Zero-emission bus economics study

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[1] This research was conducted March 2023–July 2023

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Abbreviations and acronyms

BAU	business as usual
BEB	battery electric buses
CAPEX	capital expenditure
CO2e	carbon dioxide equivalent
CO	carbon monoxide
HFCB	hydrogen fuel cell buses
MAC	marginal abatement cost
NOx	nitrogen oxides
NO2	nitrogen dioxide
NZTA	NZ Transport Agency Waka Kotahi
OPEX	operational expenditure
PTA	public transport authority
PM2.5	particulate matter 2.5
PM2.5 E	particulate matter 2.5 exhaust
TCO	total cost of ownership
VOC	volatile organic compounds
ZEB	zero-emission buses

Contents

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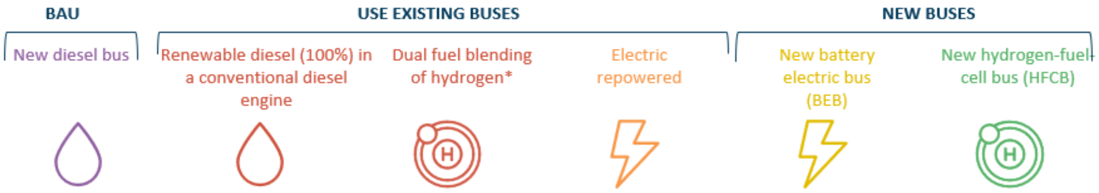
Executive summary

This report has been prepared under the assumption that the NZ Transport Agency Waka Kotahi (NZTA) will require all new urban buses to be zero-emission by 2025, in alignment with the government's goal of achieving a fully decarbonised urban fleet by 2035[2]. This rapid transition to zero-emission buses (ZEB) necessitates the phased removal of diesel buses, even those with remaining useful lives. NZTA seeks to ensure the optimal use of ZEB technology for decarbonisation while considering potential trade-offs. To comprehensively assess these trade-offs, NZTA engaged Castalia to develop the ZEB Cost Model, which calculates the total cost of ownership (TCO) and associated emissions impacts for various bus use-cases over time.

Model design and usage

The research project's objective was to develop the ZEB Cost Model, enabling public transport authorities (PTAs) and NZTA to assess the costs and benefits of bus decarbonisation strategies. The ZEB Cost Model compares six bus technologies (Figure ES.1) in 10 bus use-cases across nine route types.

Figure ES.1 Bus technologies*



*Subject to successful trial for regular commercial bus use

The model allows the user to calculate and compare TCO for the following use-cases.

- A business-as-usual (BAU) case of buying and using new diesel buses.
- Options for continuing to use all or part of existing diesel buses by:
  - replacing diesel fuel with 100% renewable diesel
  - repowering diesel buses to battery electric buses (BEB)
  - blending hydrogen with diesel to lower emissions.
- Replacing existing diesel buses with new BEB or new hydrogen-fuel-cell buses (HFCB) either:
  - at the end of the useful life of diesel buses
  - immediately, with diesel buses then scrapped
  - immediately, with diesel buses retained and used to promote mode shift by expanding public transport options.

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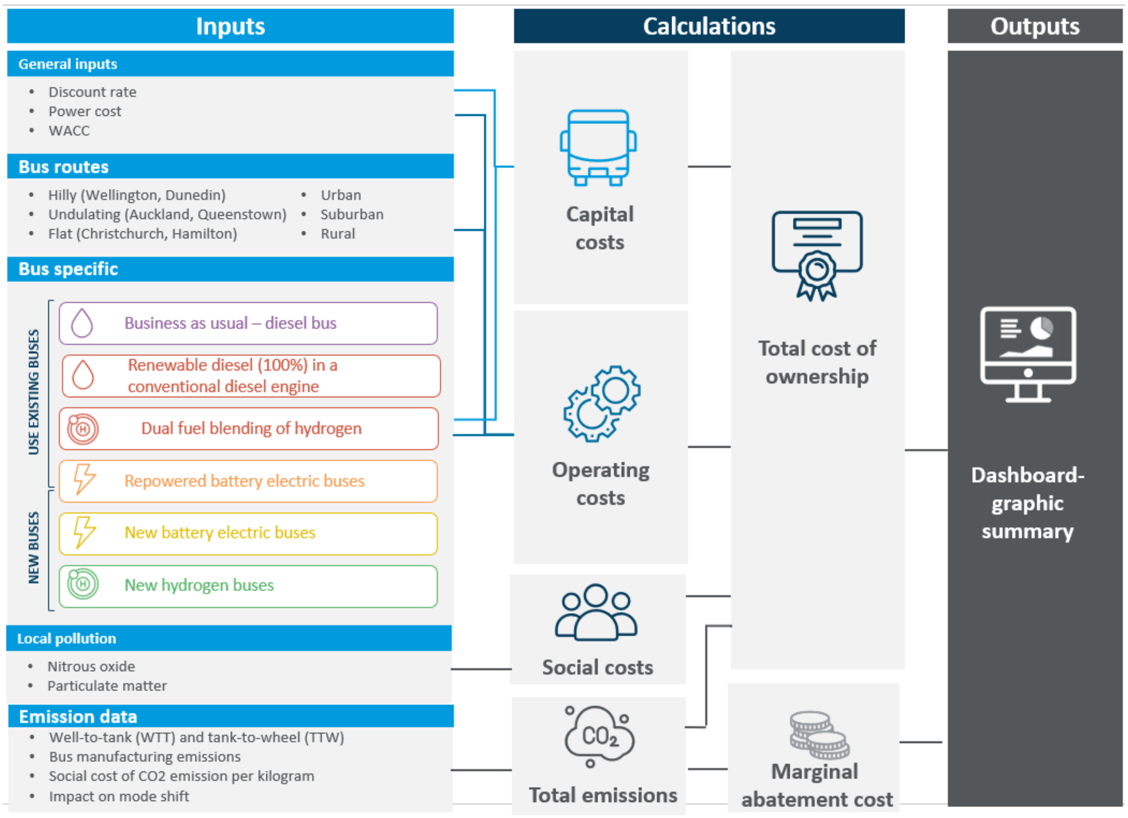
[2] The assumption is based on the NZTA policy that was in place at the time of the report's preparation in 2023.

