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

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

An Interactive Qualifying Project
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WORCESTER POLYTECHNIC INSTITUTE
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degree of Bachelor of Science

by
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Report Submitted to:

Partner Organizations:
Claudia Gallois
Friends of the Earth Melbourne
David Robertson
Public Transport Users Association

Professors Stephen McCauley and Esther Boucher-Yip
Worcester Polytechnic Institute

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.

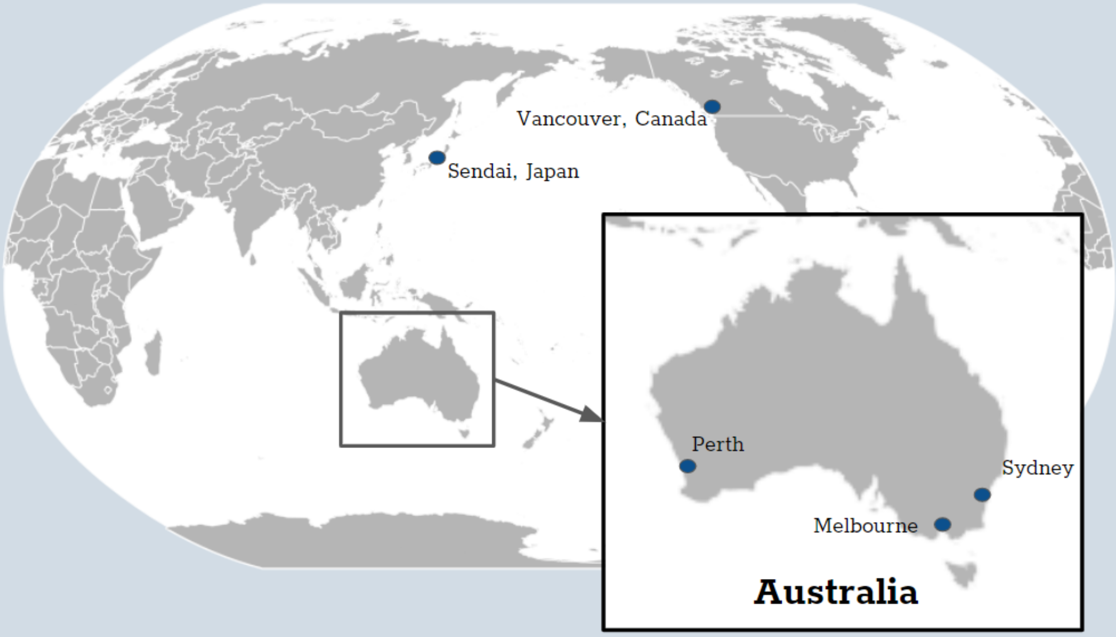


Figure 4: Map of Interview Locations (Stepshep, 2008)

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.

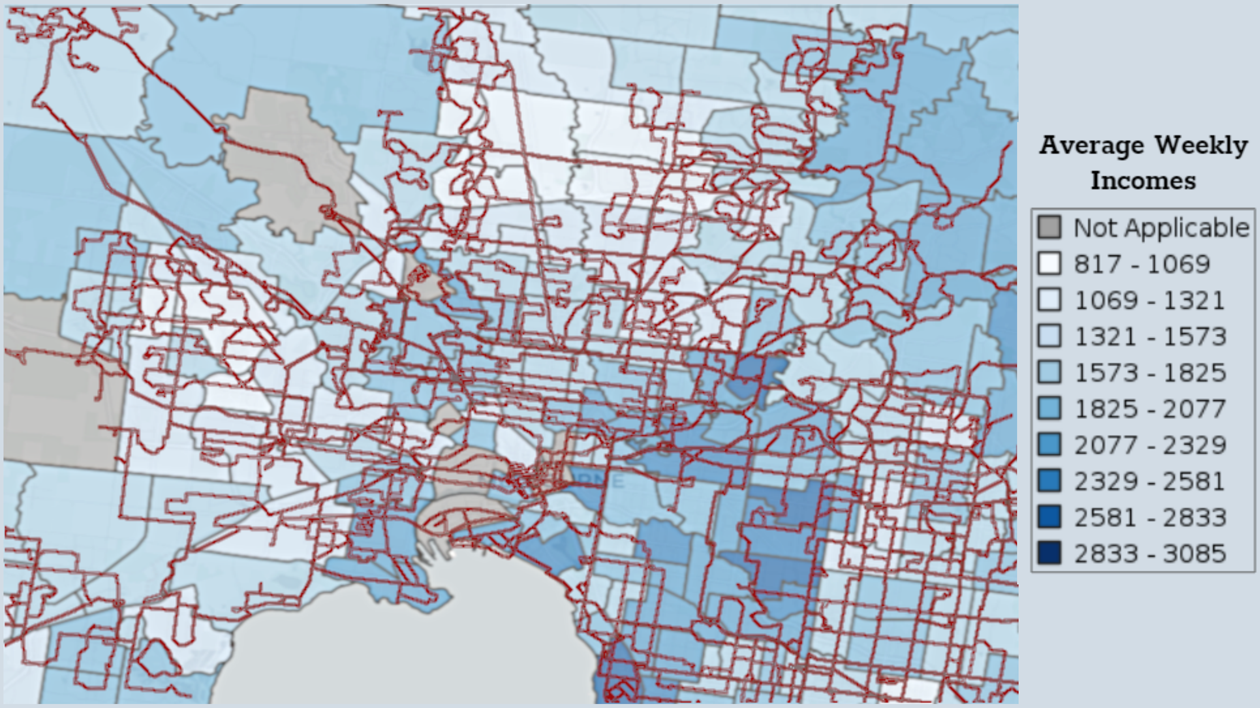


Figure 8: Bus Routes and Median Household Income in Greater Melbourne

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 (CO2e) produced by diesel fuel and electric bus batteries to demonstrate the differences in their environmental impacts. For diesel buses, we quantified the CO2e from oil extraction and tailpipe emissions, whereas for electric buses, we quantified the CO2e 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 CO2e, and each electric bus battery produces only 153 tonnes of CO2e in its lifetime.

Diesel Fuel produces

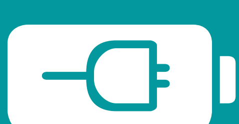
45,819

tonnes of CO2e per bus

Electric Bus Batteries produces

153

tonnes of CO2e per bus



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.

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: Total Electric Bus Savings

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.

Streets of Melbourne, Australia

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 writing on the Gordon Price interview findings, the partner organizations section, and the 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 contributed to the background chapter by writing about the sustainability and inefficiency sections of the background. 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 findings. Additionally, she researched and worked on the sustainability section of the background and collaborated on the project conclusion and recommendations. Finally, this author designed the two supplemental infographics.

Anthony LoPresti: This author was the primary contributor to the writing, analysis, and research for the life-cycle assessment of the battery-electric bus section. He also collaborated on producing the executive summary. Additionally, he helped with research throughout the inefficiency section of the background and collaborated on writing the interview findings of the report.

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Partner Organizations

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.).

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.).

Concerns with Melbourne's Bus System: Inefficency

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).

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).

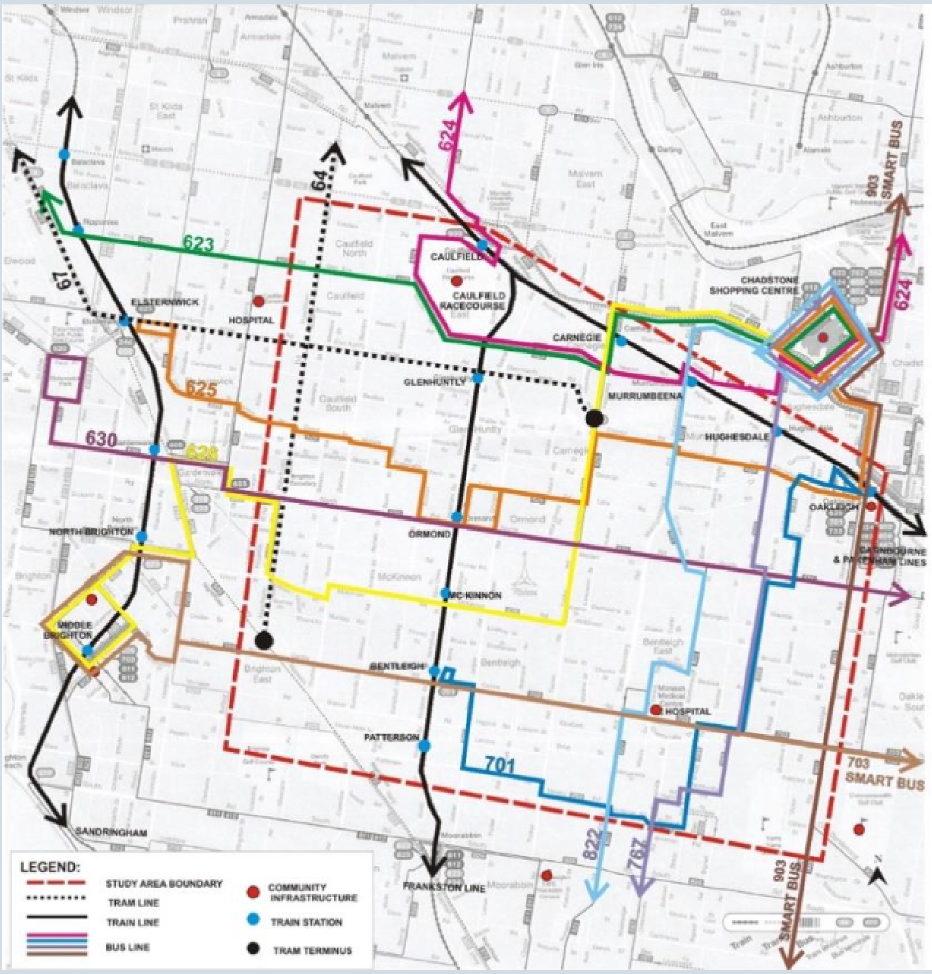


Figure 1: Current Bus Routes in Melbourne (Pandangwati & Milyanab, 2017)

Long 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 30 minutes to an hour on the weekends (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.

Passengers Waiting for Melbourne Bus, by M. Santillan, 2021

Traffic Congestion

One of the biggest roadblocks for the Melbourne bus system is traffic congestion. As shown in Figure 2, Melbourne's population has grown by 48% in the past 20 years, increasing the amount of cars on the road tremendously (World Population Review, 2021).

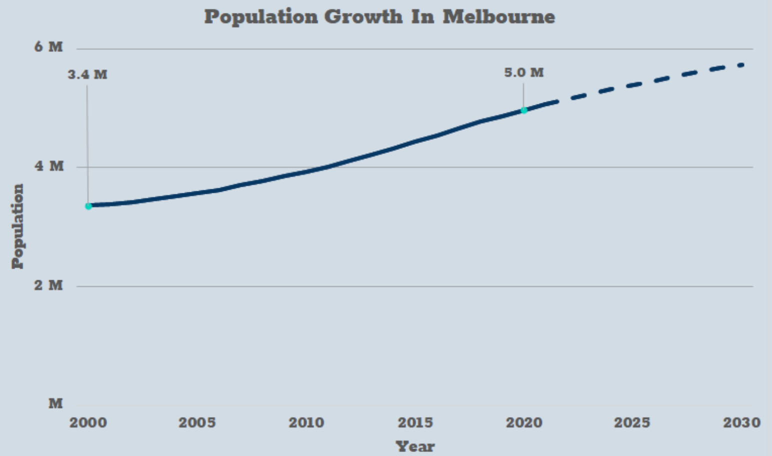


Figure 2: Population Growth in Melbourne (World Population Review, 2021)

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.

Inequity

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.

Melbourne Bus Stop, by M. Santillan, 2021

Melbourne	Sydney	Perth
Gini Coefficient:	**Gini Coefficient:**	**Gini Coefficient:**
0.68	**0.62**	**0.52**

Unsustainability

Buses vs. Passenger Vehicles

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 3 shows the average carbon emissions per kilometer for various forms of transportation (Climate Council, 2017).

