley Technical and Strategic, n.d.). Before this role, Storrie worked as a government consultant for various public and private transportation projects throughout Australia, so he has expertise in public and private relationships, as well as the similarities and differences in transportation systems across the country. We focused our interview on analyzing the relationships between bus operators and their governments. We also explored what could be learned from the transportation systems of other Australian cities to help Melbourne's bus system become more successful.

3.1.2 Sydney, Australia

Sydney, Australia has recently proposed a plan to switch to electric buses by 2030 (Rabe, 2020). We conducted an interview that focused on the policy behind the implementation of electric buses and the relationships between public and private bus operators. Our interviewee, who wished to remain anonymous, is a network planning manager for a private bus operator. From this interview, we gained a better idea of how Sydney plans to implement electric buses over the coming decade as well as what the relationship is currently like between private bus operators and the State Transit Authority, New South Wales's transportation agency.

3.1.3 Perth, Australia

It was beneficial to compare Perth to Melbourne because both are Australian cities and large metropolitan areas. As discussed earlier, Perth's local transit system, Transperth, is one of the most effective transportation networks in all of Australia. We examined various aspects of the Perth bus system including the history of bus reform in Perth, mechanisms and institutions that run the bus system today, and any plans being considered for the future. We studied how the governance of the system functions and the relationship between the Perth government and the local private bus companies that provide bus services. In order to study these factors, we interviewed Dr. Peter Newman, a professor at Curtin University and transportation activist with Transperth. We gained a better idea of Transperth's successes in terms of its bus system's efficiency and equity, and used these findings to develop recommendations for improvements to Melbourne's bus system.

3.1.4 Vancouver, Canada

We also compared Melbourne's bus system to that of Vancouver, Canada due to similarities in layout and population density. We gained a valuable perspective on their bus system by interviewing Gordon Price, a former director of The City Program at Simon Fraser University and a former member of the Vancouver city council. He was also one of the first ever members of the board for TransLink when it was first founded in 1999 (Simon Fraser University, n.d.). Through his knowledge and experience, we aimed to collect information about his time working on the board of TransLink and how they were able to run their network successfully. We also looked to learn more about the upcoming investments in electric bus projects for the city, how those got started, and how they are currently progressing.

3.1.5 Logistics of Alternative Fuel Bus Implementation

Finally, we were put in touch with Dr. Gregory Trencher, who is currently based in Sendai, Japan. He is an environmental studies professor at Tohoku University and researches sustainable and renewable energy alternatives for various cities throughout the world, such as Sacramento, Berlin, and Shenzhen (Trencher, 2019). Although the majority of his expertise is on hydrogen fuel cell buses, he still provided us with valuable information regarding the general logistics of implementing alternative fuel buses into exclusively diesel bus networks.

3.2 Investigation of Bus Accessibility

Our second objective was to gain a deeper understanding of the disparity in bus accessibility throughout Greater Melbourne in terms of economic status. We also hoped to get a grasp of what Melbourne citizens currently think of the bus system to identify areas of improvement prioritized by riders themselves. We accomplished this objective by surveying residents from councils throughout Greater Melbourne and by conducting a spatial analysis.

3.2.1 Bus Satisfaction Surveys

According to a recent report written by Worcester Polytechnic Institute students, *Improving Transportation in Hangzhou, China Through Citizen Feedback*, gaining awareness of the viewpoints of transit users is fundamental in understanding levels of user satisfaction with public transportation (Kolaya et al., 2017). To gain a first-person perspective on the quality of Greater Melbourne's current bus system, we conducted surveys with residents to understand their satisfaction levels with the system. Having participants complete our questions asynchronously allowed them to provide information on their schedule and gave them time to develop thoughtful responses (VanBaren, 2017). We were looking to understand how the coverage of the current bus system differentiates between neighborhoods of varying incomes. We distributed online questionnaires to residents via Google Forms. Our partners and project advisor Professor Stephen McCauley also helped us distribute flyers at local bus stops with a QR code that led to the Google Forms survey. A copy of the flyer can be found in **Appendix A**. The questions for the survey can be found in **Appendix B**.

Upon survey distribution in Melbourne, we recognized many cases of sampling bias. For example, to scan the QR code on the flyer or locate the online survey, the respondent needed access to a smart phone and/or the Internet to fill out the Google form. This was also a hindrance for older generations who may not understand the technology enough to be willing to complete the survey or be able to figure it out. There were also other problems with not reaching people who were busy or had their hands full, such as a mother pushing a stroller. This may have skewed some of our data.

3.2.2 Spatial Analysis

To understand the distribution of bus routes to subsequently suggest improvements throughout suburbs of Melbourne, we conducted a spatial analysis of the area. Spatial analyses involve developing a map that divides the land into sections based on specific demographic data (Fischer, 2001). We overlaid a map of Melbourne's current bus routes through Greater Melbourne with statistics that define the social statuses of various neighborhoods. To aid our research, we utilized AURIN Maps, a website that allows users to layer various statistics over a map of councils throughout Australia, and we focused specifically on Greater Melbourne. Some especially useful layers included bus routes, average weekly income levels, and population densities. We used this information to determine any correlations between bus route accessibility and income levels. Our goal was to acquire data that could provide insight into where routing discrepancies occur, such as lack of accessibility in underserved neighborhoods. This helped us determine how to potentially optimize the system to evenly cater to all residents.

3.3 Feasibility of Electric Bus Implementation

Our third objective was to assess the feasibility of integrating electric buses into Melbourne's current transportation system. We conducted a life-cycle assessment and a cost-benefit analysis to compare electric and diesel buses. These methods aided us in compiling statistics to advocate for the implementation of electric buses. Compounded with suggested route optimization, these analyses allowed us to continue our development of a proposal to increase the sustainability of Melbourne's current bus system. Both of these methods were developed by analyzing previous studies, compiling relevant data, and performing derivations.

3.3.1 Life Cycle Assessment

Conducting a life-cycle assessment allowed us to examine the environmental impacts of electric buses and diesel buses throughout their lifetimes. Through this analysis, we compared the sustainability of these two types of buses.

When assessing the life-cycle emissions of diesel buses, we focused on tailpipe emissions and the acquisition processes of diesel fuel. For electric buses, we worked with the emissions generated by the lithium-ion batteries that power the buses, since they are the most environmentally damaging component and are unique to electric buses. It was also imperative to account for emissions produced to power the charging stations for these buses. The goal was to determine whether the implementation of electric buses would be more sustainable than diesel buses throughout the buses' lifetimes. For this assessment, we referenced previously conducted analyses in our comparison of the two types of buses in Melbourne. As shown below, Figure 3 outlines the factors that were considered in the life-cycle assessment. The analysis required the consideration of the energy resource production processes as well as the maintenance required for electric bus implementation. The production steps involve the extraction, transportation, production, and distribution of the energy resources. The maintenance steps consist of the energy used to produce the charging stations and replacement batteries, as well as the environmental impacts of the discarding of equipment after it has become obsolete (Kukreja, 2018).

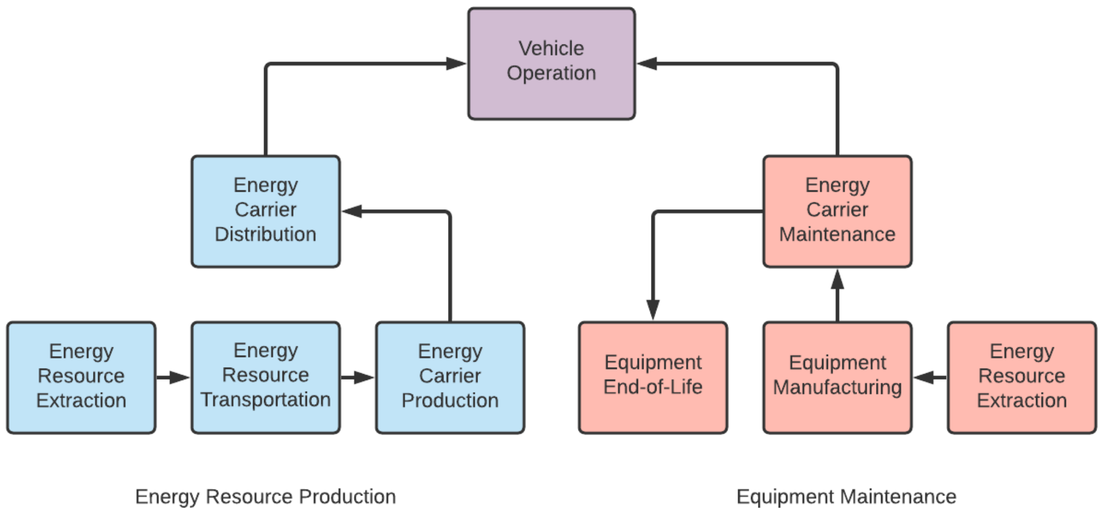

Figure 3: Life-Cycle Assessment Outline (Kukreja, 2018)

3.3.2 Cost-Benefit Analysis

Melbourne government officials have expressed a desire to shift to electric buses entirely. Conducting a cost-benefit analysis allowed us to quantify the costs and benefits associated with implementation, providing officials with further information about whether or not the proposal would be economically beneficial (Keating & Keating, 2014).

This analysis determined whether or not the benefits of fully electric buses outweigh the costs of implementation. These costs included all aspects of the switch to electric buses; for example, we accounted for the expenses related to charging, bus construction, maintenance costs, and overall externalities. In our analysis, private costs and benefits represented direct costs or savings to the government, such as maintenance, charging, and manufacturing of the buses and related technologies. Externalities encompassed the other indirect costs and savings that society incurs as a whole, such as the environmental and public health impacts of carbon. Total social benefits represented the net savings to society, which were a sum of the private costs and the externalities. To effectively conduct the cost-benefit analysis, all of these advantages needed to be monetarily quantified. We also used existing cost-benefit analyses of electric bus implementation and applied these results to the Melbourne bus system. Figure 4 summarizes the steps we took to complete this analysis.

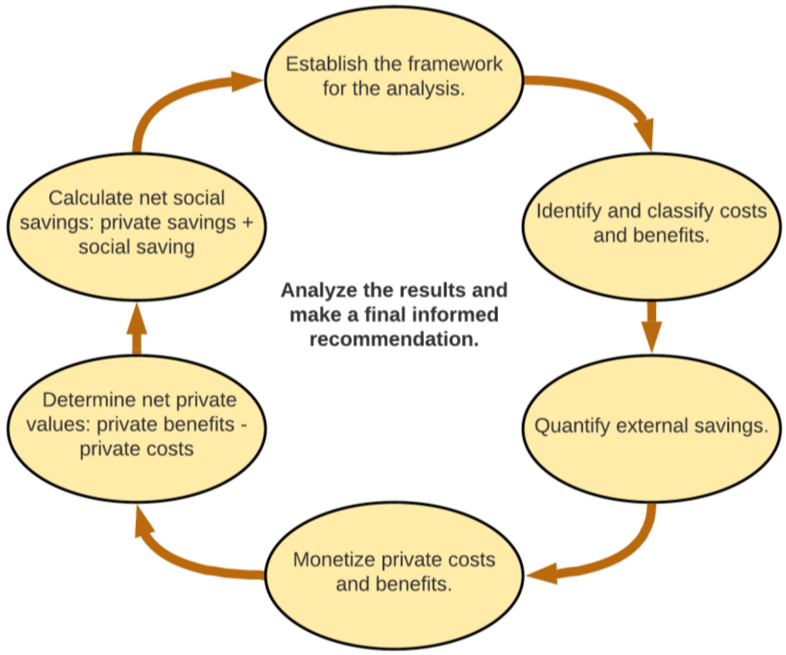

Figure 4: Steps for Cost-Benefit Analysis (Adapted from Wall Street Mojo, n.d.)

4.0 Findings and Analysis

In this chapter, we discuss what we learned from our interviews and questionnaire responses. Additionally, we present the findings of our spatial, life-cycle, and cost-benefit analyses. Our analysis will contribute to Friends of the Earth Melbourne and the Public Transport Users Association's Sustainable Cities campaign.

4.1 Various Bus Systems' Efficacy

To properly assess what changes might be advantageous for the Melbourne bus system, our team decided to look at various public transit systems, both within Australia and abroad, and explore their varying levels of efficacy in terms of efficiency, equity, public and private relationships, and sustainability. First, we interviewed experts from Melbourne to develop an accurate understanding of the current state of the network and identify areas that need to be addressed. We also interviewed experts from Sydney and Perth, as well as experts overseas in Vancouver, Canada and Sendai, Japan. Finally, we compiled all of the views and opinions into areas of improvement for the Melbourne bus system, along with their potential solutions.

4.1.1 Efficiency is the Most Important Aspect of Public Transportation

We found that having an efficient system is one of the most important aspects of a successful bus system. An efficient bus system consists of significant user satisfaction and high ridership levels. In our interview with Gordon Price, a former TransLink board member from Vancouver, Canada, we discussed the importance of high frequency services. Price continued to stress throughout the interview how essential frequency is, saying "if [he] could do one thing, it would just be frequency." One of TransLink's most notable strengths is its focus on high frequency routes, creating a system in which no one is ever waiting for a ride for more than a few minutes. Price went on to say that in Vancouver, "if you see a train coming into the station, why bother running for it? By the time you get to the platform, there's probably another train coming in." If riders know that they will not have to wait long to catch a bus, they may be more likely to consider public transportation as a viable, convenient option.

Although efficient routes are essential to increasing ridership, Melbourne continues to struggle with effective routing. Our interview with Dr. John Stone from Melbourne University gave us a first-person perspective into the issues that Melbourne's bus system currently faces. Dr. Stone emphasized that one of the system's most significant problems is the inconvenient and inefficient routing currently in place. Dr. Stone labeled the bus system as "a service for people who have no other choice" or a last resort. When we asked him what he believed to be the most critical improvement Melbourne's bus system needs, he responded with better routing choices.