The model comprises three main components to arrive at a per km TCO comparison between the 10 use-cases' inputs, calculations and outputs, as illustrated in Figure ES.2.

Figure ES.2 Overview of the ZEB Cost Model



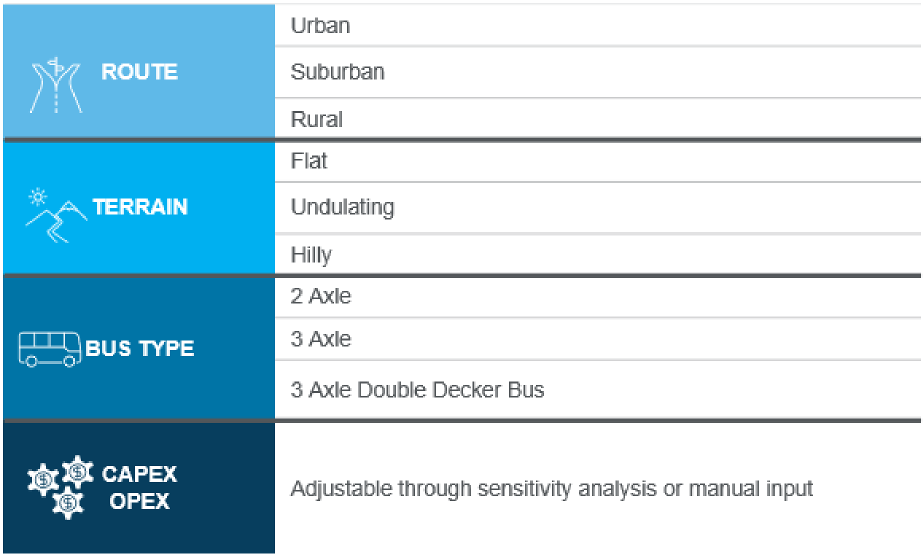
The inputs section includes details about bus routes, terrain and the type of bus, along with information on pollutants and emissions. The calculation section calculates capital costs, operating expenses and the negative cost to society of total emissions. These costs are divided by the number of kilometres to determine the TCO and marginal abatement cost, which are presented in the model's Dashboard.

To arrive at customised calculations for each user, the model evaluates three indicative routes with three terrain options for three types of buses. For each route, users can choose a terrain and a bus option that reflects their needs.

The model also allows users to adjust capital and operational cost assumptions to accommodate potential changes in technology costs over time. This is because, although the model comes pre-populated with up-to-date data on capital and operational costs (obtained during the project through desktop research and interviews with various bus producers, including Yutong, HYDI, Global Bus Ventures and The Tranzit Group), technology costs will evolve over time and may be specific to each user. To account for this, the model incorporates the capability for users to modify capital and energy costs based on their input.

As a result, the model permits users to customise for route specifics, terrain, bus type and cost estimates for different bus technologies as illustrated in Figure ES.3. The model is available at www.nzta.govt.nz/resources/research/reports/718.

Figure ES.3 Model customisation options



ROUTE	Urban Suburban Rural
TERRAIN	Flat Undulating Hilly
BUS TYPE	2 Axle 3 Axle 3 Axle Double Decker Bus
CAPEX OPEX	Adjustable through sensitivity analysis or manual input

Insights from the model design process

The purpose of the ZEB Cost Model is to empower PTAs with a tool to use when making decisions about decarbonising their transportation fleet. Thus, it does not calculate one single best use-case, due to the varying circumstances of PTAs. Nonetheless, several key insights emerged during model development and testing.

- Emissions savings from early retirement of diesel buses far outweigh emissions from earlier bus construction.
- Operations and maintenance costs – and, more specifically, energy costs – are the key driver of TCO for different bus technologies.
- Battery electric buses, whether repowered diesel buses or new battery electric buses, are the least cost option with which to replace existing diesel buses. This is because of the high cost of hydrogen in New Zealand at the time of this research and the importance of fuel costs in overall TCO.