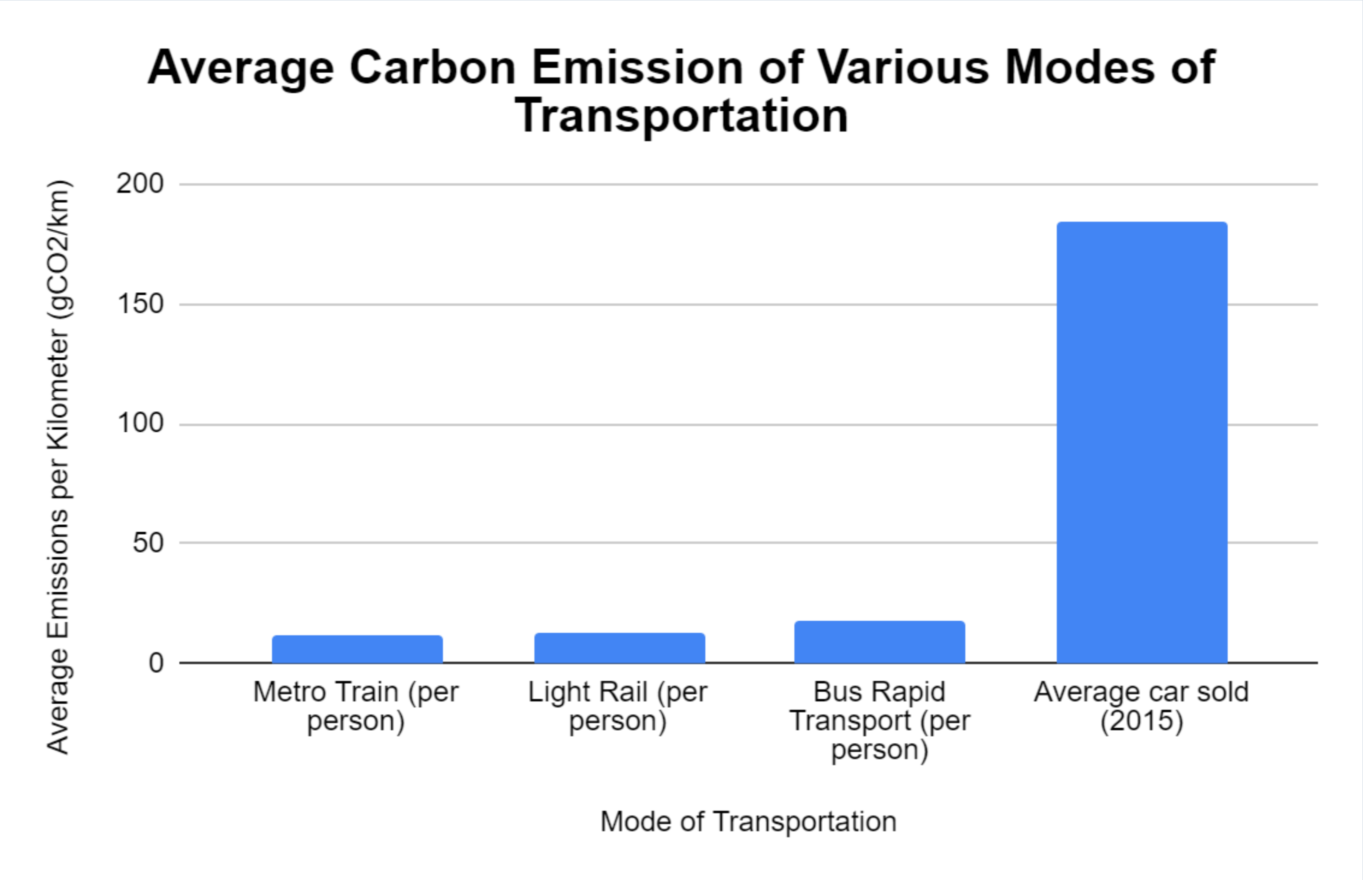


Figure 3: Carbon emissions of various modes of transportation (Climate Council, 2017)

Diesel vs. Electric Buses

Stagecoach Electric Bus (Venables, 2020)

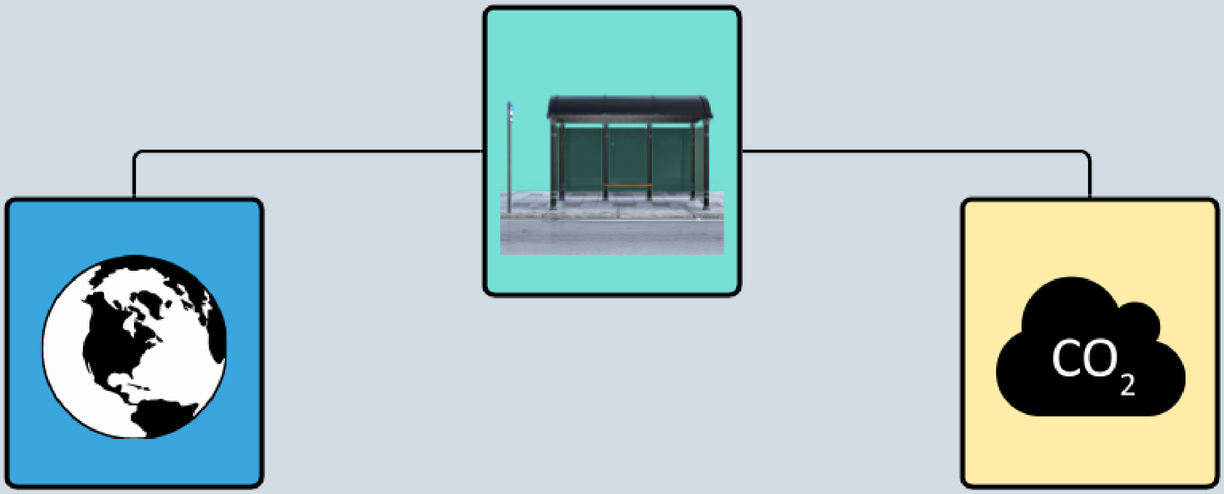
Currently, Melbourne's entire bus fleet consists of diesel buses (Schmidt, 2020). Diesel buses have significant impacts on both public health and the environment due to their high levels of greenhouse gas emissions, such as carbon dioxide emissions (CO2e) (Nunno, 2018). Melbourne's bus fleet produces around 78,300 tonnes of carbon dioxide emissions (CO2e) 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 are affecting the makeup of ecosystems, contributing 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).

Melbourne's bus fleet produces **78,300 tonnes CO2e** a year in tailpipe emissions.

This is equivalent to cutting down **3,195 trees.**

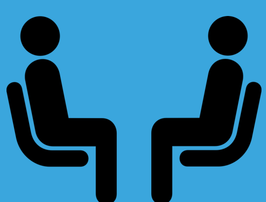
The Victorian government has expressed an interest in shifting their bus fleet to electric in the coming decades, environmentally friendly alternatives. Compared to gas or diesel-fueled vehicles, battery-powered electric buses produce significantly fewer carbon emissions throughout their lifetimes. Although the electric buses themselves do not produce emissions while running, it is crucial to also take into account the manufacturing of the buses' batteries. These processes release gases into the atmosphere. Nonetheless, the life cycle of electric buses still results in fewer carbon emissions overall than driving gas or diesel-powered buses, when the emissions produced by steps taken to recover and refine fuel are factored in (O'Dea, 2018). Electric buses can appeal to the public as well and encourage higher ridership numbers, since the buses 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).

Project Approach



Case Studies of Various Bus Systems

- 6 interviews

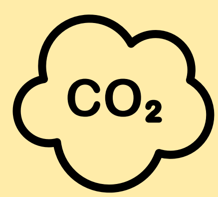


Investigation of Equity in Bus Accessibility

- Survey
- Spatial Analysis

Implications of Electric Bus Implementation

- Life-Cycle Assessment
- Cost-Benefit Analysis



Interviewees

John Storrie

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.).

Gordon Price

He is a former director of The City Program at Simon Fraser University and 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.).

Dr. John Stone

He is a professor at Melbourne University who specializes in transport and urban planning and has extensive experience researching Melbourne's transportation system and how it can be improved.

Dr. Peter Newman

He is an environmental scientist, author, and educator. He is also a professor of sustainability at Curtin University in Perth and a longtime transportation activist with Transperth.

Dr. Gregory Trencher

He is an Environmental Studies professor at Tohoku University in Sendai, Japan and researches sustainable and renewable energy alternatives for various cities throughout the world, such as Sacramento, Berlin, and Shenzhen (Trencher, 2019).

Private Bus Operator

They are a network planning manager for a private bus operator in Sydney and wished to remain anonymous for our report.

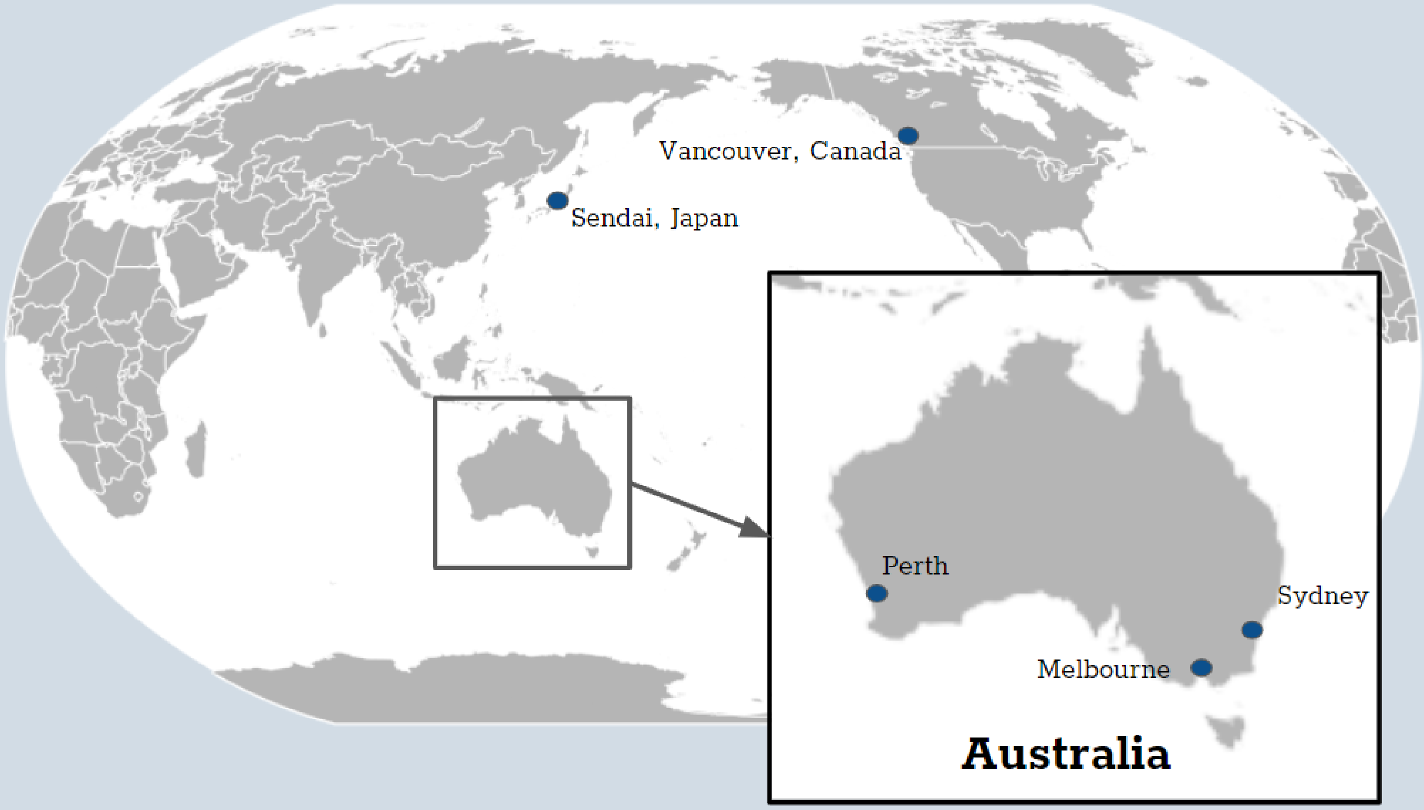
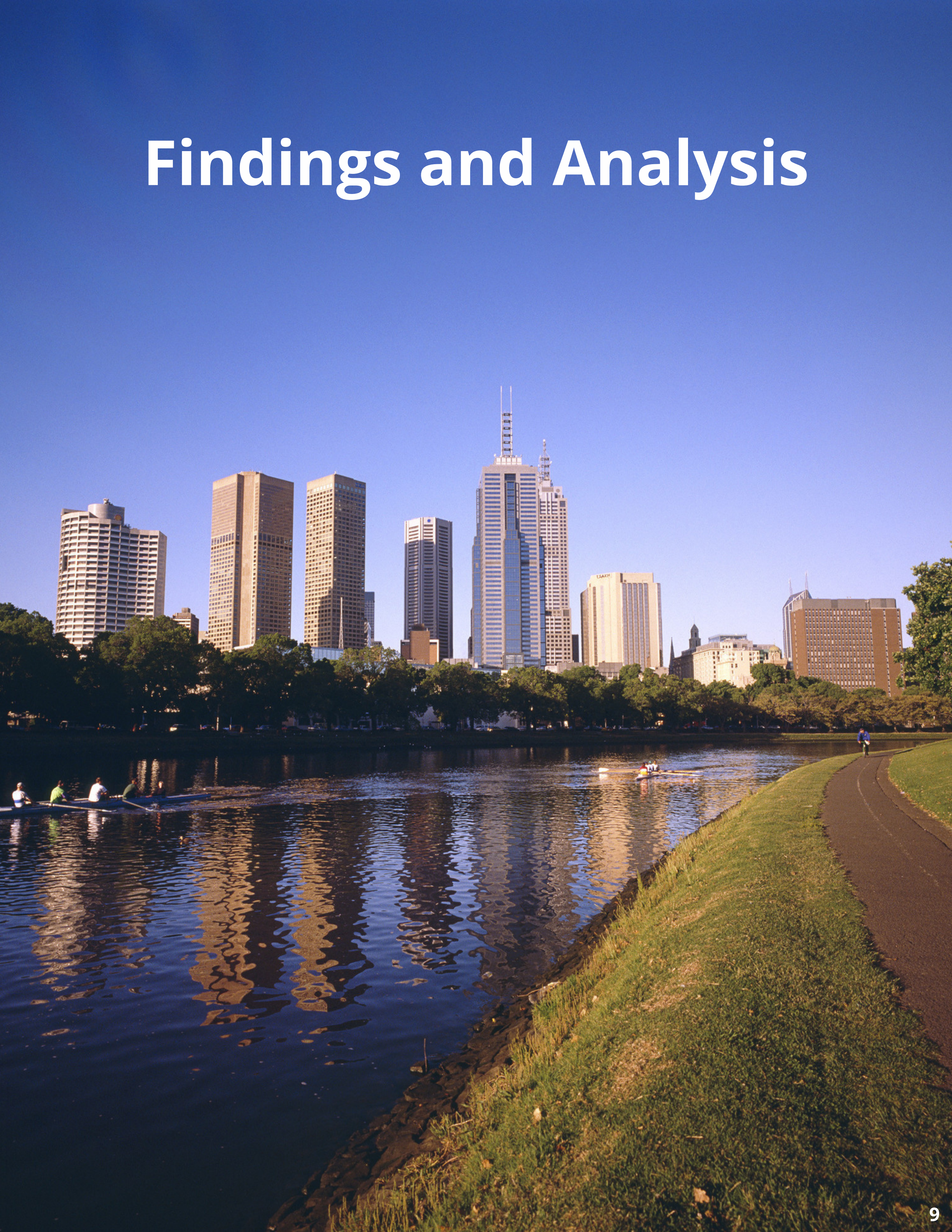