One of the additional factors contributing to poor routing in Melbourne is the lack of multi-modal transfer points, as we discussed in our background chapter. In our interview with Dr. Peter Newman, a professor at Curtin University in Perth and transportation activist, we asked what the one thing Melbourne could learn from Perth. His response was to incorporate better transfers between modes of transportation. Perth has successfully upgraded its bus system by facilitating change within the rail network so that the two systems would grow together. He said that "Melbourne's services have been upgraded significantly over the years. The bus services need to be better integrated into that rail and light rail system." Essentially, buses in Melbourne are not at the level of sophistication of the train and tram systems, so improving connections would help integrate the different modes of public transit for a more effective and attractive overall transportation system.

John Storrie, an infrastructure consultant in Melbourne, also touched on the complexities of Melbourne's current routing, and discussed how this discourages riders. He explained that as the network expanded through population growth and development of the suburbs in the early 1990s, the bus network grew as well, but it is not expanding fast enough. Therefore, the routes that once served a particular purpose in the 90s may no longer be as effective in 2021. As money was poured into the system, the complexities grew. Storrie said that "[the network is] almost illegible for people who are not regular users of those routes. . . so people just don't have the confidence to catch [the buses] because they're not entirely certain they'll get where they want to go." If routing is not intuitive, the system becomes less attractive to new riders.

Dr. Stone also offered us an explanation for why the routes are mapped so poorly. He informed us that Melbourne bus companies are currently receiving government subsidies based on the number of kilometers the buses run, as opposed to the number of passengers they carry or the number of times they complete a trip. The companies subsequently have no incentive to increase ridership, and it discourages them from developing shorter and more practical routes. Dr. Stone mentioned that the Victorian government's contract with Transdev, a major bus service provider operating nearly a third of the routes, is expiring this year. According to Storrie, this contract was not renewed for Transdev and is open for applications from other operators to take on these routes. This is a major portion of the bus system and represents a significant opportunity to provide government incentives for infrastructure changes in this new contract. Convincing the government to address how these wages are calculated or providing an incentive to increase ridership could begin to repair the bus network's reputation.

Traffic congestion is another major factor contributing to Melbourne's inefficient bus system. Through our interview with Storrie, we learned that one of the most prevalent problems with Melbourne's bus system is traffic delays. He said that in Melbourne, "there is a very limited number of right of ways where buses have free passage." This leads to slower travel times and inaccurate timetabling, causing bus travel to be less appealing than an individual vehicle that may be more comfortable to sit in while stuck in the same traffic. Storrie said that these problems "are huge financial costs on the system as well as a huge disincentive for people to catch [the buses]." Due to the current traffic congestion, buses are not an effective mode of transportation, thus lowering ridership numbers and straining the system. Storrie explained that improving congestion is a proven way to significantly achieve a gain in usage and make the network more attractive to new riders.

Storrie offered a few potential low cost solutions to the issue of traffic congestion. He suggested putting in place an initiative to improve the impacts of congestion, such as "bus lanes, signal priority, or a combination thereof. . . . [Another idea is] removing parking lanes in peak periods because peak periods are the biggest demand time." Computerized signal priority involves a GPS tracker that communicates with traffic lights so that when a bus arrives at a red light, the light will automatically turn green, giving the bus priority in the intersection. This process aims to decrease trip durations and make the buses arrive at their destinations more punctually (TRANSnet, n.d.). Most existing public transport priority systems provide a basic and repetitive right of way to vehicles at specified intersections. They use actuators that are only activated by special transponders fitted to public transport vehicles (TRANSnet, n.d.). During the interview, Storrie mentioned a new technology in this field called TRANSnet. This software uses real-time vehicle position data and map based virtual detectors that can be inputted manually by a user to create a much more efficient public transport priority system (TRANSnet, n.d.).

We have also found that switching to electric buses would provide an opportunity to improve the network's efficiency. Dr. Newman discussed the electrification of bus fleets and the potential effects on ridership and user satisfaction. For example, he emphasized that electric buses are "significantly more attractive for people to ride" and that this will lead to "more people [living] near stations because they're not noisy and smelly and full of emissions." He even added that they would be "cheaper and easier to run." All of this information from Dr. Newman corroborates the background research we conducted showing that decreasing noise pollution and incorporating cleaner buses will improve ridership through increased user satisfaction.

Overall, efficiency alone seems to drastically affect the level of success a bus system experiences. This type of success can be determined based on bus ridership levels, which seem to noticeably increase when routing is convenient and frequent. If more efficient routes can be implemented into Melbourne's bus network, the city may quickly see positive changes to the number of bus passengers.

4.1.2 An Equitable and Accessible Bus System will Satisfy More Users

Next, we learned more about the importance of an equitable and accessible bus network for riders. Buses have traditionally been a mode of transportation for those who cannot afford individual passenger vehicles. Dr. Peter Newman discussed this several times throughout our interview, particularly from the Perth government's perspective. From their point of view, the purpose of buses is to allow disadvantaged populations to travel from place to place.

From Gordon Price, we learned that Vancouver's transportation system is designed to be user-friendly through its urban centers model. Price explained how transportation in Vancouver is built around each region's urban center. There are nine major urban centers where transportation and urban development are concentrated (Metro Vancouver, n.d.). These transportation centers are hotspots for transfers between various transportation methods and make accessing efficient transportation easier. Price commented on how visitors to Vancouver are often amazed at how substantial these urban hubs are in terms of skyscrapers and urban development, whereas in most other cities, these buildings are reserved for the downtown area. This diffuse approach to important transit transfer points means it is especially easy to travel around Vancouver. Therefore all people, despite their socioeconomic status, have equal access to public transit. Dr. Newman introduced a similar concept called "land value capture." The idea is to build attractive centers for public transport that are spread throughout the city. The city is then built around these stations to encourage economic and urban development in the area. Dr. Newman said, “If you don't have land-use that relates to where your rail and bus system is going, then you've got to chase after people." Building around bus and train stations will facilitate this growth, and this could be spurred by the introduction of electric buses, which are quieter and produce less pollution. Perth and Vancouver are prime examples of cities that developed around their public transportation hubs.

In a more general sense, we discovered how new technologies, like electric buses, might improve equity for bus users. When considering individual electric passenger vehicles, there is a gap between income levels regarding the prioritized placement of new infrastructure due to the ability to afford the new technology. In contrast, Dr. Gregory Trencher, a sustainability studies professor studying alternative fuel vehicles, suggested that electric buses have a positive impact on overall equity. He explained how buses are “actually serving these poor areas, so one of the nice things that occurs here is [that] zero emission buses can promote equity, because they can provide zero emission transport to poor areas.”

Storrie also touched on the disparity in accessibility throughout the suburbs. In his view, this can be attributed to the rapid growth of the suburbs and the disproportionate expansion of the bus network in response. Buses are the only mode of transport that can be quickly spread to the suburbs due to the infrastructure challenges associated with expanding train and tram access. However, the population growth has been faster than the state could keep up with, so a gap in bus accessibility has developed between the lower income areas and the wealthier suburbs. Storrie discussed how this gap continued to widen because of the abundance of other public transportation available to the wealthier suburbs. This also ties back into frequency. In the interview, he said that “as [the suburbs] grow, there are more and more areas without service, or you've got to dilute the service offering . . . as [much] as possible and people get what is essentially a non-service. It might be an hourly service or worse.” As Melbourne’s population continues to grow, the accessibility gap between income levels is likely to worsen, whether it's due to lack of routing altogether or buses that run at such low frequencies that they are essentially unusable.

From these interviews, we concluded that having urban centers stationed throughout a city provides passengers of all socioeconomic classes with equal access to public transit.

Additionally, the implementation of electric buses into a transportation system can benefit lower income neighborhoods because this new zero emission technology is likely to cater towards these populations. If Melbourne can work towards at least one of these changes, the city may see an increase in ridership from people of all backgrounds.

4.1.3 A Public/Private Working Relationship is Crucial

In addition, we learned how other cities' transportation systems differ in their relationships between the publicly accountable government and the privately controlled bus operators. Through our interview with a private bus operator representative from Sydney, we learned that Sydney's bus system is particularly successful due to their approach to the government and private operator relationship. We found that the most important factor was that the private bus companies and the government's State Transit Authority are viewed as equals and work as partners. New South Wales governs both of them and in contrast to Melbourne, buses are not considered to be "a mode of last resort," but rather a fundamental mode of transportation.

Through our interview with Gordon Price, we learned about TransLink, the government-owned company responsible for transportation management in Vancouver. Price was one of the original founders of TransLink, and his first-hand experience gave us extensive insight into the company's role in creating a successful transportation system in Vancouver. He noted that "one of the reasons [they] created TransLink is that the region wanted a tighter connection between [their] land use, decisions, and [their] commitments as far as transit." In this quote, Price discusses how prior to TransLink, Vancouver did not have adequate control over their own transportation. Instead, it was controlled by the provincial government of British Columbia. We learned how TransLink was founded mainly so the people in Vancouver had more autonomy regarding how they manage their own transportation. Since this happened over 20 years ago, Price noted how successful the company has become for the local community. Since TransLink started recording ridership numbers back in 2000, the number of people using the system has nearly doubled, demonstrating this success (TransLink, n.d.).

Our interview with John Storrie gave us more insight on the relationship between public and private operators in Melbourne. He gave us many valuable comparisons between Melbourne and Perth in relation to the government's collaboration with private providers. In Melbourne, the private sector has always operated the buses. Instead of taking them over like Perth's government did, Melbourne decided to subsidize them, which decentralized the control. Dr. Newman said more specifically that private money can benefit public transport as a whole, as long as that money is “controlled.” In Melbourne, flexibility in ownership has created issues regarding who has true control over the system. These challenges are exacerbated by the divisive nature of the diverse private sector, because according to Storrie, “the different forces that play on the system have their respective interests.” These various existing contracts make it difficult to make changes to the system. There have been movements towards creating a more flexible model through the removal of the clause of exclusivity, allowing the system to be more responsive to the market, making it more productive.

Introducing more open and respectful communication between the public and private sectors could lead Melbourne to develop a more successful transportation system. Sydney’s acclaimed bus system can be partially attributed to the equitable relationship between public and private bus operators. Likewise, Vancouver’s network permits citizens to bring forward suggestions for changes or improvements, which has led to a system that accounts for its passengers’ best interests and preferences.

4.1.4 Electric Bus Implementation Must be Planned Thoughtfully

Finally, we gained a deeper understanding of how electric and other zero emissions buses have been implemented elsewhere and how Melbourne might go forward with this process As we learned through both our interviews and background research, there are a lot of opportunities for improving the success of a bus system by electrifying it. They can improve equity, as Dr. Gregory Trencher discussed, and the overall efficiency of the system by improving ridership and user satisfaction, which Dr. Peter Newman touched on.

Dr. Trencher provided us with insight on the difficulties related to converting an entire fleet to alternative-fuel buses. His main area of study has to do with hydrogen fuel cell buses, but similar issues arise when considering the logistics of moving away from diesel buses, regardless of the type of alternative fuel vehicle being implemented. One of the problems he posed was the issue of needing to phase out the diesel buses. He discussed how most societies are concerned with phasing in the new buses, but emphasized that “[experts] need to have [a] conversation about what we do about this old, unwanted technology.” Dr. Trencher used Shenzhen, China as an example of how to properly phase out the diesel buses and convert to a fully electric bus system. Dr. Trencher described the process, saying, “[the Chinese government] would have said, if you're going to buy 100 buses next week, 50% of those have to be batteries and then the idea is that this procurement target would increase until eventually, they can only purchase electric buses. Then you get to a situation where you have 100% new electric buses.” However, Dr. Trencher explained that this is an issue since electric buses are much more expensive than diesel buses. To counteract this, the Chinese government gave subsidies for purchasing electric buses to allow operators to meet their demands. Since subsidies were now going towards electric buses, the government stopped sending subsidies for the purchase of diesel fuel, and all financial support was moved from diesel to electric buses. This created more economic motivation to drop the old diesel buses and embrace the switch to fully electric.

Additionally, Dr. Trencher posed a similar problem to one that John Storrie brought up regarding the strain on the electricity grid. When introducing large numbers of electric buses at once, the electricity grid needs to be updated to handle the amount of electricity necessary to power all of these buses. A few buses at a time would be feasible, as the electricity grid would be sufficient to power them. Dr. Trencher brought up the point that “if you want to have 50 or 100 buses running on batteries and charging, then you have to upgrade the electricity grid to increase the amount of electricity that can be moved through the grid.” As we explored in our interview with Storrie, this is a major barrier that needs to be addressed to implement the system as a whole. However, if this switch occurred slowly, with only a few buses being added to the system at a time, the infrastructure would not need to be drastically changed all at once. This scenario is most likely to occur in Melbourne due to the different private contractors that operate the bus routes; it is likely that not all of the companies will feel compelled to convert their fleets all at once, so a gradual shift towards an upgraded electricity grid can occur as the diesel buses are being phased out.

Storrie also discussed the differences between the feasibility of battery electric buses versus hydrogen fuel cell buses in Melbourne. A problem with hydrogen fuel cell buses, which are being considered viable diesel bus alternatives both within Melbourne and elsewhere in Australia, is establishing hydrogen fueling stations, which are not products of existing infrastructure. Hydrogen fueling stations in the same location as diesel fueling stations also pose a safety hazard. In comparison, electric buses can be charged at existing depots. Storrie said that “[although] the battery electric [buses] would need investment in the system, at least [they have] a system in place, whereas hydrogen does not yet." Both Storrie and Dr. Trencher think that the most likely technology to be adopted in Melbourne are battery electric buses, rather than another form of zero-emission buses. They cost less to manufacture and would require the least change to existing infrastructure. The use of existing depots would also help address the issue posed by Dr. Trencher of phasing out the diesel buses currently in use. Storrie also posed the issue of land scarcity in Melbourne, meaning there is little space for the construction of new depots. If electric buses are adopted slowly, it will help offset the strain on the electricity grid and eliminate the need for drastic building of depots while diesel buses and electric buses are run simultaneously.