Though valuable, the analysis has limitations that require addressing by:

- expanding the data on embedded emissions from the construction of diverse bus technologies
- standardising operational expenditure data for different bus technologies
- obtaining comprehensive emissions reduction data for renewable diesel
- fostering collaboration and data-sharing among stakeholders to enhance the model's reliability.

In summary, the TCO analysis offers a comprehensive framework for PTAs to navigate ZEB transition complexities. By leveraging these insights, PTAs can propel New Zealand towards a greener and more sustainable public transportation future, enhancing environmental responsibility and citizens' quality of life.

Abstract

This report details the process to develop a user-friendly Excel model – 'the ZEB Cost Model' – that allows the user to conduct a comprehensive evaluation of the different use-cases available to replace existing diesel buses with zero-emission buses (ZEB). The use-cases include options for replacing diesel buses at the end of their useful life, retiring diesel buses early, and retaining diesel buses to induce further mode shift. Thus, the ZEB Cost Model developed under this assignment and described in this report empowers public transport authorities to make informed decarbonisation investment decisions.

Further, this report delivers several key findings revealed in the model design process. First, emissions savings from early retirement of diesel buses far outweigh emissions from earlier bus construction. Second, operations and maintenance costs – and, more specifically, energy costs (electricity, hydrogen or diesel) – are the key driver of total cost of ownership for different bus technologies. Third, battery electric buses, whether repowered diesel buses or new battery electric buses, are the least cost option with which to replace existing diesel buses. This is because of the high cost of hydrogen in New Zealand at the time of this research and the importance of fuel costs in overall total cost of ownership.

1 Introduction

This section provides the background of the project and outlines its main objectives and key tasks. Additionally, it provides an overview of the report's structure.

1.1 Background

This report has been prepared under the assumption that the NZ Transport Agency Waka Kotahi (NZTA), will require all new urban buses to be zero-emission by 2025, in alignment with the government's goal of achieving a fully decarbonised urban fleet by 2035[3]. Namely, NZTA *Requirements for Urban Buses in New Zealand* (Waka Kotahi, 2022a) mandates that all new urban buses must be zero emission from 2025. Further, the New Zealand Government has set a target for a fully decarbonised urban fleet by 2035. In addition, many public transport authorities (PTAs) are committed to decarbonising their bus fleets even sooner than 2035, accelerating New Zealand's transition to zero-emission buses (ZEB). This means that diesel buses will rapidly be phased out of New Zealand's urban bus fleet – including diesel buses that have remaining useful lives.

As a result, NZTA wants to ensure that the best bus technology is used to decarbonise public bus fleets. It is also concerned that rapidly decarbonising public transport buses may result in trade-offs against other carbon-reduction investments. This is because investing in new ZEB and scrapping diesel buses with remaining economic life could offset carbon-reduction benefits at the tailpipe by:

- creating additional emissions from new bus manufacture
- reducing opportunities for PTAs to induce transport mode shift,[4] by continuing to use diesel buses to expand public transport offerings.

To better understand these trade-offs, NZTA contracted Castalia to develop an economic model (the ZEB Cost Model) that calculates the total cost of ownership (TCO), including the full cost of emissions reductions and increases, from different bus use-cases over time.

1.2 Objective and key project tasks

The objective of this research project is to create a tool that allows PTAs and NZTA to weigh the costs and benefits of different technologies available for bus decarbonisation, and the costs and benefits of using those technologies to:

- replace and retire diesel buses right away
- replace diesel buses with ZEB on their normal routes and retain the diesel buses for expanding public transport options, with the aim of inducing mode shift
- wait until the end of a diesel bus's useful life and then replace it.

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[3] The assumption is based on the NZTA policy that was in place at the time of the report's preparation in 2023.

[4] NZTA defines mode shift as: "growing the share of travel by public transport, walking and cycling (and reduce reliance on private vehicles)." https://www.nzta.govt.nz/assets/Walking-Cycling-and-Public-Transport/docs/mode-shift-leaflet.pdf

Therefore, the key task of this project was to develop the ZEB Cost Model. The model allows the user to calculate the TCO and the marginal abatement cost (MAC), including the full cost of emissions reductions and increases, for 10 bus use-cases on nine different types of routes. The model allows the user to calculate and compare TCO for the following use-cases.

- A business-as-usual (BAU) case of buying and using new diesel buses.
- Replacing existing diesel buses with new battery electric buses (BEB) either:
    - at the end of the useful life of diesel buses
    - immediately, with diesel buses then scrapped
    - immediately, with diesel buses retained and used to promote mode shift by expanding public transport options.
- Replacing existing diesel buses with new hydrogen-fuel-cell buses (HFCB) either:
    - at the end of the useful life of diesel buses
    - immediately, with diesel buses then scrapped
    - immediately, with diesel buses retained and used to promote mode shift by expanding public transport options.
- Options for continuing to use all or part of existing diesel buses by:
    - replacing diesel fuel with 100% renewable diesel
    - repowering diesel buses to BEB
    - blending hydrogen with diesel to lower emissions.