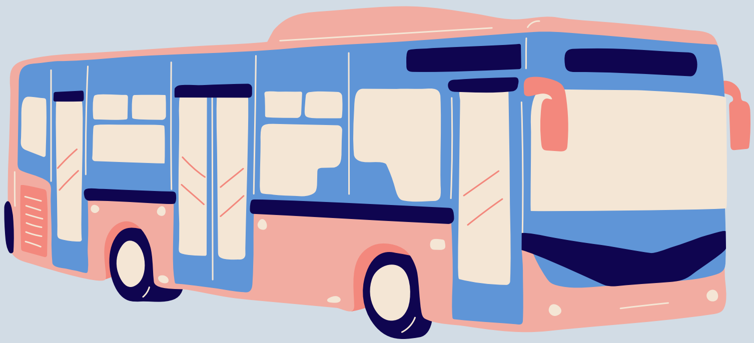
Figure 4: Map of Interview Locations (Stepshep, 2008)

Findings and Analysis



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.



Efficiency is the Most Important Aspect of Public Transportation

"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. People really like that." - Gordon Price

High frequency leads to efficiency

- An efficient bus system consists of significant user satisfaction and high ridership levels
- TransLink (Vancouver's transportation system) operates at such a high frequency that no one waits for a ride for more than a few minutes
- Price believes that high frequency is essential to any successful transportation system
- If riders know that they will not have to wait long to get picked up, they are more likely to consider public transportation a viable and even convenient option

Melbourne continues to struggle with effective routing

- Dr. Stone emphasized that one of the system's largest problems is the inconvenient and inefficient routing currently in place
- He believes the most critical improvement to Melbourne's bus system is better routing choices
- With recent population growth, there is a shift in residence and the routes no longer cater to the most reliant neighborhoods
- Melbourne bus companies are currently paid 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
- Transdev, one of the largest bus operators in Melbourne, did not have its contract renewed so the government is looking for a new operator; reforms could be introduced through contracts

Traffic congestion contributes to Melbourne's inefficiency

"There is a very limited number of right of ways where buses have free passage." -John Storrie

- Lack of bus priority leads to slower travel times, 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]"
- Because of the current traffic congestion, buses are not an effective mode of transportation, thus lowering ridership numbers and straining the system as a whole
- Storrie discussed an initiative to improve the impacts of congestion through computerized signal priority, which 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
- Improving congestion is a proven way to significantly improve ridership levels by making the network more attractive to new riders

Electric buses improve efficiency

Electric buses are "significantly more attractive for people to ride," and this will lead to "more people [living] near their stations because they're not noisy and smelly and full of emissions." -Dr. Peter Newman

- Dr. Newman discussed the electrification of bus fleets and the implications this would have on factors such as ridership and user satisfaction
- He added that they would be "cheaper and easier to run"
- This corroborates the background research we conducted that shows that decreasing noise pollution and incorporating cleaner buses will improve ridership through increased user satisfaction

An Equitable and Accessible Bus System will Satisfy More Users

Cities should use public transportation stations as centers for urban growth

“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” -Dr. Peter Newman

- The idea is to build attractive centers for public transport that are spread throughout the city, and the city will then develop around these stations to encourage economic and urban development in the area
- These transportation centers are hotspots for transfers between various transportation methods and make accessing efficient transportation easier
- This diffuse approach means it is especially easy to navigate anywhere effectively; therefore all people, despite their socioeconomic status, have equal access to public transit
- Dr. Newman called this concept "land value capture," mentioning that this idea was instrumental to the integrated bus and train system in Perth
- Price discussed that Vancouver’s user-friendly urban center model is a similar design, where there are 9 major urban centers that provide connections between other regions using various forms of transportation

Rapid population growth in Melbourne has resulted in a disparity in equal access

- Buses are the easiest form of public transport to spread to the suburbs due to the infrastructure challenges associated with expanding train and tram access
- Melbourne's population growth has been faster than the state can keep up with and a gap has developed between the lower-income areas and the wealthier suburbs
- According to Storrie, this can be attributed to the rapid population growth and the disproportionate expansion of the bus network in response
- In these outer suburbs, buses run at such a low frequency that they’re essentially unusable

“As [the suburbs] grow, there are more and more areas without service, or you've got to dilute the service offering; just sprinkle the magic bus dust as far as possible and people get what is essentially a non-service. It might be an hourly service or worse” -John Storrie

While electric passengers vehicles can be inequitable, electric bus implementation can promote equity

- New technology tends to be expensive, including the electric passenger vehicle
- Electric vehicles require infrastructure construction, and the government must prioritize the placement of charging stations and other related technology
- If the wealthier communities own more electric vehicles, the infrastructure is going to be centered in those areas
- The government wishes to promote this new, innovative technology, but in the process, they pour a greater portion of money into already wealthy areas, while less fortunate areas continue to receive little support
- Dr. Trencher explained that the implementation of electric buses has a potentially positive impact on overall equity since these electric buses would cater to lower-income communities and provide these populations with zero-emission technology

> "...so one of the nice things that occur here is [that] zero-emission buses can promote equity because they have the ability to provide zero-emission transport to poor areas."
> -Dr. Gregory Trencher

BYD Electric Bus (Galeria, 2014)

A Public/Private Working Relationship is Crucial

> "As far as I'm aware, and I only know it from my role in one of those private operators, we're all regarded as equal by Transport for New South Wales, the government department, and so they manage State Transit as they would manage us."
> -Sydney Private Bus Operator

Sydney

- Sydney's bus system is particularly successful due to its approach to the government and private operator relationship
- The private bus companies and the government's State Transit Authority are viewed as equals and work as partners
- Buses are not considered to be "a mode of last resort," but rather a fundamental mode of transportation

Vancouver

- The local region, Vancouver, used to not have adequate control of their own transportation
- TransLink was founded mainly so the people in Vancouver had more autonomy regarding how they manage their own transportation
- 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.)

Melbourne vs Perth

- In Melbourne, the private sector has always operated the buses
- Instead of taking them over as Perth's government did, Melbourne decided to subsidize them, which decentralized the control
- In Melbourne, this flexibility in ownership has created issues over who actually has control over the system

City of Perth, Australia

Electric Bus Implementation Must be Planned Thoughtfully

Phasing out diesel buses should be given as much thought as introducing electric buses

- Dr. Trencher described how the largest fully electric bus system in the world, located in Shenzhen, China, phased out diesel buses using a two-step process
- The first step was to set procurement targets that would slowly increase over time
- The second step was to stop giving out subsidies to pay for diesel fuel and instead give out subsidies to pay for the new electric buses
- The money was moved from the refueling process to the purchase of new electric buses that are more expensive than new diesel buses
- Simultaneously, any economic incentive to hold back on purchasing new electric buses and holding on to old diesel buses is extinguished since there is no longer any financial support for the diesel bus

"[experts] need to have [a] conversation about what we do about this old unwanted technology."
-Dr. Gregory Trencher

Melbourne's electricity grid will need to be upgraded

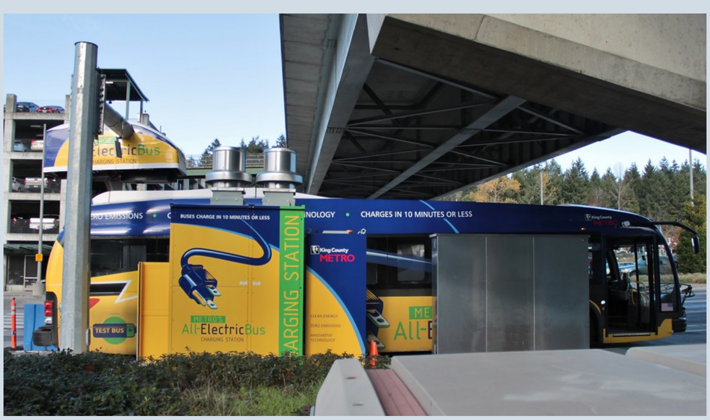
“if you want to have 50 or 100 buses running on batteries and charging, then you have to upgrade the electricity grid to increase the amount of electricity that can be moved through the grid.”
-Dr. Gregory Trencher

- To address this problem, Storrie suggested that Melbourne implement a few buses at a time so that the infrastructure would not need to be drastically changed all at once
- This is a reasonable approach for Melbourne since the bus system is made up of many different private operators and it is a safe assumption that these operators will be more open to a more gradual transition than an instant change
- As new electricity generation infrastructure is built, the city can begin to simultaneously phase out diesel buses

Battery electric buses are much more feasible in Melbourne than hydrogen fuel-cell buses

- According to Storrie, a big issue with zero-emission buses is the establishment of either hydrogen fueling stations or battery charging stations
- Storrie told us that there is a land scarcity issue in Melbourne, making new depots difficult to build
- Hydrogen fueling stations in the same location as diesel fueling stations pose a safety hazard, whereas electric buses can be charged at existing depots
- In order to phase in hydrogen fuel cell buses, entirely new infrastructure and charging stations would need to be implemented

> “[although] the battery-electric [buses] would need investment in the system, at least [they have] a system in place, whereas hydrogen does not yet.”
> -John Storrie



Proterra electric bus at Eastgate P&R (SounderBruce, 2015)

Private Operator's Point of View on the conversion to a fully electric system

> “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.”
> -Sydney Private Bus Operator

- Our private bus operator contact from Sydney mentioned that electric bus technology is constantly evolving, so no one knows where it will be in ten years
- The New South Wales government is trying to avoid having a predetermined view of the answer, so they are instead focusing on the objectives that need to be met to properly implement the system
- 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

Passenger Satisfaction with Melbourne's Bus System

We thought it would also be valuable 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, as shown in **Appendix A**, to bus passengers to assess the user satisfaction levels of the city's buses. 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 Internet access. Therefore, the numbers may not accurately reflect the positions of the entire Greater Melbourne population.