Although there are already several instances of electric buses being used globally, the private bus operators in Australia are still skeptical of implementation. First, our private bus operator contact from Sydney mentioned people do not know what kind of technology may exist in 10 years since the technology for electric buses has developed immensely over the past decade. Because of this, the New South Wales government is trying to not have a "predetermined view of the answer," but instead focus on the objectives that need to be met to properly implement the system. Our contact believes the company they work for is in line with this way of thinking. They told us that "the asset is there to serve the customer, so [they will not] make a decision about a bus technology and then retrofit a customer to it; [they will] think about the customer objective and how the technology can best enable their outcome." Currently, the private operator our contact works for has two electric buses in operation. These buses were implemented as a "test," and our contact said the private operator they work for has plans to implement more of these "test" buses in the future. In Melbourne specifically, according to Dr. John Stone, bus companies will not be willing to switch to electric buses because many of the companies are family businesses, and they will want to conserve as much money as possible. Therefore, running current buses into the ground will seem more desirable to them than investing in a new fleet. A solution to this could be to allow the companies to keep their diesel buses, but every time a bus needs to be replaced, they will have to purchase an electric bus instead. Additionally, the Victorian government could provide bus operators with additional subsidies to help pay for the electric buses, which would offset the prices in their favor. Going back to the expiring contract with Transdev, Dr. Stone suggested that it could be valuable to persuade the government to add a section into the new documents regarding a decision to implement electric buses. Compounded with the barriers that Dr. Trencher emphasized, these problems pose a significant hindrance to the implementation of electric buses. However, Dr. Trencher also said that “if we [wait to take action], we [will] not achieve our targets on time, so we have to start now.” So while it’s important to acknowledge all of these difficulties, we still must look at the larger picture.

There are many moving parts that come along with the implementation of electric buses on a broader scale. Adopting a fully electric fleet would have positive environmental implications as well as the possibility of improving equity within a city. However, a number of barriers must be thoughtfully considered to ensure a smooth, effective transition. To avoid putting strain on the electricity grid, electric buses can be introduced gradually, with charging stations at existing diesel bus depots to avoid needing to build entirely new infrastructure all at once.

4.2 Passenger Satisfaction with Melbourne’s Bus System

In addition to learning from transportation experts, we wanted to hear from residents regarding their satisfaction levels with Greater Melbourne’s bus system. We distributed a survey both via email and as a flyer with a QR code to bus passengers to assess the user satisfaction levels of the city’s buses. The survey flyer that was distributed by volunteers from Friends of the Earth and our advisor, Professor Stephen McCauley, is in **Appendix A**. The responses were compiled using Google Forms. The feedback we received from the survey complemented the efficiency information we found in our interviews quite accurately. It is important to note that only 22 people participated in our survey, and that there were also instances of sample bias due to the use of an online survey, which required access to internet technology. Therefore, the numbers may not accurately reflect the positions of the entire Greater Melbourne population.

To ensure that the respondents were familiar with Melbourne’s bus system, we asked them how frequently they take the bus. As shown in Figure 5, we found that 63.6% of the people who responded ride the bus at least once a week. This implies that the majority of the respondents have significant experience with the bus system.

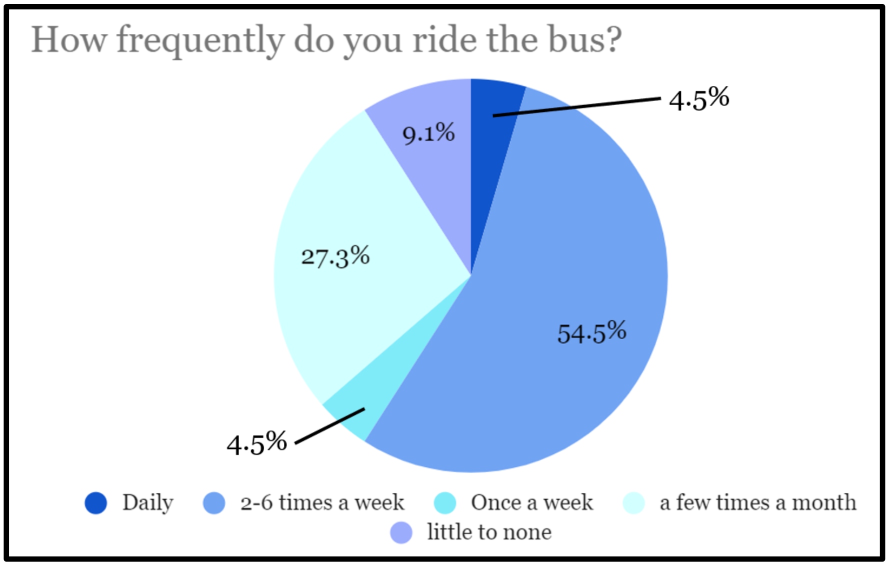

Figure 5: Frequency of Bus Ridership

Out of all the questions we asked the bus passengers, three findings stood out to us. First, an overwhelming number of respondents said that they were dissatisfied with Melbourne's current bus system. Overall, 59.1% of the respondents ranked their satisfaction levels as either a one or a two, with one being extremely dissatisfied and five being extremely satisfied. This corroborates the information that Dr. John Stone and John Storrie provided us regarding Melbourne's considerably inconvenient and unsatisfactory bus system. Figure 6 displays the responses to this question.

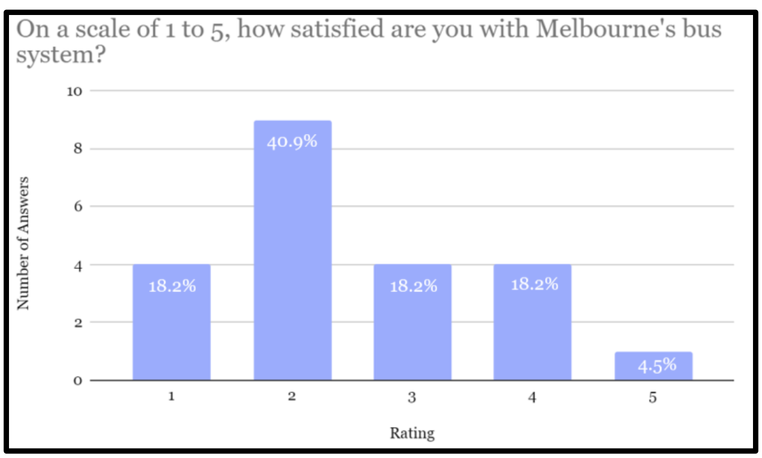

Figure 6: Overall Bus Satisfaction Ratings

Since we had previously learned that Melbourne's bus system suffers from long wait times, we asked the respondents to list the longest time they have ever had to wait for a bus in

Greater Melbourne. As discussed in our background chapter, former Public Transport Users Association president and transportation expert Paul Mees outlined in one of his books that an acceptable time to wait for a bus should be no longer than 10 minutes during peak transportation hours and only up to 30 minutes during slower times (Mees, 2009). Regardless of the time of day, our responses indicated that 59% of passengers have waited longer than 30 minutes for a bus at least once in Greater Melbourne. It is also worth noting that no respondent put down an answer that was less than 10 minutes, which was an option in our survey. Figure 7 illustrates the details of this question, with the unnecessarily high ranges in darker colors.

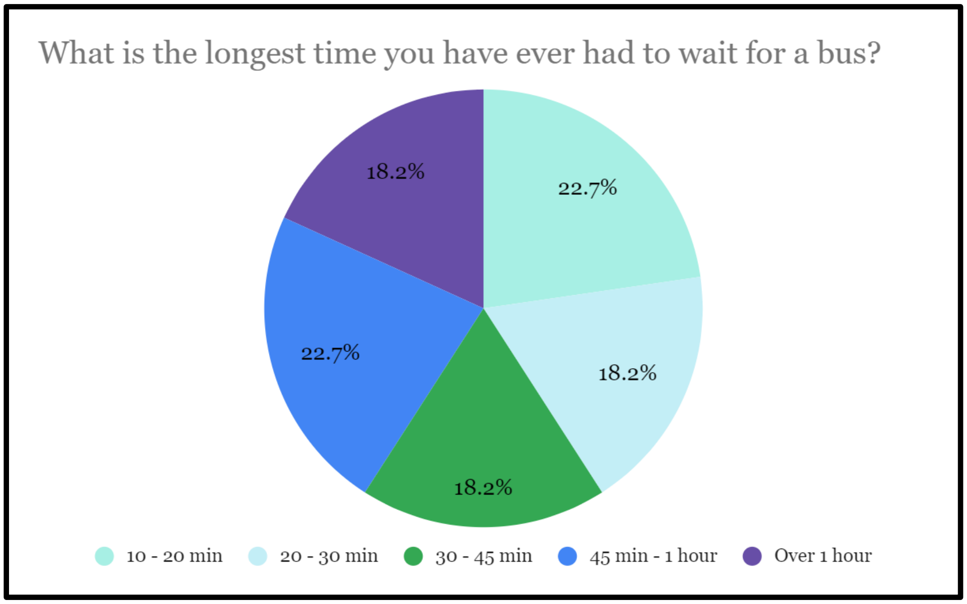

Figure 7: Longest Bus Wait Times

We also asked the passengers to provide their opinion on the most important aspect of a bus ride. The four options we listed were short trip durations, short wait times at bus stops, comfortable rides, and low carbon footprints. The vast majority of respondents chose “short wait times,” totaling 72.7%. These long wait times could be a prominent factor leading to the low satisfaction ratings shown in Figure 6. Figure 8 illustrates these answers in further detail.

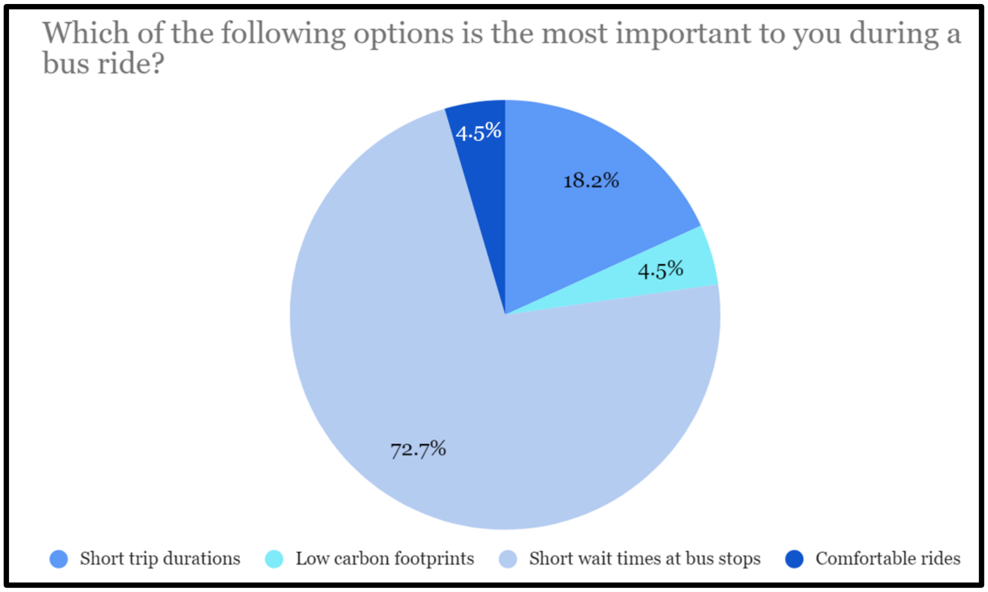

Figure 8: Important Aspects of a Bus Ride Experience

Although these statistics suggest why many passengers are dissatisfied with Greater Melbourne's current bus system, we also provided a space for respondents to write in any additional comments regarding their experiences with the system. In these comments, multiple participants emphasized the need to increase the bus system's frequency, meaning that buses should arrive at stops more often. Similarly, several respondents mentioned that the system would be more effective if the bus routes were rerouted to be more direct and easier to follow. One respondent explained their experience this way:

> At the moment, the public transport system in Melbourne is not up to the level it should be. We need a world class public transport network, with all modes - train, tram and bus, operating at a very high service level, running at least every 10 minutes or better from 5 am to 1 am, every day of the year, on all lines and routes, and with a full night network, operating from 1 am to 5 am, running 7 days per week, also on all lines and routes, at a minimum of every 20-30 minutes, to give many more people a viable transport option, a real, genuine choice, for the first time.

From this respondent, we learned how the system can be changed to become more easily accessible and convenient for commuters. They mainly focused on implementing longer operating times, which is a new perspective that our interviewees did not mention. From this, we can infer that improving efficiency not only involves establishing more frequent routing and short wait times, but also a wider variety of times that buses are available to the public.

A retired member of the PTUA also provided us with valuable information regarding the state of Melbourne's bus system. They talk about how traffic congestion continues to increase and leads to unreliable trip durations and wait times. Their offered solution was to "provide more bus routes with higher frequency buses linking to the railway system." This corroborates many of the other responses that called for more frequent buses, and also links back to our earlier claims about how buses and other modes of public transit must work in conjunction with each other so that commuters can switch between them more easily.

Overall, our survey suggests that Victorian citizens are generally dissatisfied with the buses that run throughout Greater Melbourne, especially because of the infrequent bus schedule that leads to long wait times at bus stops. These conclusions support our findings regarding efficiency; our interviewees agreed that having an efficient bus system is arguably the most important aspect of successful public transit. From this, our findings suggest that increasing the system's frequency would result in higher levels of user satisfaction and thus higher ridership levels.

4.3 Gaps in Bus Accessibility by Income

Through our background research and the various interviews we conducted, we discovered a disparity in public transportation accessibility between high and low income neighborhoods, where the bus system services more affluent neighborhoods. However, lower income populations are less likely to own individual cars, and thus rely more on public transportation to reach the inner city To further explore this issue of bus route accessibility, we conducted a spatial analysis to observe the correlation between bus route locations and both median household income and population density throughout Melbourne suburbs.