The other key task was to conduct research on available bus technologies and their performance on different types of routes, to ensure that the model is populated with recent and relevant data for each bus use-case and route type. As such, Castalia conducted a comprehensive review of recent reports and data sources on bus technologies and held in-depth interviews with industry professionals from prominent companies, including Yutong, Global Bus Ventures, HYDI and other industry experts.

However, each PTA and each route is slightly different. As a result, a further objective was to design the model to be customised by the user. As such, the assumptions and inputs for each use-case are clearly marked, allowing users to update or change them as new or user-specific information becomes available. For example, if a PTA receives a quote for the capital expenditure (CAPEX) required to purchase a BEB that is lower or higher than the pre-populated assumptions in the model, the PTA can easily change the assumption for BEB CAPEX in the model to reflect the options available to the PTA. Thus, the model is designed to be useful for the PTA's specific circumstances, and durable by allowing for adaptation over time as new information becomes available.

1.3 Structure of the report

This report is structured as follows.

- Section 2 discusses the methodology used to define the bus use-cases and collect data for those use-cases, and the approach employed to build the ZEB Cost Model.
- Section 3 delves into the primary outputs of the model and explores various sensitivities and draws some conclusions from the modelling outputs.

- Section 4 addresses research limitations and identifies opportunities for further research.
- Lastly, section 5 draws conclusions from the research analysis.

Appendix A offers the assumptions used in calculating TCO and MAC, providing transparency for the model's methodology.

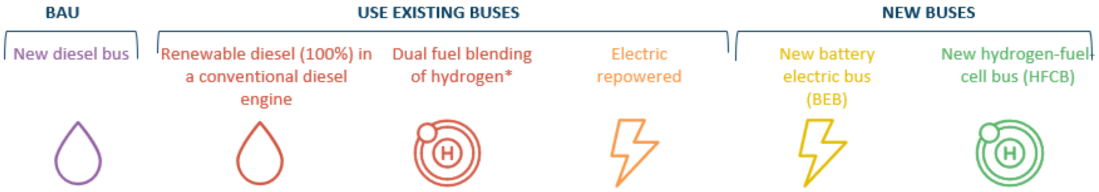
2 Method

This section discusses the approach used to achieve the objectives and complete key tasks for this research project. First, Castalia, along with the steering group, determined the use-cases that need evaluation in the model (section 2.1). Once Castalia and the steering group had defined the use-cases, Castalia initiated the data collection process by reviewing existing literature and conducting interviews with industry experts (section 2.2). Third, Castalia built the ZEB Cost Model to achieve the objectives set forth by the steering group (section 2.3).

2.1 Bus use-cases

As a first step, Castalia and the steering group defined the use-cases that the ZEB Cost Model should be able to consider. Consultation determined that the ZEB Cost Model should have the ability to evaluate six bus technologies. These are diesel (the BAU), three technologies utilising all or part of existing buses, and two technologies utilising new buses. Further, each new bus technology has three potential use-cases based on what is done with the existing diesel bus that the new bus is replacing. These bus technologies are illustrated in Figure 2.1.

Figure 2.1 Bus technologies*



*Subject to successful trial for regular commercial bus use

Further, the consultation with the steering group determined that the ZEB Cost Model should be able to evaluate each use-case based on the following factors:

- terrain: hilly, flat or undulating
- type of route: urban, suburban or rural
- bus size: two-axle, three-axle or three-axle double-decker.

Users can customise each use-case as needed to provide more accurate results for their specific circumstances when using the ZEB Cost Model. Appendix A provides a full list of assumptions relating to each bus use-case.

2.1.1 Diesel (BAU)

Diesel (BAU) is the baseline scenario representing the BAU approach using diesel buses. All other use-cases are compared against the diesel (BAU) to ensure that they offer an improvement over what would have been done without any intervention.

The ZEB Cost Model calculates the TCO of the diesel BAU case based on the capital cost of purchasing a new diesel bus, its operations and maintenance costs and emissions costs, and the salvage value of a diesel bus at the end of its operational life.

2.1.2 Use-cases that utilise existing buses

The ZEB Cost Model considers three use-cases that use all or part of existing diesel buses:

- renewable diesel
- blending hydrogen with diesel
- electric repowered.

Similar to the diesel (BAU) use-case, the TCO and MAC for existing buses include the capital cost, operational costs and emissions costs. The use-case is assumed to be implemented immediately and used until the end of the service life of the bus.

2.1.2.1 Renewable-diesel-fuelled conventional bus

Renewable diesel, which is 100% derived from sustainable feedstocks, is used as a fuel in a conventional diesel engine. This use-case allows for a reduction in emissions compared to regular diesel, while still utilising the existing diesel bus and diesel fuelling infrastructure.

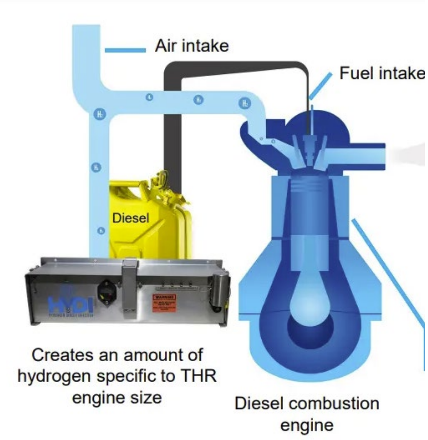
Renewable diesel is an advanced biofuel made from a range of waste and purpose-grown biomass sources. Further, renewable diesel is a drop-in fuel, because it can directly substitute for conventional diesel and does not require blending.