General Dissatisfaction

Overall, **59.1%** of participants are not satisfied with Melbourne's current bus system.

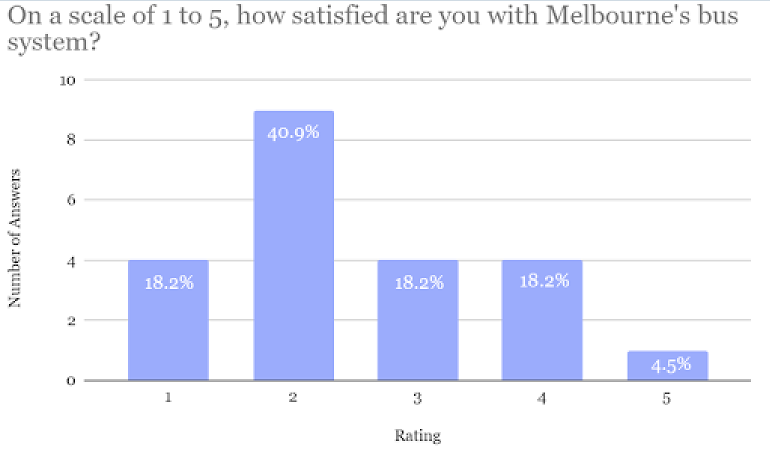


Figure 5: Overall Bus Satisfaction Ratings

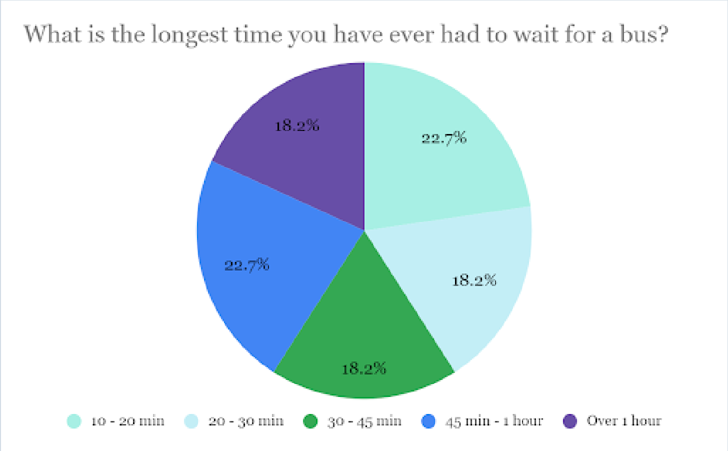


Figure 6: Longest Bus Wait Times

Long Wait Times

59% of particpants have waited over 30 minutes for a bus before.

Shorter Wait Times are Valued

The most important feature of a bus trip is having short wait times at the bus stop, according to **72.7%** of participants.

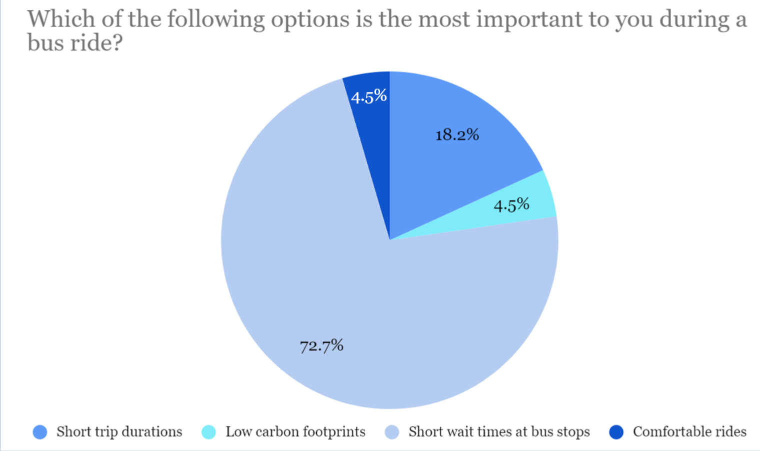


Figure 7: Important Aspects of a Bus Ride Experience

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 mainly caters to wealthier areas. However, lower income populations are less likely to own individual cars, and thus rely more on public transportation to reach the inner city, as discussed in our interview with Dr. Peter Newman. 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.

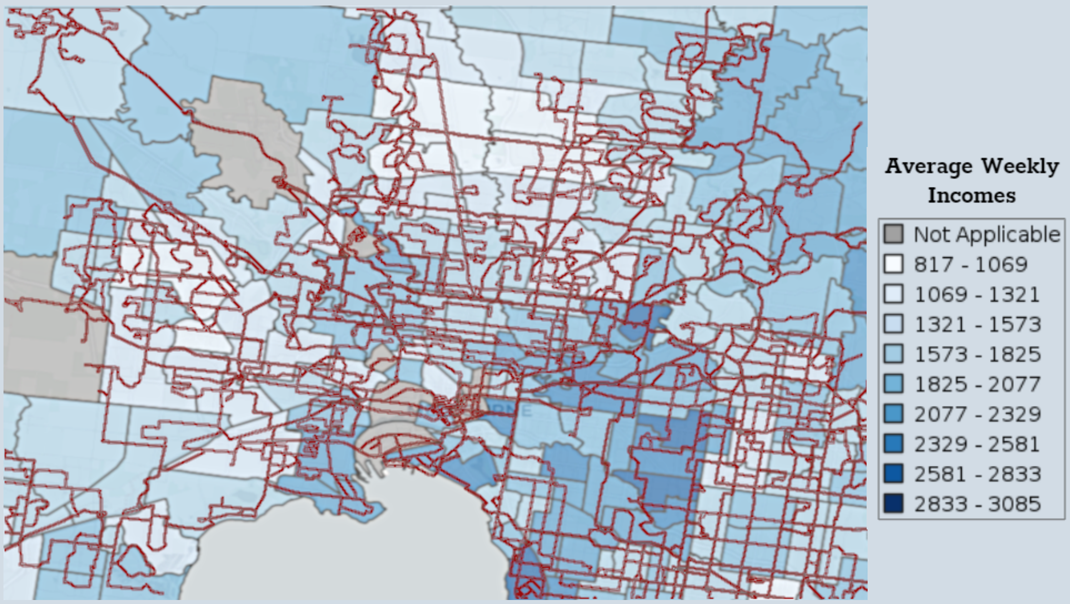


Figure 8: Bus Routes and Median Household Income in Greater Melbourne

- Outer suburbs have lower median incomes
- Sparser routes in outer suburbs
- More access in darker colored suburbs in the northeast than light colored suburbs in north and northwest
- **Conclusion:** both frequency and accessibility are inequitable in Melbourne

- Bus routes cater more to densely populated areas
- Some low income areas still have less access even with higher populations
- The north and northwest portions have little to no access even with very dense populations
- **Conclusion:** Bus routes tend to cater to higher income populations regardless of density

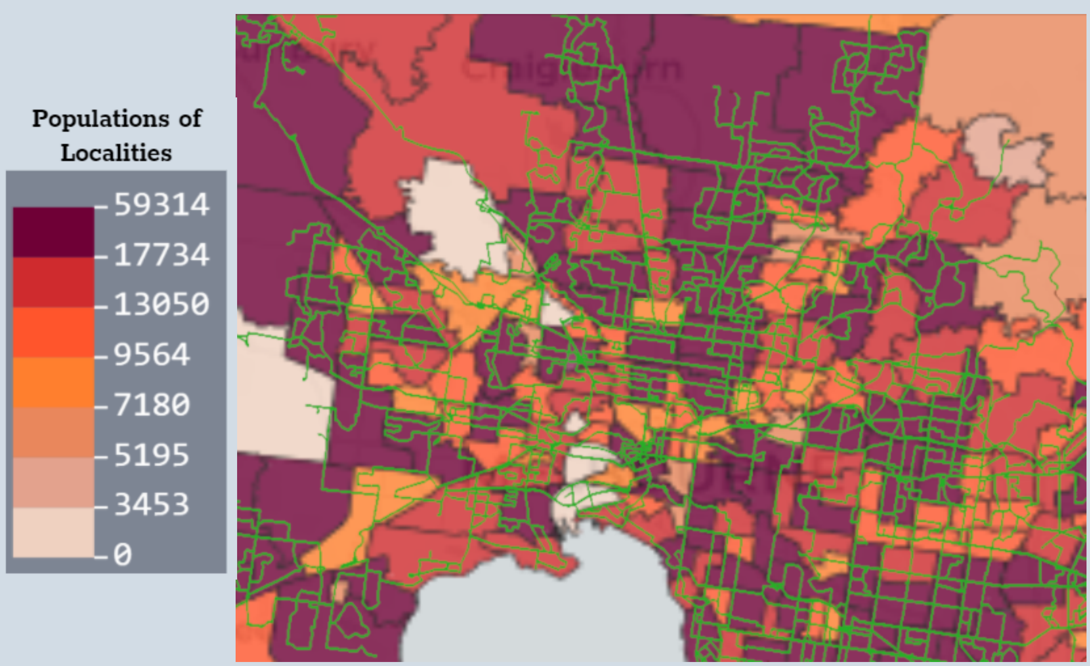


Figure 9: Bus Routes and Population Density in Greater Melbourne

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 (CO2e). 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 CO2e 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.

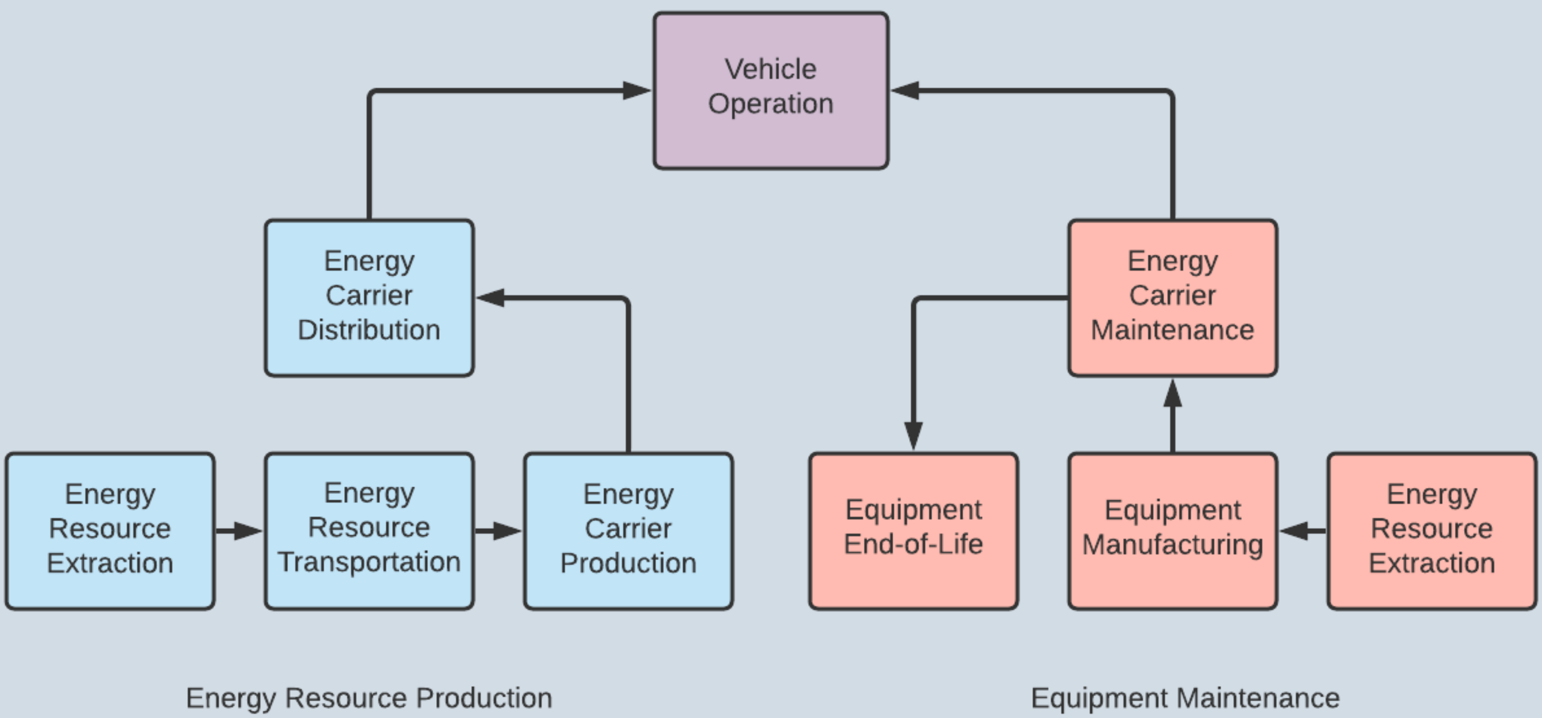


Figure 10: Life-Cycle Assessment Outline (Kukreja, 2018)

Diesel Buses Have Significant Environmental Impacts

The most environmentally destructive aspect of diesel buses is their fuel. In addition to the CO2e 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. Although oil production damages the environment in various ways, we focused on analyzing and calculating the CO2e 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.