To perform this analysis, we used QGIS to display the bus routes and localities throughout Victoria. We also obtained data from an online platform called AURIN that displayed interactive maps showing the median household incomes throughout the state. Based on an overlay of the routes and median household incomes, we were able to gauge the access to bus routes in various localities based on their income. This is shown in Figure 9.

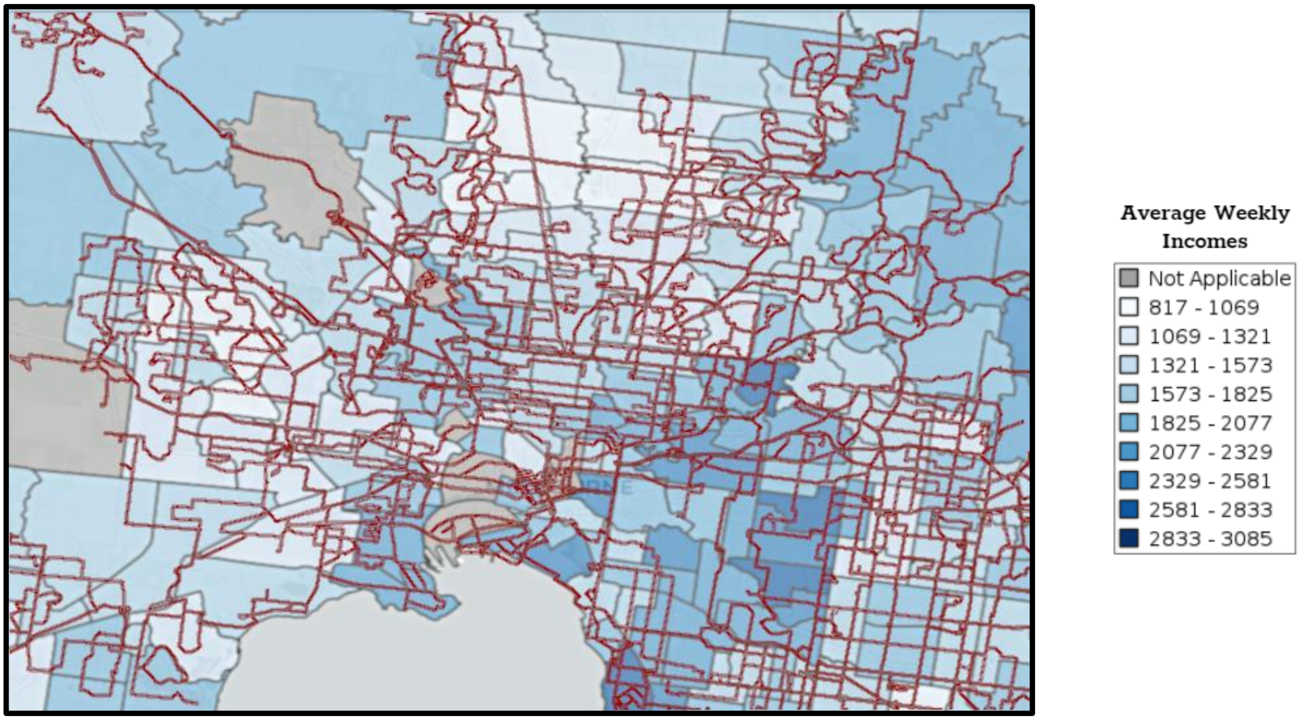

Figure 9: Bus Routes and Median Household Income in Greater Melbourne

As shown in the legend, the lighter localities have lower median household incomes. Proportional to the inner city, the median income drops as you move away from the center of Melbourne. Additionally, as suggested in our various interviews, the routing is sparser through the outer suburbs. This is a product of the rapid growth of the city over the past few decades. This growth has forced the suburbs to expand at unprecedented speeds, and as John Storrie discussed with us, the buses simply cannot expand at the rates necessary to reach these populations effectively. Even if the buses operate in these neighborhoods, they tend to run so infrequently that they are practically a non-service. Therefore, the gap in transportation accessibility between the wealthy inner suburbs and the lower income outer suburbs is widening.

In Figure 10, there is an observable unequal distribution of bus routes through the darker portions of the map versus the lighter portions. For example, the light colored suburbs in the northern portion of the map have very few routes compared to the darker colored suburbs in the northeast. The northwest has a similar problem, where these low-income suburbs have very little accessibility compared to the northeast, where the median household income is slightly higher. These discrepancies suggest that not only is frequency an issue, but access to bus routes in general is as well.

We also looked at the bus routes in relation to the population density throughout Greater Melbourne. Figure 10 shows these routes and densities.

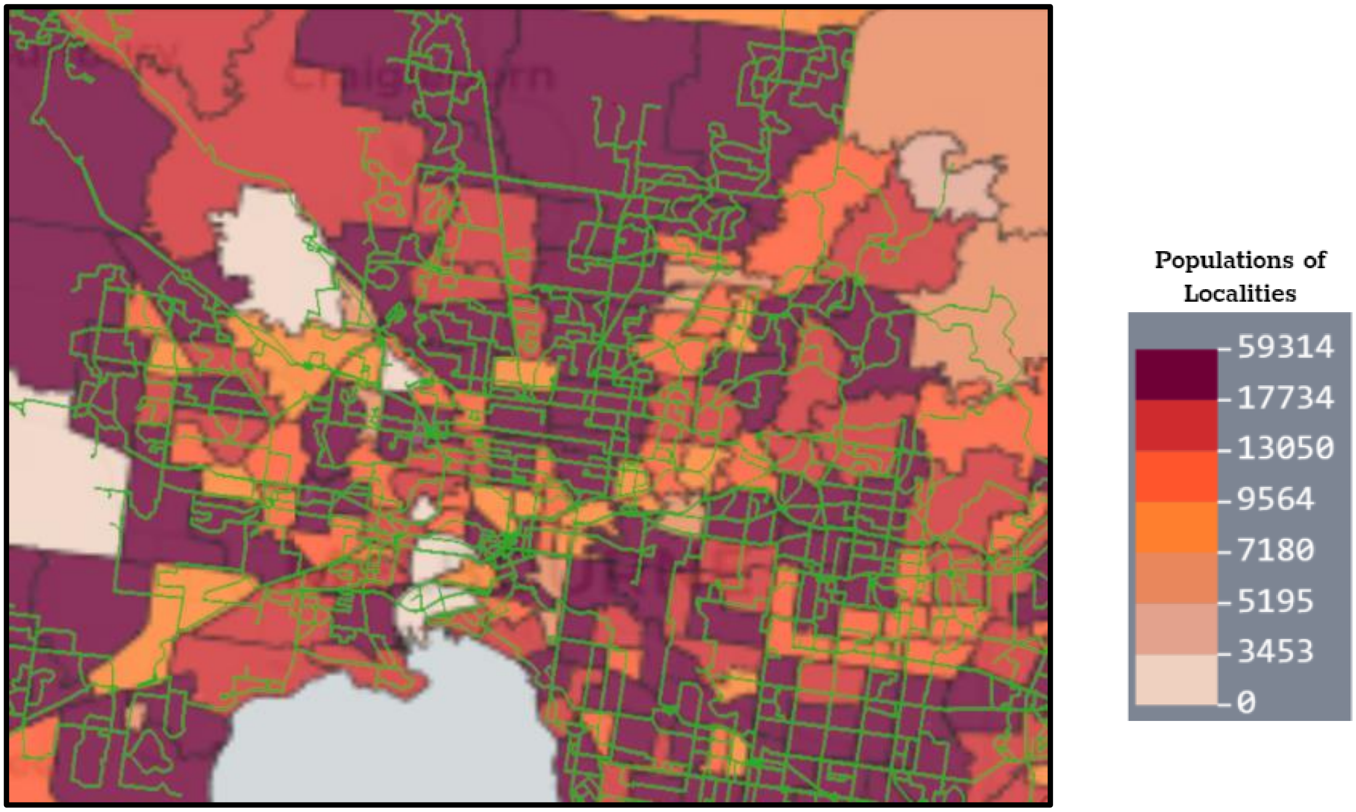

Figure 10: Bus Routes and Population Density in Greater Melbourne

Figure 10 illustrates that the bus routes cater more to densely populated areas; the darker squares have higher neighborhood populations. This helps explain why there may be lower income areas with higher levels of accessibility. The low income areas displayed in the northern portion of Figure 10 are densely populated. However, they are still experiencing low levels of accessibility despite the high density of people living in the region. There is no incentive to incorporate new routes through these low income outer suburbs despite their high population densities, because as Dr. John Stone brought up to us, bus companies are paid per kilometer, not per rider.

To address these accessibility inconsistencies, the current routing must be reconsidered to best reflect the population of the regions. They must serve not only the wealthy, highly populated areas, but have higher frequency routing throughout the growing outer suburbs with lower income populations that rely on public transportation for access to the inner city.

4.4 Environmental Implications of Electric Bus Implementation

Although electric cars and buses may seem significantly more sustainable than diesel-powered vehicles since they do not produce tailpipe emissions, there are other sustainability factors to take into account (Union of Concerned Scientists, 2018). The emissions produced during manufacturing and end of life processes must be addressed as well. The electric buses we are considering are powered by lithium-ion batteries, and the recovery and disposal of this material is damaging to the environment. We must also account for all the steps oil goes through to become diesel fuel, some of which produce staggering levels of carbon dioxide emissions (CO_2e). To develop a reliable conclusion regarding which type of bus is best for the environment, we conducted life-cycle assessments on diesel fuel and lithium-ion batteries to compare the total levels of CO_2e they produce. We chose to focus on fuel and batteries, assuming that the buses' other components, such as the shell, tires, and interior, are relatively similar in life-cycle emissions between bus types.

4.4.1 Diesel Buses Have Significant Environmental Impacts

The most environmentally destructive aspect of diesel buses is their fuel. In addition to the CO_2e the buses produce while running, it is imperative to examine fuel production and the vast levels of emissions released during this process. Figure 11 illustrates the steps oil must go through before becoming diesel fuel.

Figure 11: Steps of Oil Production (Jwa & Lim, 2018)

Although oil production damages the environment in various ways, we focused on analyzing and calculating the CO_2e released during each process so that the values can be compared to the emissions produced during the life-cycle of electric bus batteries. It is important to note that minor details were excluded from our calculations; for example, it was not feasible to factor in the emissions produced by the trucks that transport equipment to oil rigs and crude oil to loading docks.

Crude Oil Recovery

Diesel fuel begins as crude oil that is commonly recovered through drilling and hydraulic fracturing, also known as fracking (Canadian Association of Petroleum Producers, n.d.). Crude oil is a naturally occurring chemical made up of hydrocarbons from ancient animal and plant remains that can be found thousands of feet underground (US EPA, 2020c). Later on, the crude oil will be shipped to oil refineries to be separated into usable products such as petroleum, also known as diesel fuel. The vast majority of Australia's crude oil is recovered in onshore oil rigs in the Middle East (*Is Australia running out of fuel?*, 2018).

Once the oil rig is constructed and prepared for extraction, a deep hole in the ground must then be drilled to reach the crude oil. Depending on the project's complexity and the type of drilling rig used, this process takes between one and three months to complete (Lioudis, 2020). During this step, drilling rigs produce CO_2e because they are typically powered by diesel generators, which use around 26,500 liters of diesel fuel each day (Ipieca, 2013). This means that between 795,000 and 2,385,000 liters of fuel will be used throughout the drilling process, assuming 30-day months. Since roughly 0.003 tonnes of CO_2e are produced per liter of diesel fuel burned, this equates to an average of 4,200 tonnes of CO_2e per oil well (US EPA, 2016a). **Appendix D** outlines these calculations in further detail.

Next, fracking must occur to free the crude oil from the remains. A perforating gun is lowered into the oil well and aims fine explosions at the walls of the pipe to puncture the layers of rock surrounding the well, gaining access to the crude oil. Fracking contributes to air pollution because some of the CO_2e in the crude oil released from the rocks leaks into the atmosphere. A recent study found that due to fracking, the Barnett Shale region in Texas produces 42 million tonnes of CO_2e per year (Zavala-Araiza et al., 2015). Since there are 15,856 oil rigs in this region, this means that an oil rig leaks about 7 tonnes of CO_2e per day (Texas Commission on Environmental Quality, 2016). Even though fracking usually only takes between three and five days to complete, the well will continue to leak CO_2e until it is closed up (Independent Petroleum Association of America, n.d.).

After the fracking process is complete, the oil that has flowed into the well from the rocks is pulled up to the surface for production. Since crude oil is not distributed evenly underground, oil wells can produce anywhere between 15,000 and 507,000 liters a day (US EPA, 2020b). On average, the fracking and extraction of crude oil necessary to power one diesel bus throughout its lifetime result in 211 tonnes of CO_2e. The related calculations are outlined in **Appendix D**.

Overall, the drilling and fracking steps in crude oil extraction produce the most significant amounts of CO_2e. Combined, drilling and fracking produce an average of 4,411 tonnes of CO_2e to sustain a diesel bus throughout its life.

Crude Oil Transportation

After the crude oil is recovered, it must be shipped to oil refineries to be processed into diesel fuel. Australia imports the vast majority of its fuel, with China, Singapore, and South Korea as the most common exporters (*Is Australia running out of fuel?*, 2018). This means that crude oil must be shipped from the Middle East to these Asian countries before it reaches Australia in the form of diesel fuel. Before calculating the CO_2e produced during oil refining, we must first examine the emissions produced by the oil tankers that carry crude oil overseas to the refineries.