2.1.2.2 Blending hydrogen with diesel in conventional bus

Blending hydrogen with diesel in a dual-fuel engine yields a partial reduction in the bus’s emissions, while still utilising the existing diesel bus and diesel fuelling infrastructure. For the purposes of this research, the underlying technology is based on the HYDI hydrogen injection system, which can be retrofitted to an existing diesel vehicle and supplies hydrogen gas to the vehicle’s diesel engine intake. The technology has only recently been launched commercially, and its long-term application in high-use vehicles, such as buses, may need to be tested further.

On a mass-to-mass basis, hydrogen has three times the energy content of diesel and delivers a higher flame speed to improve combustion efficiency. This reduces fuel consumption and exhaust emissions, while increasing performance (HYDI, 2023). Figure 2.2 illustrates how the HYDI system functions.

Figure 2.2 HYDI unit operation (reprinted from HYDI, 2023)



Available data is limited as this technology is still in its relatively early stages of commercialisation. At present, only a few bus operators in Wellington, New Zealand, and Adelaide, Australia utilise it. As such, we caution that the cost assumptions for hydrogen blending are not as robust as costs for other well-known technologies, such as BEB. For example, it is expected that injecting hydrogen into the air intake would lead to lower maintenance costs. However, it is unclear what the exact reduction in operations and maintenance costs would be. Therefore, the assumption is that the operations and maintenance costs would be the same as those for diesel buses.

It is important to note that there are also other dual-fuel technologies that utilise hydrogen. For example, in 2023, HW Richardson Group introduced the first hydrogen-diesel dual-fuel truck in the Southern Hemisphere (Girao, 2023). Unlike HYDI technology that utilises hydrogen produced on board the vehicle, this system refuels and stores hydrogen in tanks mounted on a frame behind the cab of the truck. Each tank can hold 5 kg of hydrogen, and most truck configurations are equipped with five tanks, allowing for a total hydrogen storage capacity of 25 kg. During operation, hydrogen is injected into the engine's intake stroke. Diesel is used as the pilot fuel, and the hydrogen-diesel blend co-combusts in the engine, with the diesel auto-igniting and contributing to the power stroke (HW Richardson Group, 2023).

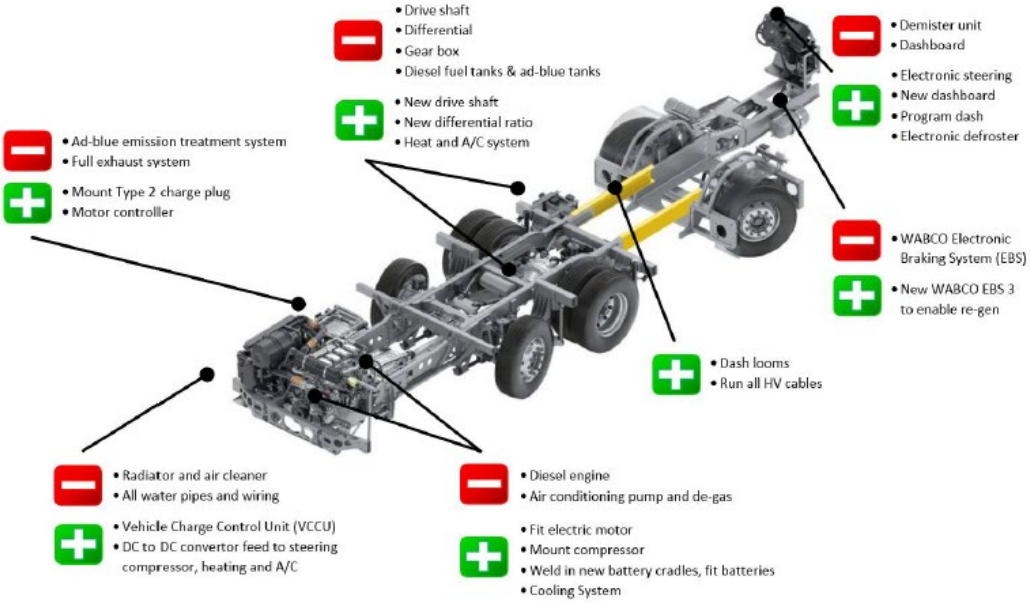
Our analysis assumes that buses would be using a hydrogen-injection system like the HYDI system.

2.1.2.3 Electric-repowered existing bus

Repowering existing buses achieves zero tailpipe emissions when existing diesel buses are repowered with electric drivetrains. The conversion from diesel to electric power allows for zero-emission operation, while utilising components of diesel buses with remaining service life.

The repowering technology assumes that the body and interior of the diesel bus remain unchanged, with the main changes occurring underneath the bus. Figure 2.3 provides a high-level overview of the parts of the diesel bus that are replaced to accommodate its operation as an electric bus.