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

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 CO2e 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 CO2e are produced per liter of diesel fuel burned, this equates to an average of 4,200 tonnes of CO2e per oil well (US EPA, 2016a). **Appendix C** outlines these calculations in further detail. 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 CO2e 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

Onshore Oil Rig

2,385,000 liters of fuel will be used throughout the drilling process, assuming 30-day months. Since roughly 0.003 tonnes of CO2e are produced per liter of diesel fuel burned, this equates to an average of 4,200 tonnes of CO2e per oil well (US EPA, 2016a). **Appendix C** 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. This process is further outlined in Figure 12. Fracking contributes to air pollution because some of the CO2e 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 CO2e 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 CO2e 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 CO2e 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 CO2e. The related calculations are outlined in **Appendix C**.

Overall, the drilling and fracking steps in crude oil extraction produce the most significant amounts of CO2e. Combined, drilling and fracking produce an average of 4,411 tonnes of CO2e 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 CO2e produced during oil refining, we must first examine the emissions produced by the oil tankers that carry crude oil overseas to the refineries.

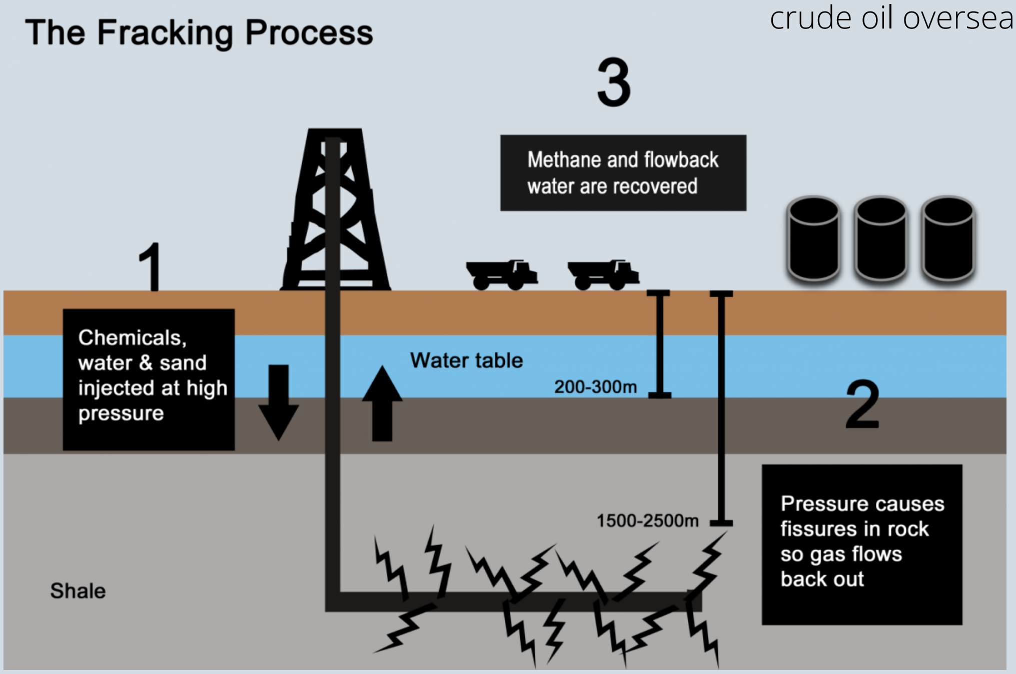


Figure 12: Hydraulic Fracturing Diagram (Energy and Climate Intelligence Unit, n.d.)

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 C**, this means that 5,000 tonnes of CO2e 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 CO2e 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 CO2e 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 CO2e 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 CO2e 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 CO2e per day. Using the calculations shown in **Appendix C**, we determined that only 60 tonnes of CO2e, or 20 tonnes of CO2e 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.

Middle Eastern Oil Tanker (Spragg, 2018)

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 C**. 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 C**, 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.

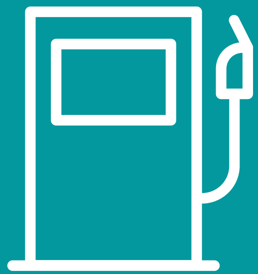
Total Emissions

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.

Diesel Fuel produces

45,819

tonnes of CO_2e
per bus



Transdev Melbourne Bus #360 (Liamdavies, 2013)

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 CO2e 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 CO2e produced during lithium extraction are fuel use, power sources, and energy intensity. On average, lithium requires an average 9 tonnes of CO2e 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. 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 CO2e (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 CO2e as shown in **Appendix D**.

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.

Battery Electric Bus (Wheeler, 2015)

Once on the road, electric vehicles (EVs) do not produce exhaust CO2e 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 CO2e per kilometer estimation. According to the Green Vehicle Guide, in 2017, an electric vehicle in Australia would get approximately 182 g CO2e/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 CO2e as shown in **Appendix D**.

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 CO2e are produced per bus, with the related calculations shown in **Appendix D**.

Electric Bus Batteries produces

153

tonnes of CO2e per bus

Life-Cycle Assessments 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 CO2e 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 CO2e per bus. Diesel-powered vehicles are a significant source of CO2e 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.

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. This process is detailed in Figure 13. When calculating monetary amounts, all findings were initially found in US$ and then converted to AU$. We used the website Xe for the conversion with rates from late February of 2021 (Xe, 2021).

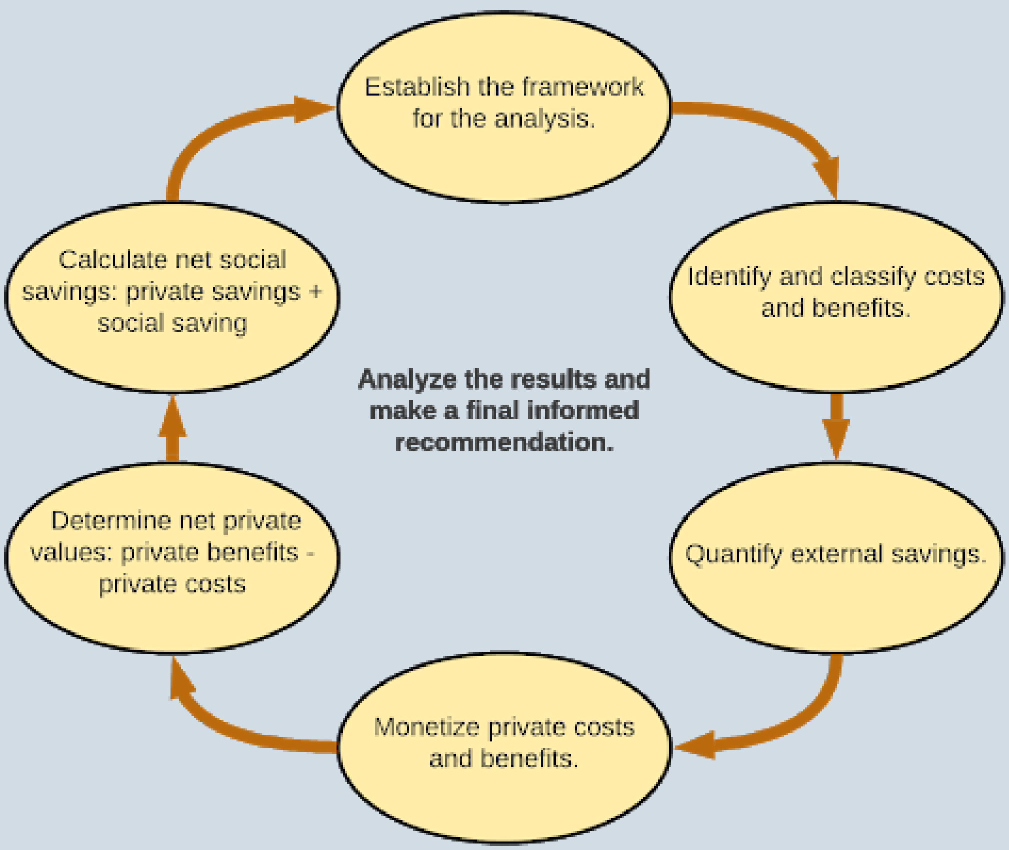


Figure 13: Steps for Cost-Benefit Analysis (Adapted from Wall Street Mojo, n.d.)

The Private Costs of Diesel and Electric Buses Are Similar

Bus

Electric buses cost AU$950,000 on average and a comparable diesel bus costs AU$635,000 on average (Maloney, 2019).

Charging Stations

The charging stations needed to power these buses range in price but average out to be approximately AU$50,000 per charging station when one is needed per bus (Shirazi et al., 2015; Islam et al., 2019).

DC Circulator Electric Bus Charging Station (BeyondDC, 2019)

Fuel

This is estimated to be AU$0.19 per kilometer for electricity while a diesel counterpart would cost AU$0.53 per kilometer (Islam et al., 2019). The service life of most transit buses is expected to be 400,000 kilometers so it will be used for our estimates (MacKechnie, C., 2019). Over that life of 400,000 kilometers of travel, the fuel cost of an electric bus would then be AU$76,000 and a diesel bus would be AU$212,000.

Maintenance

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). The difference between the two prices is so vast due to electric buses requiring less maintenance overall from having fewer moving parts compared to a diesel bus and not requiring normal maintenance like oil changes. 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.

Battery Replacement

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). 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.

Electric Bus Batteries (Spielvogul, 2014)

V2G Savings

Vehicle-to-grid (V2G) is a process that allows the batteries of electric vehicles to have a bidirectional flow of electricity to and from the local power grid (Kempton & Tomić, 2005). Because energy demands are not always consistent over a day, there are peak and nonpeak hours of electrical use. V2G allows a battery to provide its stored up electricity as an extra source back to the grid. Once charged to a sufficient amount, V2G takes over and throttles or reverses the flow of electricity back to the grid. Through the process of charging an electric bus to the power grid, V2G can earn the vehicle owner money from the power company for the privilege of using the 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 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 14 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.

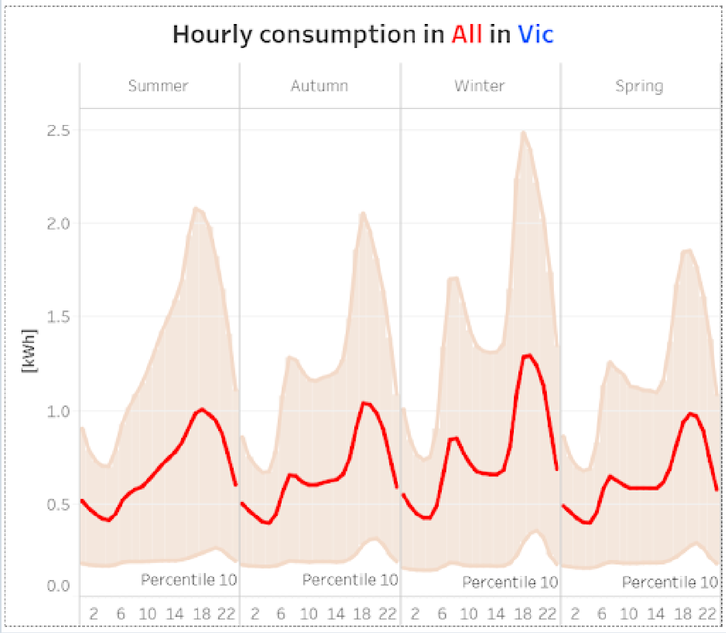


Figure 14: Average Hourly Electrical Consumption in Victoria for All Seasons (Csiro, n.d.)