Oil tankers run at an average of 41 kilometers per hour when transporting oil and consume 238,000 liters of heavy fuel oil per day in the process (FreightWaves Staff, 2020). The approximate distance from the Middle East to Singapore ports is 6,800 kilometers, so each trip takes about 7 days (Brutman, 2011). Using the calculations detailed in **Appendix D**, this means that 5,000 tonnes of CO_2e are produced per trip to Singapore (Krantz, 2016). The route from the Middle East to the ports in China is approximately 11,600 kilometers, which will take 12 days to complete (Brutman, 2011). Using the same calculations, 9,000 tonnes of CO_2e will be produced per trip to China. Finally, South Korea is 12,600 kilometers, or 13 days, from the Middle East, so 10,000 tonnes of CO_2e will be produced per trip (Brutman, 2011).

An oil tanker can carry as much as 318 million liters of oil, which is much more crude oil than a single diesel bus requires in its lifetime, so only one trip is necessary per port (*Oil tanker ship*, n.d.). Therefore, after adding up the emissions produced per trip from the Middle East to each port, a total of 24,000 tonnes of CO_2e are produced due to transportation to refineries.

Petroleum Refining

After being imported, crude oil reaches the oil refineries, which are industrial plants that convert oil into usable products, including diesel petroleum. In summary, the crude oil is first heated and exposed to hot gases. As these gases pass through the oil, they cool into liquid and collect fuels from the oil, such as petroleum (American Fuel & Petrochemical Manufacturers, n.d.).

Refineries in general are detrimental to the environment since each one produces around 534,000 tonnes of CO_2e per year (Auch, 2017). However, the number of emissions produced to convert crude oil into enough fuel for one diesel bus to use in its lifetime is almost negligible. From Auch's article, we calculated that each refinery produces 1,500 tonnes of CO_2e per day. Using the calculations shown in **Appendix D**, we determined that only 60 tonnes of CO_2e, or 20 tonnes of CO_2e per country, is produced during the refining process to power one diesel bus**.** Therefore, although the continued usage of oil refineries is damaging, the number of emissions per bus during this step in the oil production process is not significant.

Petroleum Distribution

The final step before the fuel reaches local gas stations in Greater Melbourne is refined oil distribution. Like the crude oil transportation process, oil tankers must carry barrels of fuel from Singapore, China, and South Korea to Australia. Using information about the length of routes from Brutman, we determined that the trip from Singapore to Melbourne is 6,000 km, China to Melbourne is 7,200 km, and South Korea to Melbourne is 9,000 km (Brutman, 2011). The sum of these trips equates to 17,000 tonnes of CO_2e, as derived in **Appendix D**. As with the crude oil transportations, only one trip from each country is necessary to power a diesel bus throughout its life since oil tankers carry millions of liters of oil each trip.

Vehicle Operation

Finally, diesel buses produce CO_2e throughout their lifetimes through tailpipe emissions. In **Appendix D**, we determined that diesel buses directly release a total of 348 tonnes of CO_2e in their lifetimes. It is important to note that this value is rather insignificant compared to the emission produced during most of the steps in oil production, which is why it is crucial to consider the effects of oil production in the life-cycle of diesel buses.

Total Emissions

The combination of crude oil extraction, crude oil transportation, petroleum refining, and petroleum distribution produce roughly 45,471 tonnes of CO_2e per diesel bus. If we include the effects of vehicle operation in this total, the final result is 45,819 tonnes of CO_2e per diesel bus. It is worth noting that the emission produced by the entire diesel-powered bus fleet may vary depending on various factors that were not feasible to calculate in this assessment, such as the total number of oil rigs used or overseas trips made to fuel the buses.

4.4.2 Electric Buses Produce Fewer Emissions

The most environmentally destructive part of an electric bus's life cycle is the production and usage of its battery, so this analysis focuses on the CO_2e produced during these processes. Another process this analysis takes into consideration is the type of energy consumed to produce electricity in Melbourne.

Lithium is a rare earth metal extracted from deep beneath earth's surface. Its physical and chemical properties, and it's energy density and rechargeability, make it an integral part of battery-electric vehicles (Komanoff, C, 2021). The factors that need to be taken into consideration when determining total CO_2e produced during lithium extraction are fuel use, power sources, and energy intensity. On average, lithium requires an average 9 tonnes of CO_2e for every tonne of refined lithium carbonate equivalent (LCE) produced. A typical battery cell has a couple of grams of lithium in it and a typical electric vehicle can have about 5,000 battery cells (Root, 2020). Building from there, a single electric vehicle battery can have about 10 kilograms or .01 tonnes of lithium in it. This means the extraction of a single electric bus-battery produces about .01 tonnes of CO2e. These derivations are further outlined in **Appendix E**.

There are three components of a lithium-ion battery: the cells containing the active materials, the battery management system that controls the battery's performance and safety, and the battery pack holding the cells (Melin, n.d.). In a life-cycle analysis completed in 2014, the manufacturing of lithium-ion batteries was found to produce a total of about .247 tonnes/kWh of CO_2e (Dunn et al., 2014). The first electric bus built in Victoria and operated by Transdev has a 324kWh capacity (Schmidt, 2020). During this process, electric bus batteries produce 80 tonnes of CO_2e as shown in **Appendix E**.

During usage of an electric bus, electricity will need to be generated. Electricity generation is required when the individual components of the battery are constructed and when the battery needs to be charged during usage. Therefore, we need to consider the source of energy generation. With the increasing demand of electric buses throughout the world, the use of lithium-ion batteries has expanded to a global level. The source of energy used throughout the process of producing the battery varies depending on the manufacturing location. For example, companies may use different sources for heat generation which can either be supplied indirectly through electricity or directly by using fuel such as natural gas (Melin, n.d.). Companies may choose to actively source energy from specific generation modes through agreements with their energy supplier, such as “green power”, and they can also generate energy themselves by building microgrids with solar or wind power (Melin, n.d.). These differences in energy generation methods can majorly affect the climate impact of the production and usage of a lithium-ion battery.

Once on the road, electric vehicles (EVs) do not produce exhaust CO_2e from a tailpipe. However, during usage, a lithium-ion battery needs to be charged at regular intervals by being plugged into a charging station or wall outlet. The electricity used to charge this battery can be produced in various ways, such as burning fossil fuels, generating renewable energy, etc. If you know what type and what percentage of energy is used to generate the electricity used to charge a vehicle, you can convert the ratios into grams of CO_2e per kilometer estimation. According to the Green Vehicle Guide, in 2017, an electric vehicle in Australia would get approximately 182 g CO_2e/km. An electric bus over a 12 year life span travels approximately 400,000 km (MacKechnie, C., 2019). During this time an electric bus will produce approximately 80 tonnes of CO_2e as shown in **Appendix E**.

The production and usage of electric bus batteries are the most environmentally costly aspect of electric bus implementation. When every stage of the life cycle of the electric-bus battery is taken into consideration a total of 153 tonnes of CO_2e are produced per bus, with the related calculations shown in **Appendix E**.

4.4.3 Life-Cycle Assessment Summary

Through the life-cycle assessments of diesel fuel and lithium-ion batteries, we found that electric buses are significantly less detrimental to the environment throughout their lifetimes. Electric buses only produce 153 tonnes of CO_2e per bus due to the production and usage of their batteries, whereas diesel buses produce significantly more emissions since they require fuel, totaling in 45,819 tonnes of CO_2e per bus. Diesel-powered vehicles are a significant source of CO_2e throughout the world. While switching from crude-oil power generation to electricity can reduce emissions, a conversion from diesel buses to fully electric buses is only one component of the bigger picture. Using cleaner renewable energy generation in conjunction with converting to electric buses will more substantially reduce emissions.

4.5 Social Savings of Electric Bus Implementation in Melbourne

To determine how valuable a switch to electric buses would be for the Melbourne bus network, we conducted a cost-benefit analysis of all social costs and benefits related to the conversion. These social benefits represent the net savings to society in terms of both private costs and benefits as well as externalities. For this analysis, we broke it down into two distinct sections. First, we quantified the private costs and benefits of electric buses by doing a cost comparison of the lifetime cost to purchase and maintain electric buses versus the relevant costs for diesel buses. In our analysis, private costs and benefits represent direct costs or savings to the government, such as maintenance, charging, and manufacturing of the buses and related technologies. Second, we quantified all externalities of electric buses by determining all indirect societal benefits and costs incurred through the switch, then converted them into monetary savings. Externalities are the other indirect costs and savings that society incurs as a whole, such as the environmental and public health impacts of carbon. In the end, we made a complete comparison of costs saved or incurred due to electric buses on both per bus and fleet wide metrics. When calculating monetary amounts, all findings were initially found in USD and then converted to AUD. We used the website Xe for the conversion with rates from late February of 2021 (Xe, 2021).

4.5.1 The Private Costs of Diesel and Electric Buses Are Similar

When considering the private and strictly monetary costs of the bus system, the first area of discussion is the cost of the bus itself. On average, an electric bus costs AU$950,000, whereas the average diesel bus costs AU$635,000 (Maloney, 2019). In addition to a fleet of new buses, the building of new infrastructure must be considered for a switch to electric buses. The charging stations needed to power these buses range in price but average out to be appoximately AU$50,000 per charging station when one is needed per bus (Shirazi et al., 2015; Islam et al., 2019). Although this may make it seem as if electric buses are much more expensive, the fuel cost of an electric bus is only the cost of electricity used for the charging stations. This is estimated to be AU$0.19 per kilometer, while a diesel counterpart would cost AU$0.53 per kilometer (Islam et al., 2019). This source was originally in USD per mile but was converted for this analysis. The service life of most transit buses is expected to be 400,000 kilometers

(MacKechnie, C., 2019). Over these 400,000 kilometers, the fuel cost of an electric bus would then be AU$76,000, whereas a diesel bus would be AU$212,000.

Next, post-installation costs are to be considered. Maintenance costs for an electric bus are expected to be about AU$0.43 per kilometer, while diesel bus maintenance is expected to be about AU$1.20 per kilometer (Maloney, 2019). Electric buses require less maintenance overall, causing a significant difference between the two prices. Additionally, routine maintenance for diesel buses, such as oil changes, are eliminated by using an electric bus. Over the same 400,000 kilometers of service life, the maintenance cost of an electric bus would then be AU$172,000 and a diesel bus would be AU$480,000.

In addition to normal maintenance, we must also look into the long term viability of the main power source of each bus. Both diesel and electric buses have an expected average service life of about 12 years (MacKechnie, 2019; Guerrero, 2017). However, batteries of electric buses usually only last 6 to 8 years (Guerrero, 2017). This means a battery replacement is typically necessary at least once over the lifetime of an electric bus. The cost to replace the battery of an electric bus is found to be about AU$380 per kWh of preexisting battery (Shirazi et al., 2015). Recently, Victoria tested a few electric buses with batteries of 324kW (Parkinson, 2020). Using this as our battery capacity, it would cost AU$123,120 to replace the battery of an electric bus.

One potential financial incentive for electric buses would be the utilization of vehicle-to-grid (V2G) technology. V2G is a process that allows the batteries of electric vehicles to have a bidirectional flow of electricity to and from the power grid (Kempton & Tomić, 2005). This power grid is the interconnected flow of electricity between all devices that use electricity. Because energy demands are not always consistent, there are peak and nonpeak hours of electrical use. V2G allows a battery to provide its stored up electricity as an additional source back to the grid. Once charged to a sufficient amount, V2G takes over and reverses the flow of electricity back to the grid. Through the process of charging an electric bus, V2G can earn the vehicle owner money from the power company for the privilege of using your battery as auxiliary electrical storage.

The largest downside of V2G technology is that it is very difficult to be maximally profitable with the current technology. V2G is a very successful endeavor for cars as they spend most of their day parked in a garage, driveway, or parking lot. This is when they would be charging and serve as a usable battery for the grid. In contrast, buses are constantly on the move.

When electric buses need to charge, they stop for a minimal amount of time to start back on their route as fast as possible. This means V2G cannot be used for much time at all during these quick stops. The system would be the most profitable towards the end of the day when the number of buses operating routes drops off. For the sake of simplicity, we will assume that all buses have a consistent schedule and no night buses are run. We do not expect profitability to change significantly when the bus timetables are more variable.

Some additional considerations must be made if the Victorian government chooses to apply V2G to the Melbourne bus network. The operational times of the bus systems vary drastically from route to route, but most buses run between the times of 7:00 AM and 7:00 PM (Public Transport Victoria, n.d.). This leaves 12 hours each day for the buses to charge and connect to the power grid. Power consumption in Melbourne varies throughout the day and even depends on the time of year. Figure 12 demonstrates the average peak energy use times for the grid in military time (Csiro, n.d.). Based on these average energy needs, the system charging timelines up with increasing energy needs for about 5 hours total. The exact number of hours per bus will vary depending on during what times each one operates, with its effectiveness directly related to its timetable. When the bus first stops for the day, it must charge first before it can provide the energy support, which takes about 3 hours to reach a usable level (Marshall, 2016). For this estimate of V2G savings, we used a conservative estimate of 2 hours a day of peak usable time after charging is sufficient rather than the 5 hours of peak. Dependent on scheduling, energy demands, and charging time, this value could be much higher. In the end, the total savings from V2G is AU$24,528 per bus over its lifetime. For a full breakdown of how this calculation was reached, reference **Appendix F**.