Figure 2.3 Conversion from diesel to electric power (reprinted from Tranzit Group, 2022, p. 2)



We caution that the cost assumptions for repowering are not as robust as costs for other well-known technologies, such as BEB. Although these costs are based on real numbers provided by Global Bus Ventures and other industry experts that have successfully repowered a few diesel buses to BEB, it is a very small and recent sample.

For example, the first conversion in the Southern Hemisphere of a high capacity BCI double-decker bus from EURO 6 diesel to battery powered was achieved by Tranzit Group from mid-2021 to early 2022. This vehicle, used on Metlink services within Wellington, gained its new certification as an electric bus in October 2021, and has now been operating successfully on the public transport network for over a year (Tranzit Group, 2022).

Furthermore, the limited number of bus conversions means that the cost of bus conversions may reduce if diesel bus conversion achieves larger scale. For example, based on feedback from industry experts, it is estimated that conversion costs can be reduced by 20% to 30% if greater scale is achieved.

2.1.3 Use-cases that utilise new buses

There are two use-cases that replace existing diesel buses with new ZEB:

- BEB – diesel buses are replaced with new BEB and their associated charging infrastructure
- HFCB – diesel buses are replaced with new HFCB and their associated hydrogen fuelling infrastructure.

Both HFCB and BEB are widely available commercially, and we have consulted with bus manufacturers as well as bus operators on their CAPEX and operational expenditure (OPEX), including their operations and maintenance costs.

2.1.3.1 Battery electric bus

BEB are powered by electricity stored in onboard batteries, which results in zero tailpipe emissions, reduced noise levels and lower operating costs compared to conventional diesel buses. This makes BEB an excellent alternative, especially because public transport vehicles often return to a depot at the end of the day, allowing for overnight charging. Electrifying buses can play a crucial role in decarbonising our transport system, as buses typically operate for many hours a day. Auckland trials demonstrated operating costs for BEB were 70% to 85% lower than for equivalent diesel bus services on the same route (Waka Kotahi, 2023a).

BEB have already been successfully implemented on multiple routes in Auckland, Tauranga, Wellington and Christchurch, and many public transport contracting authorities are eager to accelerate their roll-out. As of mid-2023, New Zealand has 240 electric buses, constituting approximately 9% of the public transport bus fleet and this number is rapidly increasing (Waka Kotahi, 2023a).

2.1.3.2 Hydrogen-fuel-cell bus

HFCB utilise hydrogen as a fuel source to generate electricity through a chemical reaction in the fuel cells. The fuel cells combine hydrogen with oxygen from the air to produce electricity, powering an electric motor that drives the bus. The remarkable feature of HFCB is that the only by-product of this process is water vapour, making them true zero-emission vehicles at the tailpipe. When coupled with the use of green hydrogen, sourced from renewable energy, HFCB achieve completely emission-free operation.

With New Zealand's growing interest in renewable energy and sustainable technologies, HFCB have emerged as a promising alternative to conventional diesel buses. Their zero-emission operation aligns perfectly with the country's commitment to reducing its carbon footprint and transitioning to cleaner transportation options.

Despite the potential benefits, the use of HFCB in New Zealand is still in its early stages, and their adoption has been limited. As of 2022, only one HFCB was in operation in the country, designed and built by Global Bus Ventures in collaboration with Auckland Transport.

2.1.3.3 Options for retiring diesel buses

Under the BEB and HFCB use-cases, the ZEB Cost Model considers three possible options for retiring diesel buses. This allows the ZEB Cost Model to assess the impact of:

- the emissions from producing new buses sooner than expected
- retaining diesel buses to expand public transport options and encourage mode shift.

The three options are as follows.

Option 1: End-of-life diesel bus replacement with BEB or HFCB

Diesel buses operate until the end of their operational life or to 2035, whichever comes first, and are then replaced with new BEB or HFCB. The year 2035 is the target set by the New Zealand Government for decarbonisation of the public transport bus fleet (Waka Kotahi, 2023a)[5]. Under

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[5] This report has been prepared under the assumption that NZTA will require all new urban buses to be zero-emission by 2025, in alignment with the government’s goal of achieving a fully decarbonised urban fleet by 2035.

this option, new BEB and HFCB are assumed to be purchased one year prior to the end of the operational life of a diesel bus for modelling purposes.

As a result, the TCO of Option 1 (TCO 1) includes the costs related to operating a diesel bus for up to 12 years (this is a variable assumption in the ZEB Cost Model for the average remaining life of diesel buses), and the cost of purchasing and running a new BEB or HFCB for up to 20 years. It also includes the cost of emissions from both types of bus technologies.

Option 2: Early scrapping of diesel buses

New BEB or HFCB are purchased immediately, while the existing diesel buses are retired and not deployed on any alternative routes or during different times. Any residual value of a bus, be it for scrap, export or some other purpose, is captured in the salvage value of the bus, which is included in the formula for TCO.

Thus, the TCO of Option 2 (TCO 2) includes the cost of purchasing and operating a new BEB or HFCB, while also accounting for the impact of avoided emissions from retiring a diesel bus early. The ZEB Cost Model deducts the emission associated with running a diesel bus for the rest of its service life from the TCO, while also adding the emissions impact of constructing a new bus earlier than would have otherwise been done.