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 E**.

Private Costs Total

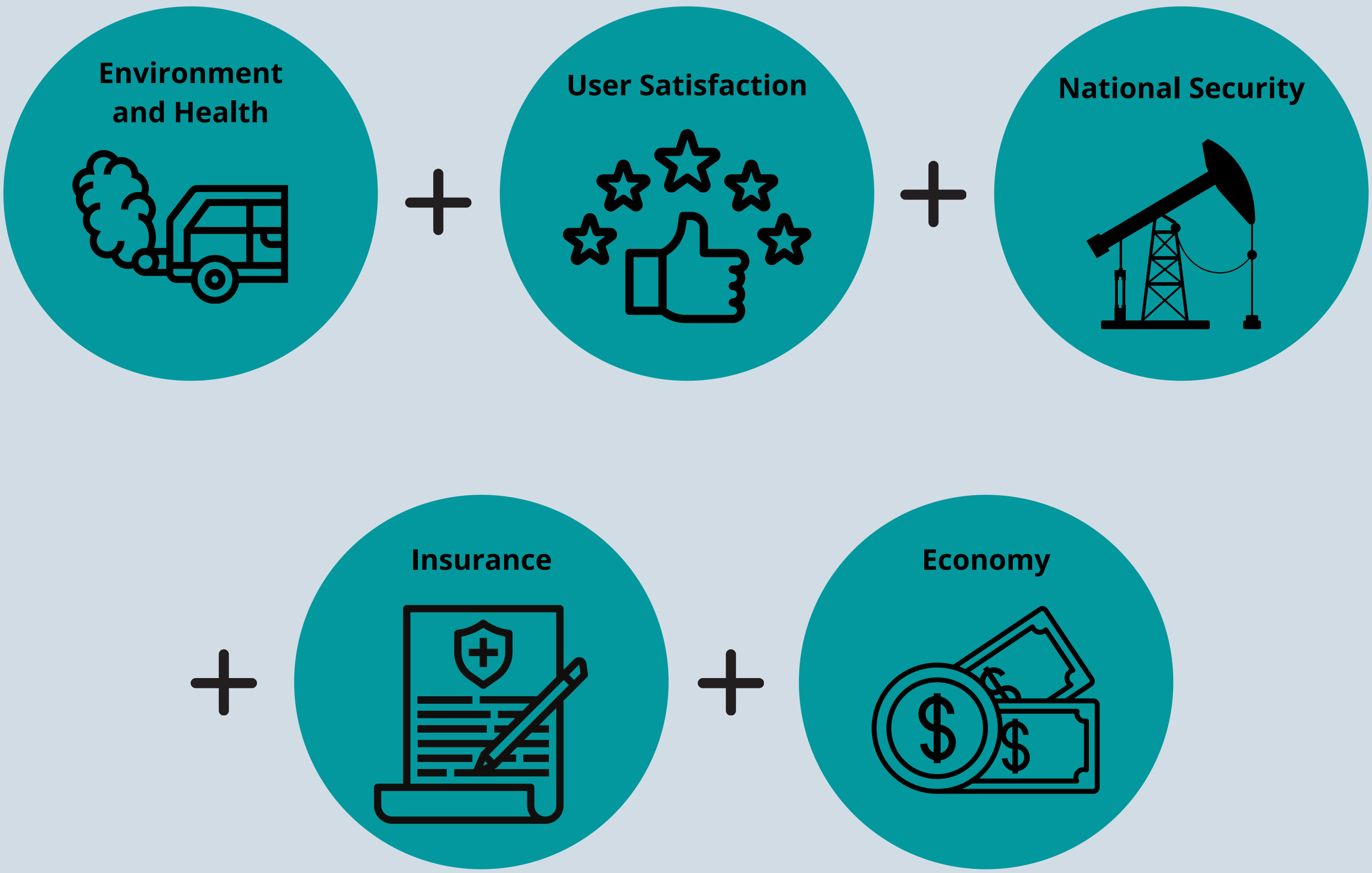
Overall, we found a large disparity in costs for diesel and electric buses between their different components. When all is summed up, an electric bus only costs **AU$19,582** more than a diesel bus. Despite being more expensive, it's actually a great price as newer technologies tend to be more expensive than their conventional counterparts and prices are expected to decrease over time. Table 1 shows the total costs comparison per section for diesel and electric

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$76,000
Battery Replacement	AU$0	AU$123,120
V2G Savings	AU$0	-AU$24,538
Total	AU$1,327,000	AU$1,346,582

Table 1: Private Costs

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.



Emissions Impacts

Carbon and particulate matter emissions have both environmental and public health impacts that make the use of diesel buses costly for society. The factors used in our calculations are depicted in Figure 16.

Transdev Melbourne Bus #190 (Thebusofdoom, 2015)

Public Health

In a study conducted in 2016, it was determined that an individual electric car saves about AU$2,058 over its lifetime in societal public health expenses (Malmgren, 2016). To compare this to the savings of an electric bus, we compared the amount of emissions from a car to the amount of emissions from a bus to determine that there are savings of almost AU$11,000 due to public health impacts over the lifetime of a single electric bus.

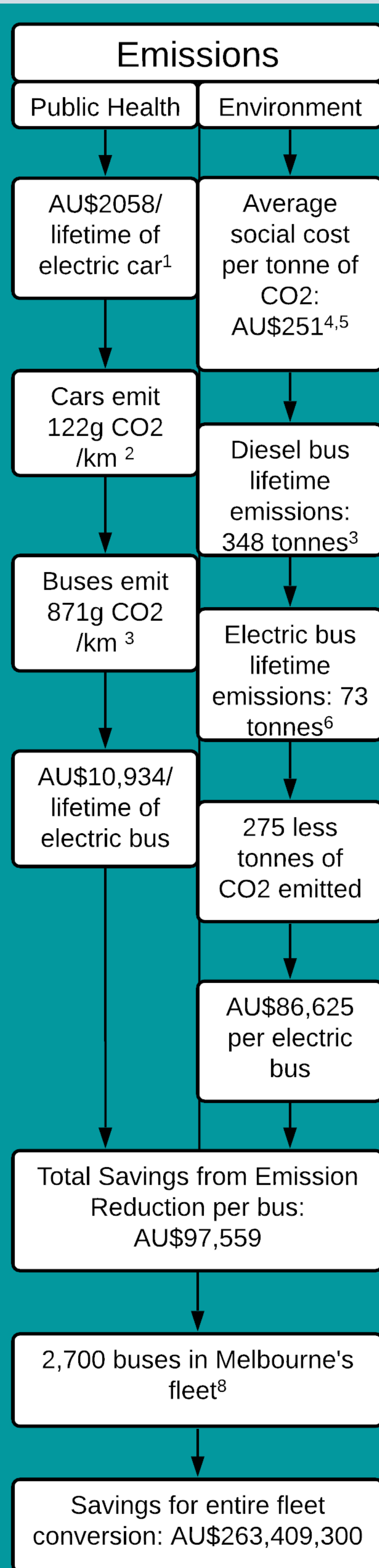
Environmental Impacts

There are also numerous environmental impacts of carbon emissions. On average, the social cost per single tonne of carbon dioxide emitted is AU$251 (Than, 2015; Nuccitelli, 2020). Considering only tailpipe emissions, since these are the only emissions directly impacting Melbourne citizens, electric buses emit 275 less tonnes of carbon per bus over their lifetime (Chang, 2019; Green Vehicle Guide, n.d.). Therefore, per bus, electric buses save a $AU86,625 per bus.

Total Emission Reduction Savings

Per Bus: **AU$97,559**

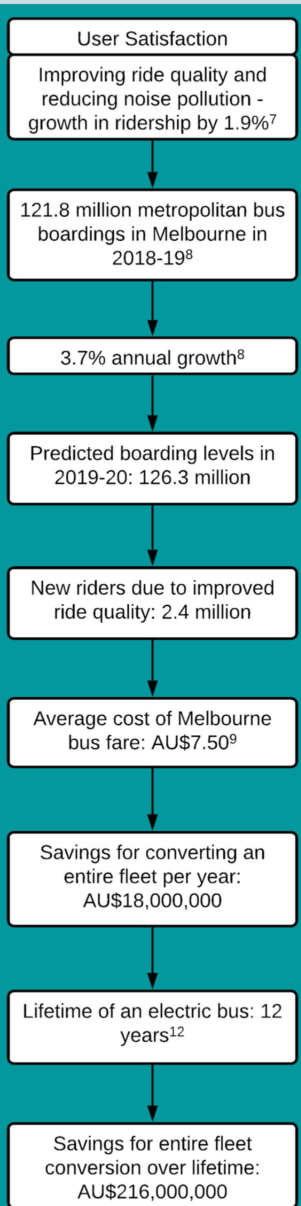
Fleet: **AU$263,409,300**



1. Malmgren, 2016
2. Department for Transport, 2015
3. Chang, 2019
4. Than, 2015
5. Nuccitelli, 2020
6. Green Vehicle Guide, n.d
8. Public Transport Victoria, 2019

Figure 15: Emission Savings of Electric Buses

User Satisfaction



7. Currie et al., 2018
8. Public Transport Victoria, 2019
9. Public Transport Victoria, 2021
12. MacKechnie, 2019

Figure 16: User Satisfaction Savings

There are added conveniences that come with electric buses. For example, electric buses provide smoother, quieter travel, and stronger acceleration (US EPA, n.d.). There are also more opportunities for amenities that may increase ridership and give more value to bus use, such as air conditioning, onboard WiFi, and charging ports.

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). With average ticket costs and annual ridership in Melbourne there will be an estimated profit of about AU$18,000,000 for the whole fleet per year, or AU$216,000,000 saved over the 12 year lifetime of the fleet. This is AU$80,000 per bus for a fleet of 2,700 buses, as shown in Figure 17 (Public Transport Victoria, 2019). **Appendix F** details these calculations in more detail.

Total User Satisfaction Savings

Per Bus: **AU$80,000**

Fleet: **AU$216,000,000**

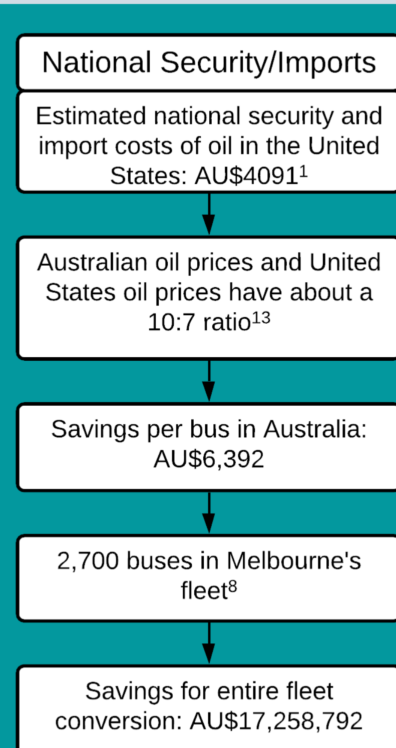
National Security and Imports

A lot of strain is put on international relations and military efforts required to obtain the oil to fuel diesel buses. In the United States, the costs would be upwards of AU$4,091 per bus (Malmgren, 2016). Australian oil prices are much higher, so the estimated savings are upwards of AU$6,392 per bus, as shown in Figure 18 (OECD, 2019).