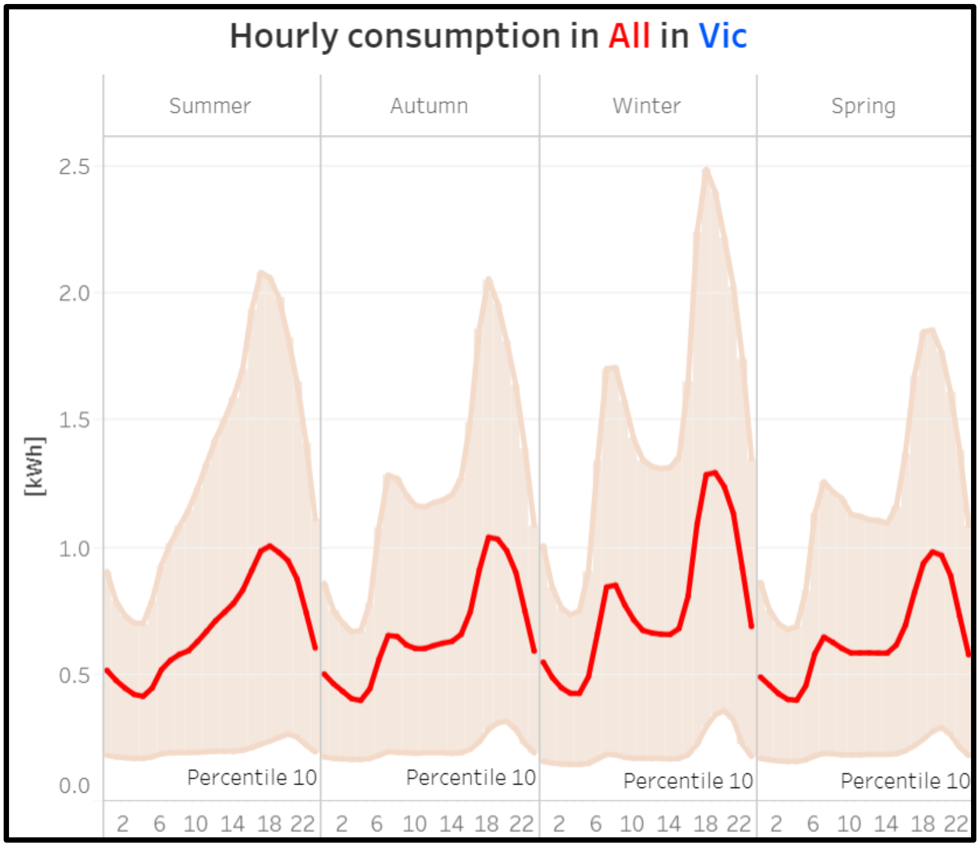

Figure 12: Average Hourly Electrical Consumption in Victoria for All Seasons (Csiro, n.d.)

It is also possible that using V2G could negatively affect the lifespan of the vehicle's battery. This is because all batteries have a finite number of times they can be charged, and V2G increases the number of times a battery is charged and discharged. Despite this, it has been found that general battery care and mitigation measures such as limiting the depth of discharge to 80% while using V2G might make any adverse effects negligible (Steward, 2017). Another way to mitigate extra battery use is using batteries in a second life as an auxiliary power holder. Batteries will need to be replaced whether V2G is used or not and prices are always lowering so V2G will only be more financially beneficial in the long term.

Overall, we found a large disparity in costs for diesel and electric buses between their different components. When all is summed up, an electric bus only costs AU$19,582 more than a diesel bus. Despite being more expensive, it's actually a great price as newer technologies tend to be more expensive than their conventional counterparts and prices are expected to decrease over time. A chart showing all numbers and this result is located in **Appendix G**.

4.5.2 Electric Buses Suggest Significant External Savings

The switch to electric buses involves a variety of costs and benefits to society as a whole; these social costs and benefits include not only the private costs to the government and operators, but the external effects on society. These quantities are important in determining the overall impact and net benefits of moving away from the use of diesel-fueled buses. In addition to private costs, social costs and benefits include various additional factors such as public health, sustainability, rider satisfaction, national security and military efforts, job loss and creation, and insurance costs. This is not an exhaustive list, but all of these different factors can be monetarily quantified to give a social value to electric bus implementation.

Diesel buses have a significant impact on the environment due to greenhouse gas emissions and the release of particulate matter via tailpipe emissions. The burning of fossil fuels to power these buses and the release of CO_2e through operation have destructive effects on different ecosystems and the human race as a whole (US EPA, 2015). As we explored in our background section, global warming is extremely disruptive to biodiversity and climate worldwide (Nunez, 2019). Additionally, the fine particulate matter contained in the direct tailpipe emissions from diesel buses contributes to local air pollution, which can damage local ecosystems (US EPA, 2016b). To quantify the social costs of carbon emissions, we considered only the tailpipe emissions of the buses, as these are the only CO_2e that directly affect citizens in Melbourne. The average diesel bus produces 871g of CO_2e per kilometer (Chang et al., 2019). According to numbers contained in the life-cycle analysis, this translates into 348 tonnes of CO_2 emitted over the lifetime of a diesel bus. In comparison, electric buses produce approximately 182 g of CO_2e per kilometer due to the emissions related to electricity production, or approximately 73 tonnes of CO_2 emitted over the lifetime of an electric bus (Green Vehicle Guide, n.d.). Therefore, electric buses release 275 tonnes less CO_2 over their lifetime per bus than diesel buses. According to a study conducted by researchers at Stanford in 2015, the social cost of carbon is about AU$315 per metric ton (Than, 2015). Another study found it is between AU$143 to AU$286 per metric ton, so we assumed the social cost per ton of carbon is about AU$251 per metric ton for the purposes of our study. It is predicted that this cost will continue to climb as we approach the new century, increasing to nearly AU$859 per metric ton (Nuccitelli, 2020). Therefore, by reducing the amount of lifetime carbon emitted, there is a social savings of around AU$86,625 per bus.

The fine particulate matter emitted from the tailpipes of diesel buses can have significant impacts on public health as well as the environment. The adverse effects of inhalation/exposure to these particles represent another significant external cost, as they pose serious health risks and medical bills are expensive. Tailpipe emissions also contain greenhouse gases, which have various severe, exposure related health impacts (National Institute of Environmental Health Sciences, n.d.). Through research and analysis of previous studies working to quantify the health impacts of tailpipe emissions, the estimated health savings over the lifetime of an electric vehicle is about AU$2,058 (Malmgren, 2016). This estimate was more specifically for electric cars, but the net benefit would be similar. Although buses have lower emissions per passenger if ridership is great enough an individual bus has considerably higher volumes of tailpipe emissions than an individual car over their lifetimes. In contrast to the 871 gCO_2e/km that a bus produces, a car releases an average of 122 gCO_2e/km (Department for Transport, 2015). Therefore, this health savings estimate of AU$2,058 is likely on the lower range of external benefits gained from switching to electric buses. If we apply this ratio of approximately 3:16 between cars and buses to the savings estimate, the savings would be upwards of AU$10,934 due to public health improvements from tailpipe emission reductions.

Aside from environmental and health impacts, other social factors need to be accounted for to view the full picture of the externalities surrounding the switch to electric buses. One such externality is the loss and creation of jobs through the shift in the industry. As diesel buses go out of use, the oil industry will experience major job losses. Gas stations, auto maintenance, and mechanics will also suffer job loss (Malmgren, 2016). However, there are also a variety of new jobs that would be created through the implementation of electric buses. Both direct and indirect jobs will be created; direct jobs in the auto industry in manufacturing, research and development, and battery manufacturing, as well as indirect jobs centered around installation and maintenance of equipment (Malmgren, 2016). Overall, more jobs will be created than lost through the switch, yielding a net benefit in terms of job gain/loss. In addition, the economy is stimulated by keeping more money local. According to the U.S. Energy Information Administration, over 80% of the cost of gas leaves the local economy (Malmgren, 2016). When money leaves the local economy, there is a drop in GDP, employment levels, and an increase in government debt (Pettinger, 2017). Therefore, to garner a full understanding of the effect of diesel on society, we also accounted for this money flow. A study conducted in Oregon concluded that the adoption of a single electric car could save between AU$551 and AU$1,945 over the vehicle's lifetime (Malmgren, 2016). Since buses hold more than double the amount of gas held by a car, the savings would be even greater per vehicle. According to a recent study, electric vehicles adopted through 2030 are estimated to add AU$5,242 per vehicle to the regional economy (Bonneville Environmental Foundation, 2020).

Additionally, there are added conveniences that come with electric buses. For example, electric buses provide smoother, quieter travel, and stronger acceleration (US EPA, n.d.). The quieter travel is especially important to society's net benefits, as it represents a reduction in local noise pollution. Environmental noise pollution can have a variety of negative health impacts on the local population. For example, studies suggest a relationship between exposure and hypertension, as well as sleep disruption and noise induced hearing loss (Hammer et al., 2014) . There are also various psychological effects, including stress and annoyance (Stansfeld & Matheson, 2003). Additionally, there are more opportunities for amenities that may increase ridership and give more value to bus use. Aside from smoother and quieter travel, there are more options for air conditioning, onboard WiFi, and charging ports. Although perhaps more expensive for installation, these amenities have the potential to attract far more riders and thus bring in more money for the operators. They also raise the external benefits of electric bus implementation, as there is greater user satisfaction. It was estimated that ride quality and noise reduction due to the switch will lead to an average increase in riders by 1.9% (Currie et al., 2018). For the purposes of our study, we used the average increase in riders by 1.9% as our baseline for understanding user satisfaction benefits due to electric bus implementation. Based on average ticket costs and annual ridership, there will be an estimated profit of about AU$18,000,000 per year, or AU$216,000,000 over the 12 year lifetime of electric buses. This represents the savings for the conversion of an entire bus fleet. In Melbourne, with a fleet of about 2,700 buses, the additional profits per bus would be approximately AU$80,000 (Public Transport Victoria, 2019). The related calculations are shown in **Appendix H**.

Additional costs and benefits incurred through the implementation of electric buses include national security and insurance. To extract the oil necessary to fuel and maintain diesel buses, a lot of strain is put on international relations and military efforts required to obtain the oil. According to an estimate of the national security and military expenses of oil extraction in the United States, the costs would be upwards of AU$4,091 per bus. This is a conservative estimate, which does not include all military operation costs in more volatile regions of the world (Malmgren, 2016). However, the price would be much higher in Australia. According to the Organization for Economic Cooperation and Development (OECD), oil import prices over the past 20 years have been between AU$13 and AU$26 greater for Australia than they were for the United States. This trend is illustrated below in Figure 13 (OECD, 2019).

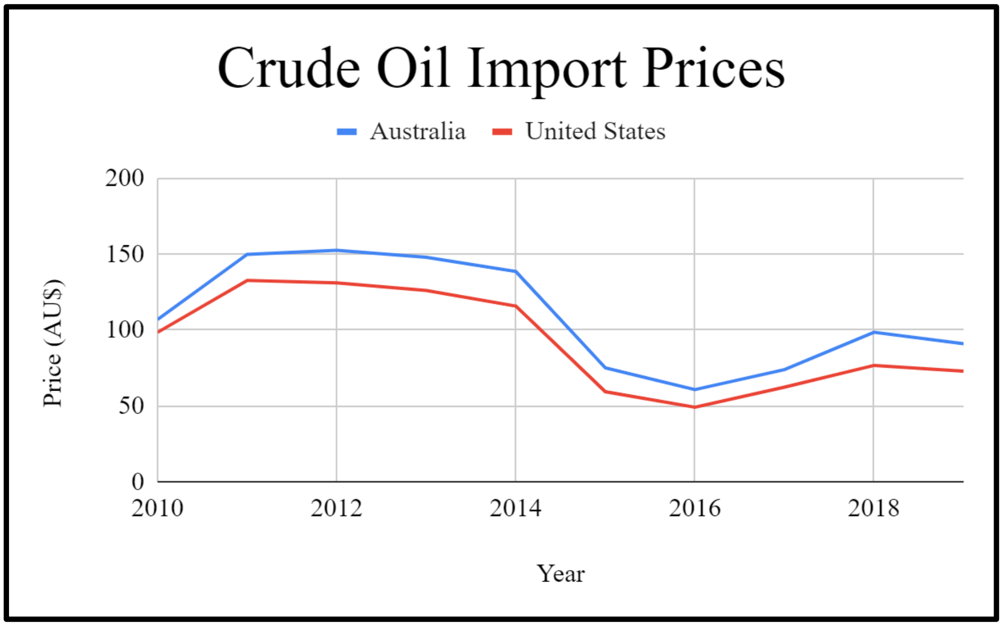

Figure 13: Crude Oil Import Prices in Australia and the United States (OECD, 2019)

Assuming a relatively constant ratio of about 7:10 when comparing the United States and Australia, the adjusted savings are upwards of AU$6,392 per bus. This is still a conservative estimate, as there are additional costs incurred to refine and transport the oil. It is also dependent on the fluctuation of oil prices over the years.

Insurance costs are also significantly greater for diesel buses than they are for electric buses. Operators would have to spend far less money to insure an electric vehicle due to their lower maintenance and operation needs. Insuring an electric car is, on average, AU$256 less a year than insuring a conventional car (Malmgren, 2016). More specifically, the average insurance for a bus comes to a total of approximately AU$38,353 for primary liability, physical damage, umbrella policy, medical payments, and workers' compensation (Bus Insurance HQ, n.d.). In comparison, the average full-coverage insurance costs of a car are only about AU$2,222 per year (Rivelli, 2021). When considering the AU$256 savings by switching to an electric car, we calculated a proportional savings value relative to the increased insurance costs of buses. The new savings in insurance costs is thus about AU$4,413 per year. These savings are specific to American insurance prices. Citizens of Victoria pay an average of AU$1,900 for car insurance, so the prices are comparable, although not exactly the same (Iliakis, 2019). The average lifetime of an electric bus is 12 years (Guerrero, 2017). Therefore, over the lifetime of an electric bus, we found that there would be a net savings of AU$52,961 per bus.