Option 3: Mode shift

Diesel buses are immediately replaced with new BEB or HFCB on the routes originally operated by diesel buses. However, the diesel buses are not retired and are instead retained by the PTA to expand public transport options to induce mode shift. Consultation between the steering group and Castalia revealed that there are many potential uses for retained diesel buses by PTAs, or by other parties if PTAs were not to retain them but they were to remain in use in New Zealand. However, Castalia and the steering group determined that the ZEB Cost Model would assume that diesel buses with a remaining service life are retained by the PTA, and used to expand public transit options and induce mode shift during peak hours on urban roads, as this is viewed as the most likely and most efficient use of diesel buses retained by a PTA.

Thus, the TCO of Option 3 (TCO 3) includes the costs of purchasing and operating the new BEB or HFCB, and the operational costs of the existing diesel buses used for mode shift.

Mode shift is expected to occur when individuals who originally planned to drive a car during peak hours choose to take the bus instead. This shift is attributed to the increased operational frequency and reduced bus crowding on a route. As a result, TCO 3 accounts for the emissions produced by both the ZEB (BEB or HFCB) and the diesel buses, and the avoided emissions resulting from cars being taken off the road because of mode shift. The ZEB Cost Model uses the average bus occupancy to calculate the approximate number of cars taken off the road, based on the average vehicle occupancy in urban areas in New Zealand (Sullivan & O'Fallon, 2003). The average occupancy for each size of a bus was computed using data from Auckland Transport (2019).

Note that the model calculates three different TCOs for BEB and HFCB. However, the MAC for BEB and HFCB is only calculated for TCO 2 (or the early scrapping of diesel buses option). This approach enables the model to fairly compare the MAC for BEB and HFCB against other technologies that assume an immediate transition of existing diesel buses.

2.2 Data collection methods

The objective of data collection for this research task was to gather comprehensive information about the costs, emissions and other specific considerations related to the bus technologies considered for each use-case and their performance on the different types of routes considered. To ensure the accuracy and credibility of the ZEB Cost Model, the data collection process involved two key methodologies: a comprehensive review of recent reports and data sources on bus technologies; and in-depth interviews with industry professionals from prominent companies, including Yutong, Global Bus Ventures, HYDI, Hiringa, Mitsui and other industry experts that preferred to remain anonymous in this study.

The literature review formed the basis of the research, offering a wealth of information from various credible sources, such as the National Renewable Energy Laboratory, Ministry of Business, Innovation and Employment, Ministry of Transport and NZTA. Through a systematic search of databases, such as academic journals and industry-specific websites, the review encompassed a wide range of topics related to bus technologies, capital, operational and maintenance costs, operational and embedded carbon emissions, and mode shift. This method allowed us to identify recent developments and best practices within the public transport sector.

However, it's important to note that much of the data in academic journals and industry-specific papers pertains to the US, Europe or Australia. Therefore, to complement the literature review with region-specific insights, we conducted several semi-structured interviews with key industry professionals based in New Zealand and Australia, including Yutong, Global Bus Ventures, HYDI and others. These industry professionals shared their expertise on various ZEB technologies, including BEB, HFCB, repowered buses and hydrogen-fuel-blending buses. They provided quantitative data on the performance, capital costs, operational expenses, maintenance costs, and other relevant factors affecting the TCO of public buses. These interviews also provided valuable qualitative data, which played a crucial role in enriching the ZEB Cost Model. For example, Yutong and Global Bus Ventures indicated the maintenance costs for two- and three-axle buses are practically identical. Although they did not provide specific numbers, they provided a general approach that we then incorporated into the model.

The combination of the literature review and interviews allowed for a robust analysis of the data, employing both qualitative and quantitative methods. In the following sections, the findings from the literature review and the interviews are discussed in more detail.

2.2.1 Capital and operations and maintenance costs

During our research, obtaining the most relevant and accurate cost information for both CAPEX and OPEX costs for each bus technology was one of our main priorities, as they constitute the majority of the TCO.

2.2.1.1 Capital costs

To ensure that the capital costs reflected the reality of the New Zealand market, we relied on cost references shared by industry professionals. Since the capital costs of different bus technologies varied, we used an average cost derived from several reliable sources. Notably, the cost of diesel buses remained the lowest compared to ZEB, including repowered buses, BEB and HFCB. Also, repowering diesel buses has a lower capital cost than purchasing new BEB or HFCB. We have provided a list of costs associated with each technology in Appendix A.

2.2.1.2 Operations and maintenance costs

One of the main challenges we faced was obtaining accurate information about the operations and maintenance costs of different bus technologies. This is because different public transport operators include or exclude various components in their operations and maintenance costs, such as insurance, labour, general bus maintenance (eg, doors, seats, wiper blades, tyres) and others. As a result, maintenance costs can vary significantly.