Total National Security Savings

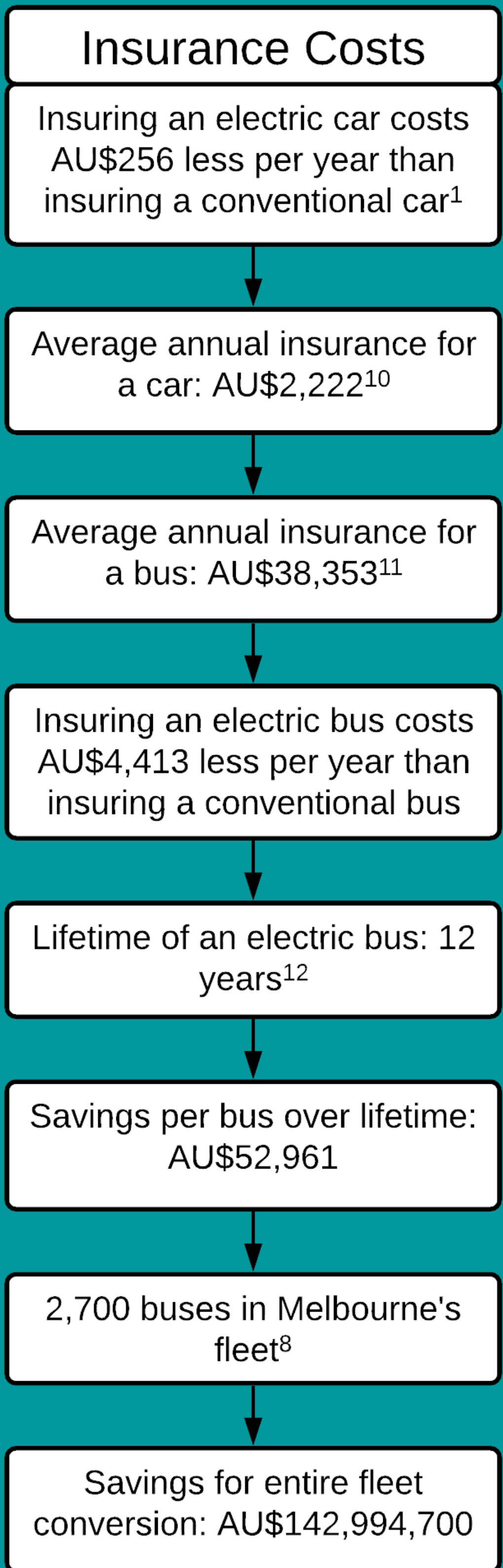
Per Bus: **AU$6,392**

Fleet: **AU$17,258,792**



1. Malmgren, 2016
8. Public Transport Victoria, 2019
13. OECD, 2019

Figure 17: National Security Savings



1. Malmgren, 2016
8. Public Transport Victoria, 2019
10. Rivelli, 2021
11. Bus Insurance HQ, n.d.
12. Guerrero, 2017

Figure 18: Insurance Savings

Insurance Savings

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; when considering cars, insuring an electric car is AU$256 less a year on average 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). The proportional savings in insurance costs for a bus is thus about AU$4,413 per year. Over the lifetime of an electric bus, we found that there would be a net savings of AU$52,961 per bus. This process is detailed in Figure 19.

Total Insurance Savings

Per Bus: **AU$52,961**

Fleet: **AU$142,994,700**

Economic Changes

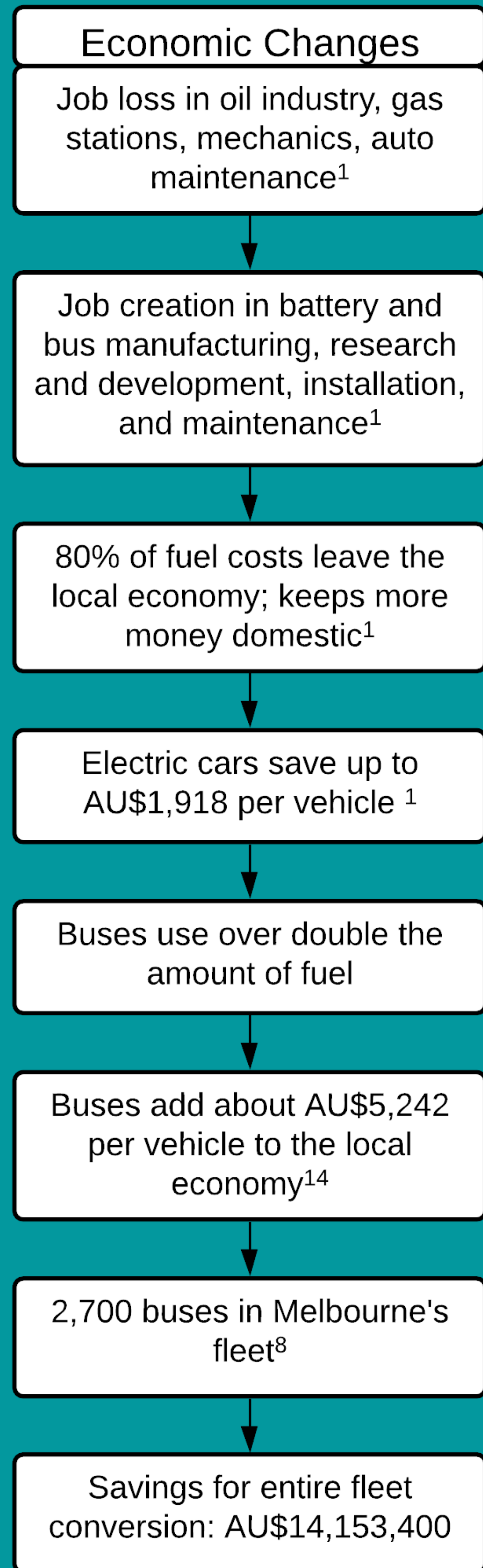
As diesel buses go out of use, the oil industry will experience major job losses. Gas stations, auto maintenance, and mechanics will also suffer job loss (Malmgren, 2016). However, there are also a variety of new jobs that would be created through the implementation of electric buses. Both direct and 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, creating a net benefit in terms of job gain/loss.

In addition, the economy is also stimulated by keeping more money local. According to the U.S. Energy Information Administration, over 80% of the cost of a gallon of gas leaves the local economy (Malmgren, 2016). 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 lifetime of the vehicle (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). These processes are depicted in Figure 20.

Total Economic Gains

Per Bus: **AU$5,242**

Fleet: **AU$14,153,400**



1. Malmgren, 2016
8. Public Transport Victoria, 2019
14. Bonneville Environmental Foundation, 2020

Figure 19: Economic Gains

Cost-Benefit Analysis Summary

Without considering the externalities, the implementation of an electric bus fleet is not entirely cost-effective due to more 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, which include 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 2 shows the combined total savings when considering both private savings and external savings, where the externalities no longer account for insurance and national security savings.

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: Total Electric Bus Savings

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**.

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.

Transdev Melbourne Bus #200, by M. Santillan, 2021

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 CO2e. 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 CO2e 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.

References

Alter, L. (2018). *Does cutting down a tree create greenhouse gas?* Treehugger. https://www.treehugger.com/does-cutting-a-tree-create-greenhouse-gas-4857564#:~:text=Cutting%20those%20trees%20releases%20the,the%20life%20of%20the%20building

American Fuel & Petrochemical Manufacturers. (n.d.). *How refineries work*. https://www.afpm.org/industries/operations/how-refineries-work?gclid=Cj0KCQiA6t6ABhDMARIsAONIYyytXie2tZaO2MGvugytTCg0VDNMqn62JpK0_xRZATCqZgVfkzS0RCUaAodrEALw_wcB

Auch, T. (2017). *Tracking global oil refineries and their emissions*. Fractracker Alliance. https://www.fractracker.org/2017/12/global-oil-refineries-emissions/

Australian Energy Regulator. (2014). *Wholesale statistics*. https://www.aer.gov.au/wholesale-markets/wholesale-statistics

Australian Infrastructure. (2016). *Crowding and congestion.* https://www.infrastructureaustralia.gov.au/sites/default/files/2019-08/Urban%20Transport%20Crowding%20and%20Congestion%20Fact%20Sheet%20-%20Melbourne%20and%20Geelong.pdf

BeyondDC. (2019). *DC Circulator electric bus charging station*. SmugMug+Flickr. https://www.flickr.com/photos/beyonddc/47480365031

Bonneville Environmental Foundation. (2020). *EV cost benefit analysis summary: Electric vehicle costs and benefits for BPA full requirements customers.* http://www.b-e-f.org/wp-content/uploads/2020/06/BEF_EV-cost-benefit-study_2020.pdf

Brutman, D. (2011). *China's reliance on shipping crude oil through the Straits of Malacca*. https://sites.tufts.edu/gis/files/2013/02/Brutlag_Daniel.pdf

Bus Insurance HQ. (n.d.). *How much does bus insurance cost?* https://www.businsurancehq.com/bus-insurance-cost/

Canadian Association of Petroleum Producers. (n.d.) *Oil extraction*. https://www.capp.ca/oil/extraction/

Chang, C., Liao, Y., & Chang, Y. (2019). Life cycle assessment of carbon footprint in public transportation: A case study of bus route no. 2 in Tainan City, Taiwan. *Procedia Manufacturing, 30*(2019), 388-395. https://doi.org/10.1016/j.promfg.2019.02.054

Corones, M. (2015). *Mapping world oil transport*. Reuters. http://blogs.reuters.com/data-dive/2015/03/27/mapping-world-oil-transport/

Csiro. (n.d.). *Typical house energy use*. Australian housing data. https://ahd.csiro.au/other-data/typical-house-energy-use/

Currie, G., Estgfaeller, N., De Gruyter, C., & Fridman, I. (2018). *Ridership and resource impacts of conventional and advanced electric bus technologies.* Transportation research board. https://trid.trb.org/view/1494377

Currie, G. (2017). *Melbourne buses, bus ridership growth and LGA data.* Melbourne Bus Research Group. http://publictransportresearchgroup.info/wp-content/uploads/2017/03/PRESENTATION-2017-MTF-General-Meeting-Melbourne-Buses.pdf

Department for Transport. (2015). *New car carbon dioxide emissions*. GOV.UK. https://www.gov.uk/government/publications/new-car-carbon-dioxide-emissions

Dunn, J. B., Gaines, L., Kelly, J. C., James, C., & Gallagher, K. G. (2014). The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. *Energy & Environmental Science*, *8*(1), 158–168. https://doi.org/10.1039/C4EE03029J

FreightWaves Staff. (2020). *How many gallons of fuel does a container ship carry?* American Shipper. https://www.freightwaves.com/news/how-many-gallons-of-fuel-does-a-container-ship-carry#:~:text=Most%20ship%20engines%20have%20been,drops%20sharply%20as%20speeds%20decrease

Friends of the Earth Melbourne. (n.d.). *Friends of the Earth Melbourne.* https://www.melbournefoe.org.au/

Green Vehicle Guide. (n.d.). *Vehicle emissions*. https://www.greenvehicleguide.gov.au/pages/Information/VehicleEmissions

Guerrero, A. (2017). *Are hybrid and electric buses viable just yet?* World Bank Blogs. https://blogs.worldbank.org/transport/are-hybrid-and-electric-buses-viable-just-yet

Hammer, M. S., Swinburn, T. K., & Neitzel, R. L. (2014). Environmental noise pollution in the United States: Developing an effective public health response. *Environmental Health Perspectives*, *122*(2), 115–119. https://doi.org/10.1289/ehp.1307272

Henriques-Gomes, L. (2018). *Transport emissions continue to rise as Australia lags behind other nations.* The Guardian. https://www.theguardian.com/environment/2018/sep/13/transport-emissions-continue-to-rise-as-australia-lags-behind-other-nations

Independent Petroleum Association of America. (n.d.). *Hydraulic fracturing*. https://www.ipaa.org/fracking/#studies

Ipieca. (2013). *Offshore drilling rigs*. https://www.ipieca.org/resources/energy-efficiency-solutions/units-and-plants-practices/offshore-drilling-rigs/

Islam, A. & Lownes, N. (2019). When to go electric? A parallel bus fleet replacement study. *Transportation Research Part D: Transport and Environment*, *72*, 299–311. https://doi.org/10.1016/j.trd.2019.05.007

Is Australia running out of fuel? PM orders supply review. (2018). BBC news. https://www.bbc.com/news/business-44027042#:~:text=Where%20do%20Australia's%20oil%20supplies,diesel%2C%20aviation%20fuel%20and%20petrol

Jacks, T. (2019). *Running on empty: Secret data reveals Melbourne's "ghost buses"*. The Age. https://www.theage.com.au/national/victoria/running-on-empty-secret-data-reveals-melbourne-s-ghost-buses-20190424-p51gpm.html