Although there are numerous benefits of electric bus implementation, there are a few downfalls that may make electric bus travel less appealing to riders, representing external costs. Some such externalities include the shorter driving range of an electric bus and their longer charging times. The driving ranges of electric vehicles are improving, but they have shorter ranges per full battery charge than a conventional vehicle has on a full tank of gas (US EPA, n.d.). Charging the battery pack is also very time-intensive, as fully recharging the pack can take 3-12 hours; even a "fast charge" to 80% capacity can take 30 minutes (US EPA, n.d.). Both of these factors may make travel less efficient and convenient for both riders and operators. However, there is evidence to the contrary. For example, as of 2016, Proterra fast-charging buses can run up to 560km on a single charge (Marshall, 2016). This can be enough to cover a single day's worth of rides, which means it does not take away from the profitability of the bus. Additionally, reports state that electric buses have charging time ranges from as short as an hour to as long as eight hours, with an average charging time of about 3.5 hours (MacKechnie, 2019; GregoryPoole, 2020). This leaves the buses plenty of time to fully charge, since the majority have off-peak hours between 7:00 PM and 7:00 AM (Public Transport Victoria, n.d.). Therefore, electric buses have the ability to run long enough to cover the amount of distance needed in one day, and the charging can be completed overnight, so the shorter driving ranges of these buses will not affect the efficiency of the bus routes.

We have found that electric buses have virtually no additional costs to society; as technology advances and charging becomes even more efficient, there will be no impact on profitability. Overall, the external savings came to be approximately AU$242,154 per bus, and AU$653,816,800 for converting the entire fleet. These numbers are relatively conservative estimates, so there is a considerable opportunity for additional social savings in the switch to electric buses. The breakdown for these numbers and the process behind obtaining them can be found in the externalities process flowchart in **Appendix I**, and more concisely in **Appendix J**.

4.5.3 Cost-Benefit Analysis Summary

Without considering the externalities, implementing an electric bus fleet is not entirely cost-effective due to new, expensive technologies. When considering private expenses that do not affect society as a whole, such as fuel, maintenance, charging stations, etc., implementation would cost AU$52,871,400 more for the entire fleet, which is AU$19,582 per bus. However, there are additional costs incurred by society and the government through the use of diesel buses. If insurance and national security costs are accounted for, including savings of AU$52,961 and AU$6,392 respectively per bus, electric buses are far more cost-effective. There would subsequently be a net savings of AU$39,771 per bus or AU$107,381,700 for the entire fleet. Table 1 shows these new savings. Additionally, when accounting for externalities such as environmental degradation, health effects, insurance, etc., we found that the true social savings are much higher. Table 2 shows the combined total savings when considering private savings and external savings, where the externalities no longer account for insurance and national security savings.

Private Costs		
	Savings for Fleet	Savings per Bus
Private	-AU$52,871,400	-AU$19,582
National Security/Insurance	AU$160,253,100	AU$59,353
Total	AU$107,381,700	AU$39,771

Table 1: Private Costs

Social Costs and Benefits		
Cost	Savings for Fleet	Savings per Bus
Private	AU$107,381,700	AU$39,771
Externalities	AU$493,562,700	AU$182,801
Total	AU$600,944,400	AU$222,572

Table 2: Social Costs and Benefits

When accounting for both private savings and external savings, we found that the switch to an entire electric fleet of buses suggests a saving of AU$600,944,400, or approximately AU$222,572 per bus.

5.0 Conclusions and Recommendations

The goal of our project was to assist Friends of the Earth Melbourne and the Public Transport Users Association with their Sustainable Cities campaign, which advocates for a more liveable city experience. Through our research, we learned of the inefficiency, inequity, and unsustainability of the current bus system. We initially hoped to suggest some changes to routing and timetabling to improve this, but due to the rapid evolution of zero-emission bus technology, our work shifted to focus on ways to advocate for an effective transition to an electric bus fleet. We also focused on identifying areas where routing could be improved through understanding patron preferences. Our research and findings thus provided our partner organizations with a framework to further assist their campaign.

The efficiency of Melbourne's bus system can be gauged by ridership levels and user satisfaction. Our first recommendation to help improve efficiency is to implement computerized signal priority, an emerging software that will allow buses to better avoid traffic. The specific software that was mentioned during our interview with John Storrie was called TRANSnet. We also learned that the current bus system is rather confusing for new users. To help attract more riders, we suggest developing a comprehensive usage guide either in a physical form or an app. Finally, we learned from our interviews and survey responses that it is crucial to improve the frequency of buses and sync public transit timetables. This will result in shorter wait times at bus stops and smoother transfers. One way to achieve this would be to revisit Melbourne's bus operator contracts to incentivize more efficient routing options.

We also focused on the existing inequities of Melbourne's bus system. One way to combat this would be to implement urban centers throughout Greater Melbourne so that all users have easy access to major modes of public transportation. The implementation of electric buses may also contribute to a more equitable system by making zero-emission vehicles accessible to users regardless of socioeconomic status. Finally, significantly increasing bus frequency would ensure that all routes are viable transportation options. After completing our spatial analysis, we found that a larger future project to significantly improve Melbourne's transportation equity and efficiency would involve a deeper reassessment of the bus routes throughout the city and surrounding suburbs. If the routes can be optimized to cater to neighborhoods of all incomes, with a focus on areas that heavily rely on public transit, the city would make considerable progress in alleviating some inequities. This would also require reconsideration of the bus operator contracts. Upon contract expiration, the government could incentivize these routing changes. Overall, these three components combine to make a more universally accessible bus system.

We also examined the feasibility of electric bus implementation and concluded that switching Melbourne's bus fleet from diesel-powered to fully electric would be advantageous. First, compared to diesel buses, electric buses are generally more attractive to the public since they ride more smoothly, are quieter on the road, and provide more amenities such as air conditioning and free WiFi. Additionally, as illustrated in our life-cycle assessments, electric buses are significantly better for the environment than diesel buses and do not produce any harmful tailpipe emissions during usage. Finally, we determined through our cost-benefit analysis that electric bus implementation presents an opportunity for significant social savings. Altogether, these factors lead to ultimate societal benefits and satisfaction with the bus system.

To facilitate the change to electric buses, we have several suggestions for enabling a smoother transition. First, we would suggest implementing charging stations at existing depots. From our interviews, we learned of the land scarcity concerns in Melbourne and how new infrastructure would likely require more land than is available. Dr. Trencher discussed how it is possible to safely charge battery-electric buses alongside existing diesel bus fueling stations, so this is a viable way to avoid drastic infrastructure changes while still transitioning the fleet. To supplement this, we also suggest a gradual implementation of electric buses. There are concerns about how much power is necessary to charge a fleet of electric buses, which some experts argue would require upgrading the existing power grid. There are potentially some alternative ways to charge the buses, such as installing solar panels, which could be looked into in the future. This slow implementation would not only help keep costs down, but it provides a solution to phasing out diesel buses as electric buses are introduced. This is the most feasible way for Melbourne to proceed due to the different contracts the routes are operated under; the government does not have the ability to impose widespread reforms to the fleet all at once. Lastly, we would suggest incentivizing implementation in contract renewal in a way that is similar to the routing reforms, which would contribute to the gradual transition and allow for electric bus adoption once diesel buses are at the end of their lifetimes.

Although they are significantly better for the environment, electric buses still produce significant levels of CO_2e. Instead of producing tailpipe emissions, electric bus emissions depend on the generation of electricity for charging stations using non-renewable sources. Australia is slowly decreasing the amount of gas and coal production used to generate electricity by shifting to zero-emission electricity generation. Future studies can look into how to further improve the climate impact of electricity generation in Australia. Additionally, despite our project's focus on reducing CO_2e through the implementation of electric buses, the impact of the end-of-life of an electric bus battery should not be ignored. It is predicted that the battery will need to be replaced at least once during its lifetime (Guerrero, 2017). When a battery is not recycled, it becomes toxic waste (Kattenburg, n.d.). At some point during the implementation process, this will need to be addressed, and battery recycling plants will need to be constructed. Furthermore, over the timeline of the electric bus implementation process, new technologies will develop that will make the switch to electric buses even more cost-effective. All of these factors should be taken into account during future advocacy work.

Overall, our findings and analyses provide Friends of the Earth Melbourne and the Public Transport Users Association with extensive suggestions for how Melbourne's bus network can be improved in terms of efficiency, equity, and sustainability.

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Appendix A: Bus Satisfaction Flyer

Appendix B: Survey Questions for Residents

1. **Where did you hear about this survey?**
   - ○ Friends of the Earth outreach
   - ○ At a bus stop
   - ○ Other
2. **In which city do you live?**
   - ○ Hume
   - ○ Nillumbik
   - ○ Other
3. **3. On a scale of 1 to 5, how satisfied are you with your experiences with the bus system in Melbourne?**

   1 2 3 4 5

   Very dissatisfied Neutral Very satisfied
4. **Do you feel as though you have convenient access to the bus system in your neighborhood?**

   1 2 3 4 5

   Strongly Disagree Neutral Strongly Agree
5. **Rank the following aspects from least important (1) to most important (4):**
   - ❑ Accessibility (having bus stops near your house)
   - ❑ Short wait times at the bus stop
   - ❑ Fast trips
   - ❑ Ease of connection between the bus and different forms of transportation
6. **How frequently do you take the bus?**
   - ○ Daily
   - ○ 2-6 times a week
   - ○ Once a week
   - ○ A few times a month

- Little to none

7. **How frequently do you take other forms of public transportation? (tram, commuter train)**
   - Daily
   - 2-6 times a week
   - Once a week
   - A few times a month
   - Little to none
8. **Which form of travel do you use the most frequently?**
   - Bus
   - Tram
   - Train
   - Car
   - Bicycle
   - Foot
   - Other
9. **What is the longest you have ever had to wait for a bus?**
   - Less than 5 minutes
   - Between 5 and 10 minutes
   - Between 10 and 15 minutes
   - Between 15 and 20 minutes
   - Between 20 and 30 minutes
   - Between 30 and 45 minutes
   - Between 45 and 1 hour
   - Between 1 hour and 1½ hours
   - More than 1 ½ hours

10. **On average, how long does it take you to get to the nearest bus stop from your home?**
    - ○ Less than 1 minute
    - ○ Between 1 and 5 minutes
    - ○ Between 5 and 10 minutes
    - ○ Between 10 and 15 minutes
    - ○ Between 15 and 20 minutes
    - ○ More than 20 minutes
11. **Which of the following options is the most important to you during a bus ride?**
    - ○ Short travel time of buses
    - ○ Reducing carbon emissions from buses
    - ○ Less wait time between buses
    - ○ Comfort and amenities of the bus ride
    - ○ Other
12. **Do you have any additional comments regarding Melbourne's bus system?**
13. **If you would like to receive updates on the Sustainable Cities campaign, please include your email below:**

Appendix C: Gantt Chart

Task	Week						
	2/1 - 2/5	2/8 - 2/12	2/15 - 2/19	2/22 - 2/26	3/1 - 3/5	3/8 - 3/12	3/15 - 3/18
Life-Cycle Assessment							
Cost-Benefit Analysis							
Survey							
Interviews							
Spatial Analysis							
Final Analysis							

Appendix D: Oil Production Calculations

Production Process	Calculations	Statistics
Crude Oil Recovery: Drilling		**26,500 L of fuel/day** to power drilling rigs[1]
		1 to 3 months to drill[2]
	(26,500 L)*(1 month)*(30 days/month) = 795,000 L (26,500 gal)*(3 months)*(30 days/month) = 2,385,000 L (2,385,000+795,000 L)/2 = 1,590,000 L	**1,590,000 L of fuel** used during the drilling process
		1 L of diesel fuel = 0.00264 tonnes of CO_2e[3]
	(1,590,000 L)*(0.00264 tonnes/L) = 4,200 tonnes	**4,200 tonnes of CO_2e** produced during drilling
Crude Oil Recovery: Fracking		**15,856 rigs** in the Barnett Shale region[4]
		42 million tonnes/year of CO_2e leak during fracking in Barnett Shale[5]
	(42,000,000 tonnes/year)*(1 year/365 days)*(1/15,856 rigs) = 7.257 tonnes CO_2e/day	**7.257 tonnes of CO_2e/day** leaked per oil rig
		1 L fuel = 3.65 L crude oil[6]
		Diesel buses travel **400,000 km** in their lifetime[7]
		Diesel buses run on **2.05 km/L of fuel**[8]
	(400,000 km)/(2.05 km/L fuel) = 195,000 L fuel	**195,000 L of fuel** used in one bus' lifetime
	(195,000 L fuel)*(3.65 L crude oil/L fuel) = 712,000 L crude oil	**712,000 L of crude oil** used in one bus' lifetime
		15,000 to **507,000 L/day crude oil** extracted from oil wells[9]

	(712,000 L crude oil)/(15,000 L/day) = 48 days (712,000 gal crude oil)/(507,000 L/day) = 2 days	**2** to **48 days** to pump up enough oil to fuel one bus after fracking is completed
		Takes **3** to **5 days** to complete fracking[10]
	(7.257 tonnes CO_2e/day)(3+2 days) = 36 tonnes CO_2 (7.257 tonnes CO_2e/day)(5+48 days) = 385 tonnes CO_2 (36+385)/2 = 211 tonnes CO_2e	**211 tonnes of CO_2e** produced during fracking
Crude Oil Transportation	(37+45 mph)/2 = 41 kmh	Oil tankers run at an average of **41 kilometers per hour**[11]
		Oil tankers consume **238,000 L of fuel oil/day**[11]
Singapore		Distance from Middle East to Singapore: **6,800 km**[12]
	(6,800 km)/[(41 kmh)*(24 hours/day)] = 7 days	Duration of trip from Middle East to Singapore: **7 days**
	(238,000 L of fuel oil/day)*(7 days) = 1,666,000 gal	**1,666,000 L of fuel oil** consumed per trip
		Tankers release **0.00317 tonnes of CO_2e per L of fuel oil** consumed[13]
	(0.00317 tonnes CO_2e/L fuel oil)*(1,666,000 L fuel oil) = 5,000 tonnes CO_2e	**5,000 tonnes of CO_2e** are released per trip
China		Distance from Middle East to China: **11,600 km**[12]
	(11,600 km)/[(41 kmh)*(24 hours/day)] = 12 days	Duration of trip from Middle East to China: **12 days**
	(238,000 L of fuel oil/day)*(12 days) = 2,856,000 L	**2,856,000 L of fuel oil** consumed per trip
	(0.00317 tonnes CO_2e/L fuel oil)*(2,856,000 gal fuel oil) = 9,000 tonnes CO_2e	**9,000 tonnes of CO_2e** are released per trip to China
South Korea		Distance from Middle East to South Korea: **12,600 km**[14]