Jwa, K. & Lim, O. (2018). Comparative life cycle assessment of lithium-ion battery electric bus and Diesel bus from well to wheel. Energy Procedia, 145(2018), 223-227. https://doi.org/10.1016/j.egypro.2018.04.039
Kattenburg, K. (n.d.). What do batteries do to the environment if not properly recycled? Sciencing. https://sciencing.com/environmental-problems-batteries-cause-7584347.html
Komanoff, C. (2021). Lithium Mining The Hidden Environmental Cost of EVs. Streetsblog USA. https://usa.streetsblog.org/2021/02/09/lithium-mining-and-the-hidden-environmental-costs-of-evs/
Krantz, G. (2016). CO2 and sulphur emissions from the shipping industry. Exhaust Gas Cleaning Systems Association. https://www.egcsa.com/wp-content/uploads/CO2-and-sulphur-emissions-from-the-shipping-industry.pdf
Kukreja, B. (2018). Life cycle analysis of electric vehicles: Quantifying the impact. The University of British Columbia. https://sustain.ubc.ca/sites/default/files/2018-63%20Lifecycle%20Analysis%20of%20Electric%20Vehicles_Kukreja.pdf
Lioudis, N. (2020). Oil production timeline. Investopedia. https://www.investopedia.com/ask/answers/061115/how-long-does-it-take-oil-and-gas-producer-go-drilling-production.asp#:~:text=Depending%20on%20the%20depth%20of,work%20for%20an%20oil%20producer
MacKechnie, C. (2019). *How long do buses and other transit vehicles last?* LiveAbout. https://www.liveabout.com/buses-and-other-transit-lifetime-2798844
Malmgren, I. (2016). Quantifying the Societal Benefits of Electric Vehicles. *World Electric Vehicle Journal*, *8*(4), 996-1007. https://doi.org/10.3390/wevj8040996
Maloney, P. (2019). *Electric buses for mass transit seen as cost effective*. American Public Power Association. https://www.publicpower.org/periodical/article/electric-buses-mass-transit-seen-cost-effective
Marshall, A. (2016). *This new electric bus can drive 350 miles on one charge*. Wired. https://www.wired.com/2016/09/new-electric-bus-can-drive-350-miles-one-charge/
Marshall, A. (2019). *Why electric buses haven't taken over the world—yet.* Wired. https://www.wired.com/story/electric-buses-havent-taken-over-world/
Mees, P. (2009). *Transport for suburbia: Beyond the Automobile Age*. Earthscan.
Melin, H. E. (2019). *Analysis of the climate impact of lithium-ion batteries and how to measure it*. Transport environment. https://www.transportenvironment.org/sites/te/files/publications/2019_11_Analysis_CO2_footprint_lithium-ion_batteries.pdf
Metro. (n.d.). *Timetable search.* https://www.metrotrains.com.au/timetables/?line=Sandringham&dir=1&ts=1614722161807
Nuccitelli, D. (2020). *The Trump EPA is vastly underestimating the cost of carbon dioxide pollution to society, new research finds.* Yale Climate Connections. https://yaleclimateconnections.org/2020/07/trump-epa-vastly-underestimating-the-cost-of-carbon-dioxide-pollution-to-society-new-research-finds/
Nunez, C. (2019). *Carbon dioxide levels are at a record high. Here's what you need to know.* National Geographic. https://www.nationalgeographic.com/environment/global-warming/greenhouse-gases/
O'Dea, J. (2018). *Electric vs. diesel vs. natural gas: Which bus is best for the climate?* Union of Concerned Scientists. https://blog.ucsusa.org/jimmy-odea/electric-vs-diesel-vs-natural-gas-which-bus-is-best-
Organisation for Economic Co-operation and Development [OECD]. (2019). *Crude oil import prices.* http://data.oecd.org/energy/crude-oil-import-prices.htm
Oil tanker ship. (n.d.). All oil tank. https://alloiltank.com/oil-tanker-ship/
Pandangwati, S. T. & Milyanab, N. A. (2017). Bus network redesign for inner southeast suburbs of Melbourne, Australia. *IOP Conference Series: Earth and Environmental Science*, *70*. https://doi.org/10.1088/1755-1315/70/1/012024
Parkinson, G. (2020). *Victoria to spend $20 million on three-year trial for zero emissions bus fleet.* The Driven. https://thedriven.io/2020/11/15/victoria-to-spend-20-million-on-three-year-trial-for-zero-emission-bus-fleet/
Public Transport Users Association. (n.d.). *What is the PTUA?* https://www.ptua.org.au/policy/whatis/
Public Transport Victoria. (2019). *2018-2019 annual report.* Docklands, Victoria: Public Transport Development Authority. https://www.ptv.vic.gov.au/assets/default-site/footer/data-and-reporting/annual-report/6b8c2cff5a/PTVH4043-Annual_Report_2019-A4-v1_ONLINE.pdf
Public Transport Victoria. (2021). *Metropolitan fares.* https://www.ptv.vic.gov.au/tickets/fares/metropolitan-fares/
Public Transport Victoria. (n.d.). *Timetables*. https://www.ptv.vic.gov.au/timetables/
Rabe, T. (2020). *Sydney aims to turn entire bus fleet electric by 2030*. The Sydney Morning Herald. https://www.smh.com.au/national/nsw/sydney-aims-to-turn-entire-8000-bus-fleet-electric-by-2030-20201202-p56jui.html
Ricciardi, A. M., Xia, J., and Currie, G. (2015). Exploring public transport equity between separate disadvantaged cohorts: A case study in Perth, Australia. *Journal of Transport Geography, 43*. 111-122. https://doi.org/10.1016/j.jtrangeo.2015.01.011
Rogerson, P. A. (2013). The Gini coefficient of inequality: A new interpretation. *Letters in Spatial and Resource Sciences*, *6*(3), 109–120. https://doi.org/10.1007/s12076-013-0091-x
Root, A. (2020). Why lithium could be a new risk for Tesla and other electric-vehicle makers. Barron's. https://www.barrons.com/articles/new-risk-tesla-other-electric-vehicle-makers-lithium-supply-batteries-51601498472

Roskill Information Services Ltd. (2020). Roskill: CO2 emissions from lithium production set to triple by 2025. GlobeNewswire. http://www.globenewswire.com/news-release/2020/10/05/2103285/0/en/Roskill-CO2-emissions-from-lithium-production-set-to-triple-by-2025.html
Scheurer, J., Curtis, C., & McLeod, S. (2017). Spatial accessibility of public transport in Australian cities: Does it relieve or entrench social and economic inequality? Journal of Transport and Land Use, 10(1), 911-930. https://www.jstor.org/stable/26211762
Schmidt, B. (2020). First Victoria-built electric bus gets thumbs up from bus expert. The Driven. https://thedriven.io/2020/04/27/first-victoria-built-electric-bus-gets-thumbs-up-from-bus-expert/
Simon Fraser University. (n.d.). Gordon Price. https://www.sfu.ca/continuing-studies/instructors/m-p/gordon-price.html
Shirazi, Y., Carr, E., & Knapp, L. (2015). A cost-benefit analysis of alternatively fueled buses with special considerations for V2G technology. Energy Policy, 87, 591–603. https://doi.org/10.1016/j.enpol.2015.09.038
Smedley Technical and Strategic. (n.d.). Advice, assistance, and direction. http://smedtech.com.au/#advice
Song, B. L. (2019). Sydney Opera House and Harbour Bridge dusk. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Sydney_Opera_House_and_Harbour_Bridge_Dusk_(2)_2019-06-21.jpg
SounderBruce. (2015). *Proterra electric bus at Eastgate P&R.* SmugMug+Flickr. https://www.flickr.com/photos/sounderbruce/23543038541
Spielvogul. (2014). *SOR bus EBN 11. Traction batteries.* Wikimedia Commons. https://commons.wikimedia.org/wiki/File:SOR_bus_EBN_11._Traction_batteries._Spielvogel_2014.JPG
Spragg, B. (2018). Bougainville. LPG tanker. [Photograph]. GetArchive. https://picryl.com/media/bougainville-lpg-tanker-a6f601
Stansfeld, S. A. & Matheson, M. P. (2003). Noise pollution: Non-auditory effects on health. British Medical Bulletin, 68, 243–257. https://doi.org/10.1093/bmb/ldg033
Texas Commision on Environmental Quality. (2016). Barnett Shale maps and charts. https://www.tceq.texas.gov/airquality/barnettshale/bshale-maps
Than, K. (2015). Estimated social cost of climate change not accurate, Stanford scientists say. Stanford University. http://news.stanford.edu/news/2015/january/emissions-social-costs-011215.html
Thebusofdoom. (2015). CDC Melbourne (Wyndham) Scania K230UB. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:CDC_Melbourne_(Wyndham)_Scania_K230UB.jpg
Transdev Melbourne. (n.d.). Maps and timetables. https://www.transdevmelbourne.com.au/travel-information/maps-and-timetables/
TransLink. (n.d.) Ridership. https://www.translink.ca/plans-and-projects/data-and-information/accountability-centre/ridership
Trencher, G. (2019). Assoc. Prof. Gregory Trencher. https://www.gregorytrencher.net/
Union of Concerned Scientists. (2018). *Electric trucks and buses.* https://www.ucsusa.org/sites/default/files/images/2018/09/electric-buses-trucks.pdf
US EPA. (2016a). *Carbon dioxide emissions coefficients*. https://www.eia.gov/environment/emissions/co2_vol_mass.php
US EPA. (2016b). *Health and environmental effects of particulate matter (PM).* https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pM
US EPA. (2020a). *Frequently asked questions: How many gallons of gasoline and diesel fuel are made from one barrel of oil?* https://www.eia.gov/tools/faqs/faq.php?id=327&t=9#:~:text=Petroleum%20refineries%20in%20the%20United,gallon%20barrel%20of%20crude%20oil
US EPA. (2020b). *Petroleum and other liquids: U.S. oil and natural gas wells by production rate*. https://www.eia.gov/petroleum/wells/#:~:text=Most%20U.S.%20oil%20and%20natural,3%20and%204%2C%20respectively
US EPA. (2020c). *Oil and petroleum products explained*. https://www.eia.gov/energyexplained/oil-and-petroleum-products/
US EPA. (n.d.). *Explaining electric & plug-in hybrid electric vehicle.* https://www.epa.gov/greenvehicles/explaining-electric-plug-hybrid-electric-vehicles
Utah Transit Authority. (2018). Public transit ridership increases and air pollution decreases on Free Fare Friday. https://www.rideuta.com/news/2018/01/Public-Transit-Ridership-Increases-and-Air-Pollution-Decreases-on-Free-Fare-Friday
Venkataraman, R. (2020). *U.S. refinery processing, over the years*. Medium. https://medium.com/@rangys3/u-s-refinery-processing-over-the-years-ee97179dc938
Wall Street Mojo. (n.d.). *Cost-benefit analysis.* https://www.wallstreetmojo.com/cost-benefit-analysis/
Wheeler, E. (2015). Proterra electric bus demonstration. SmugMug+Flickr. https://www.flickr.com/photos/metrotransitmn/1738802492
World Population Review. (2021). *Melbourne population 2021*. https://worldpopulationreview.com/world-cities/melbourne-population
Xe. (2021). *1 USD to AUD: Xe currency converter.* https://www.xe.com/currencyconverter/convert/?Amount=1&From=USD&To=AUD
Xia, J., et al. (2016). *A multi-dimensional view of transport-related social exclusion: A comparative study of Greater Perth and Sydney*. https://espace.curtin.edu.au/bitstream/handle/20.500.11937/43746/245887.pdf?sequence=2&isAllowed=y
Zavala-Araiza et al. (2015). Reconciling divergent estimates of oil and gas methane emissions. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(51), 15597-15602. https://doi.org/10.1073/pnas.1522126112

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. **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: Diesel Fuel 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 D: Electric Bus Battery 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
		Total emissions during production of battery = 78 tonnes CO_2e
Charging the battery	400,000 km * 182 g/km = 72,800,000 grams CO_2e 72,800,000 grams CO_2e = 80 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
	158 tonnes * .9 = 143 tonnes CO2e per bus	
Total CO_2 Emissions of Lithium-Ion Battery: **143 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 E: Vehicle-to-Grid (V2G) Calculations

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 F: User Satisfaction Calculations

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[1]**:** 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)