	(12,600 km)/[(41 kmh)*(24 hours/day)] = 13 days	Duration of trip from Middle East to South Korea: **13 days**
	(238,000 L of fuel oil/day)*(13 days) = 3,094,000 L	**3,094,000 L of fuel oil** consumed per trip
	(0.00317 tonnes CO_2e/L fuel oil)*(3,094,000 gal fuel oil) = 10,000 tonnes CO_2e	**10,000 tonnes of CO_2e** are released per trip to South Korea
		Oil tankers transport up to **318 million L of crude oil per trip**[15]
	318 million L >> 712,000 L (amount of crude oil a diesel bus uses in its lifetime, calculated during fracking process)	**1 trip needed per port**
Oil Refining		**286.2 million tonnes of CO_2e/year** produced by all oil refineries in the world[16]
		536 oil refineries in the world[14]
	(286,200,000 tonnes CO_2e/year)/(536 refineries) = 534,000 tonnes CO_2e/year per refinery	**534,000 tonnes of CO_2e/year** produced per refinery
	(534,000 tonnes CO_2e/year)*(1 year/365 days) = 1,500 tonnes CO_2e/day	**1,500 tonnes of CO_2e/day** produced per refinery
		Refineries process **45 million L of crude oil/day**[17]
	[(45 million L crude oil/day)/(712,000 L crude oil)]*(1 day/24 hours) = 1 hour	Takes **1 hour** to process enough crude oil to fuel a diesel bus throughout its lifetime
	(1,500 tonnes CO_2e/day)/(24 hours/1 day) = 60 tonnes CO_2e per diesel bus	**60 tonnes of CO_2e** produced during the refining process
Fuel Distribution: Singapore		Distance from Singapore to Melbourne: **6,000 km**[14]
	(6,000 miles)/[(41 kmh)*(24 hours/day)] = 6 days	Duration of trip from Singapore to Melbourne: **6 days**
	(238,000 L of fuel oil/day)*(6 days) = 1,428,000 L	**1,428,000 L of fuel oil** consumed per trip
China		Distance from China to Melbourne:

		7,200 km[14]
	(7,200 km)/[(41 kmh)*(24 hours/day)] = 7 days	Duration of trip from China to Melbourne: **7 days**
	(238,000 L of fuel oil/day)*(7 days) = 1,666,000 L	**1,666,000 L of fuel oil** consumed per trip
South Korea		Distance from South Korea to Melbourne: **9,000 km**[14]
	(9,000 km)/[(41 kmh)*(24 hours/day)] = 9 days	Duration of trip from South Korea to Melbourne: **9 days**
	(238,000 L of fuel oil/day)*(9 days) = 2,142,000 L	**2,142,000 L of fuel oil** consumed per trip
	(1,428,000+1,666,000+2,142,000 L)*(0.00317 tonnes CO_2e per L of fuel oil) = 17,000 tonnes CO_2e	**17,000 tonnes of CO_2e** released during the distribution process
Vehicle Operation		Diesel buses produce **0.871kg of CO_2e/km**[18]
	(0.871 kg/km)*(400,000 km travelled in lifetime)*(.001 metric ton/kg) = 348 tonnes CO_2e	**348 tonnes of CO_2e** released from tailpipe emissions
Total CO_2 Emissions of Diesel Fuel: **45,819 tonnes CO_2e per bus**		

Sources

1. (Ipieca, 2013)
2. (Lioudis, 2020)
3. (US EPA, 2016a)
4. (Texas Commision on Environmental Quality, 2016)
5. (Zavala-Araiza et al., 2015)
6. (US EPA, 2020a)
7. (MacKechnie, 2019)
8. (O'Dea, 2018)
9. (US EPA, 2020b)
10. (Independent Petroleum Association of America, n.d.)
11. (FreightWaves Staff, 2020)
12. (Brutman, 2011)
13. (Krantz, 2016)
14. (Corones, 2018)
15. (*Oil tanker ship*, n.d.)
16. (Auch, 2017)
17. (Venkataraman, 2020)
18. (Chang et al., 2019)

Appendix E: Battery Production Calculations

Production Process	**Calculations**	**Statistics**
Mining for Lithium	10 kg = .0110231 tonnes 9 * .0110231 = .01 tonnes CO_2e (negligible)	For every 1 ton of lithium 9 tonnes CO_2e[1] Amount of lithium needed to produce battery: 10 kg[2]
Production of the Cell for a NCM111	859 / 4184 = .2 tonnes CO_2e/kWh .2 * 324 = 65 tonnes CO_2e	Precursor and LiCO3: 181 MJ/kWh Cathode Production: 228 MJ/kWh Anode + anode production: 99 MJ/kWh Separator: 8 MJ/kWh Electrolyte: 35 MJ/kWh Binder: 5 MJ/kWh Current Collectors: 87 MJ/kWh Cell production: 216 MJ/kWh Total: 859 MJ/kWh Number of MJ in a ton: 4184 MJ Capacity of Electric bus battery in Victoria: 324 kWh[3]
Production of the Battery Pack	178 / 4184 = .04 tonnes CO_2e/kWh .04 * 324 = 13 tonnes CO_2e	Wrought Aluminum: 153 MJ/kWh Plastics: 1 MJ/kWh Steel: 1 MJ/kWh Coolant: 1 MJ/kWh Assembly: 22 MJ/kWh Total: 178 MJ/kWh Number of MJ in a ton: 4184 MJ Capacity of Electric bus battery in Victoria: 324 kWh
Electricity Generation During Production		2 tonnes of CO2e
		Total emissions during production of battery = 80 tonnes CO_2e
Charging the battery	400,000 km * 182 g/km = 72,800,000 grams CO_2e 72,800,000 grams CO_2e = 72 tonnes CO_2e	Travel distance of an average bus: 250,000 miles or about 400,000 kilometers CO_2 emissions for an electric vehicle in Australia: 182 g/km[4]
End of Life	.1 tonnes CO_2e (negligible)	Estimated end of life emissions of a electric bus: .1 tonnes CO_2e
Total CO_2 Emissions of Lithium-Ion Battery: **153 tonnes CO_2e per bus**		

Sources

1. (Roskill Information Services Ltd, 2020)
2. (Root, 2020)
3. (Schmidt, 2020)
4. (Green Vehicle Guide, n.d.)

Appendix F: Vehicle-to-Grid (V2G) Calculation

V2G Formula: Rev = ToH * AER * PDR[1]

Key:

Rev: Total revenue per year

ToH: Total hours of use per year

AER: Average electricity rate

PDR: Power distribution rate

ToH = 2 hours a day * 365 days a year = 730 hours[2]

AER = AU$40/MWh[3]

PDR = 0.07 MW (70 kW)[4]

Rev = 730 hours * AU$40/MWh * 0.07 MW = AU$2044 per year

Total Revenue = Rev * 12 years = AU$2044 * 12 = ***AU$24,528 overall***

Sources:

1. (Kempton & Tomić, 2005)
2. (Csiro, n.d.)
3. (Australian Energy Regulator, 2014)
4. (Shirazi et al., 2015)

Appendix G: Private Costs Table

Private Costs Table		
Costs	**Diesel Bus**	**Electric Bus**
Bus	AU$635,000	AU$950,000
Charging Station	AU$0	AU$50,000
Fuel	AU$212,000	AU$76,000
Maintenance	AU$480,000	AU$172,000
Battery Replacement	AU$0	AU$123,120
V2G Savings	AU$0	-AU$24,538
Total	AU$1,327,000	AU$1,346,582

Appendix H: User Satisfaction Calculation

Melbourne metropolitan bus boardings in 2018-2019[1]: 121.8 million boardings

Annual growth[1]: 3.7%

Predicted boarding levels 2019-2020 with the same 3.7% growth: (121.8 million)*(1.037) =126.3 million boardings

Ride quality & noise reduction ridership growth[2]: 1.9%

New riders due to increased user satisfaction: (126.3 million)*(0.019) = 2.4 million new boardings

Cost of Melbourne bus fare, zones 1 & 2[3]: AU$9

Cost of Melbourne bus fare, zone 2[3]: AU$6

Average cost of bus fare: AU$7.50

Total profit for the entire fleet: (2.4 million new boardings)*(AU$7.50) = AU$18,000,000

Profit over 12 years: (AU$18,000,000)*(12 years) = AU$216,000,000

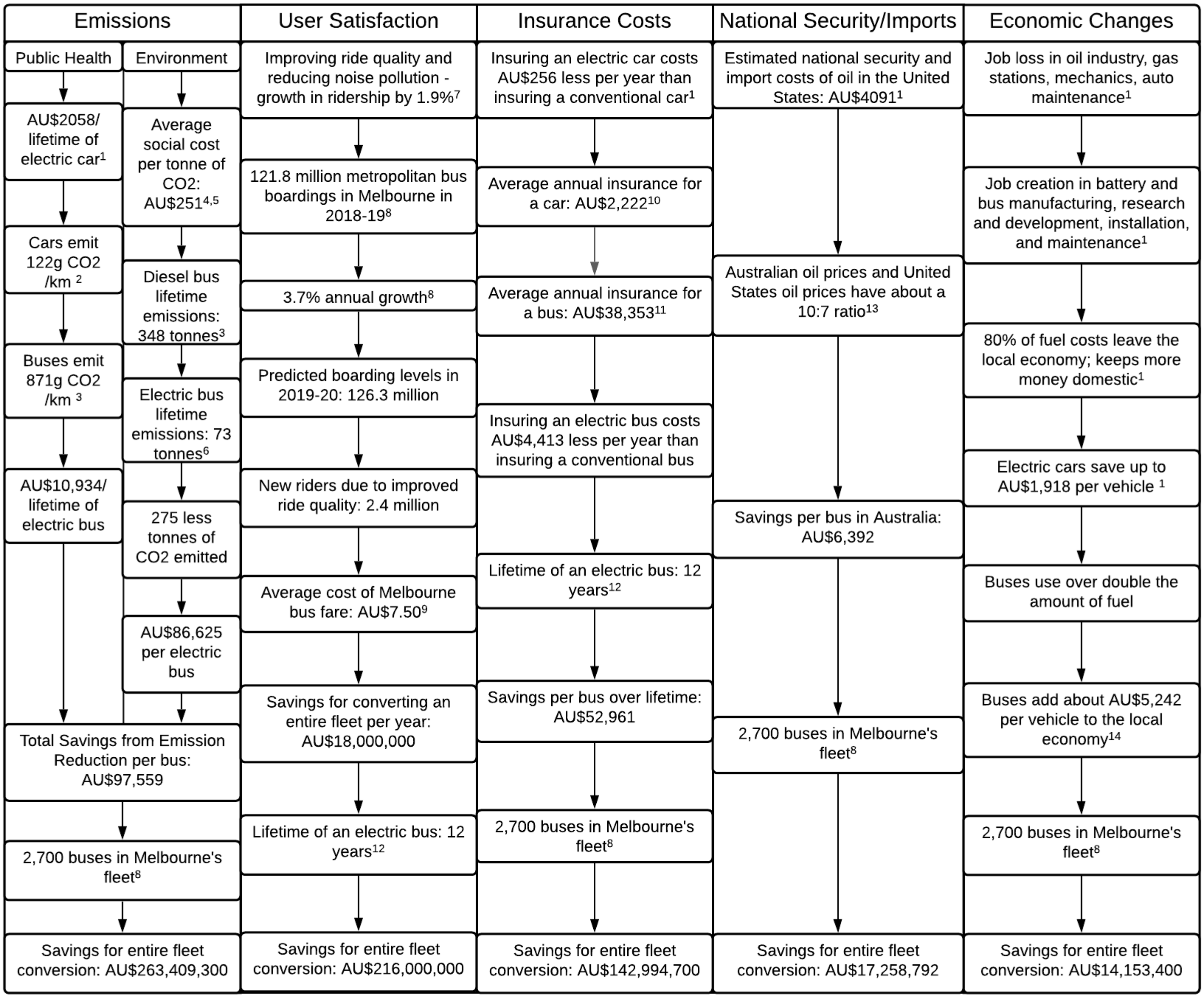
Number of buses in Melbourne's fleet: 2,700

Profit per bus: (AU$216,000,000)/(2,700 buses) = AU$80,000

Sources:

1. (Public Transport Victoria, 2019)
2. (Currie et al., 2018)
3. (Public Transport Victoria, 2021)

Appendix I: Externality Process



Sources:

1. (Malmgren, 2016)
2. (Department for Transport, 2015)
3. (Chang et al., 2019)
4. (Than, 2015)
5. (Nuccitelli, 2020)
6. (Green Vehicle Guide, n.d.)
7. (Currie et al., 2018)
8. (Public Transport Victoria, 2019)
9. (Public Transport Victoria, 2021)
10. (Rivelli, 2021)

11. (Bus Insurance HQ, n.d.)
12. (Guerrero, 2017)
13. (OECD, 2019)
14. (Bonneville Environmental Foundation, 2020)

Appendix J: External Savings Table

External Savings Table		
Externality	**Savings For Whole Fleet**	**Savings Per Bus**
Carbon Emissions	AU$233,887,500	AU$86,625
Health Impacts	AU$29,521,800	AU$10,934
Economy - Job Loss/Gain	AU$14,153,400	AU$5,242
User Satisfaction/Noise Pollution	AU$216,000,000	AU$80,000
Oil Import Prices	AU$17,258,400	AU$6,392
Insurance	AU$142,994,700	AU$52,961
Total:	AU$653,815,800	AU$242,154