Overall, the maintenance cost of BEB ranges between $0.45 per km (Johnson et al., 2020) and $0.64 per km (Hensher et al., 2021)[6]. In comparison, the maintenance cost for diesel buses ranges between $0.62 per km (Johnson et al., 2020) and $0.88 per km (Johnson et al., 2020)[7]. As for HFCB, their maintenance cost falls within the range of $0.56 to $0.58 per km (Hensher et al., 2021). Appendix A provides a full list of operations and maintenance costs.

In our analysis, we utilised an average maintenance cost obtained from multiple sources. Furthermore, our research indicates that the maintenance cost of BEB is notably lower than for diesel buses, typically ranging from 50% to 60% of the maintenance cost of diesel buses per kilometre (Hensher et al., 2021). We employed this cost differentiation as a sense check to verify that the maintenance costs between diesel buses, and BEB and repowered buses, adheres to this scale.

2.2.2 Energy costs

The cost of fuel and energy plays a crucial role in the OPEX of buses. Figure 2.4 illustrates cost projections for different fuel types used in the model, including diesel, renewable diesel, hydrogen and electricity.

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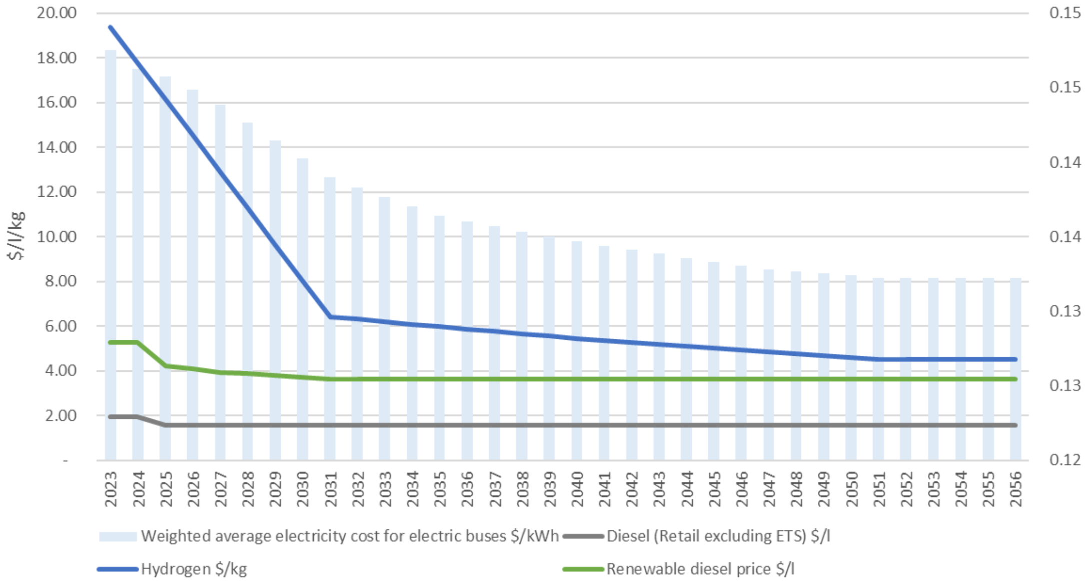
[6] Per km cost is calculate based on an annual cost of AUD$50,000 or NZD$53,842, and the assumption that on average a bus would cover 85,000 km/year.

[7] Per km cost is based on an annual cost of AUD$46,000 or NZD$49,535, and the assumption that on average a bus would cover 85,000 km/year.

Figure 2.4 Fuel and energy price projections (adapted from Envisory, 2023; Climate Change Commission, 2021)



Under a prior agreement with the Ministry of Business, Innovation and Employment, Envisory supplied us with the forecast for diesel and renewable diesel prices.

Diesel prices are projected to remain relatively stable after 2025, as illustrated in Figure 2.4. Additionally, it is important to note that the price of diesel excludes the costs associated with the carbon tax. This is to avoid double counting when the TCO analysis later adds emissions costs. Currently, renewable diesel is not widely produced and is trading at nearly three times the cost of fossil fuel diesel. It is expected that a reasonable premium will persist for renewable diesel over the foreseeable future, as stated by the ministry (Ministry of Business, Innovation and Employment, 2021b).

The current cost of hydrogen in New Zealand at the scale required to supply buses is estimated at around $20 per kg. However, our analysis indicates that the cost of hydrogen is anticipated to decrease, reaching approximately $6.40 per kg by 2032. After 2032, the cost of hydrogen is expected to continue decreasing, although at a slower rate.

For electricity, the ministry projections suggest that the cost of electricity will decrease over the projected period, providing a potential cost advantage for electric buses in the long run (Ministry of Business, Innovation and Employment, 2020).

2.2.3 Emissions and their costs

This section examines our findings on the emissions and their assumed costs to society from the different bus technologies. Further, this section explains how Castalia calculated well-to-wheel emissions that result from operating the bus; embedded emissions that result from the manufacturing of a bus; and the price that is placed on all emissions.

2.2.3.1 Well-to-wheel emissions

Well-to-wheel emissions refer to the total greenhouse gas emissions associated with an energy source for a bus over its entire lifecycle, including fuel production, distribution and vehicle operation. Well-to-wheel emissions from the energy source account for the vast majority of emissions during a bus's lifetime

Well-to-wheel analysis provides a comprehensive view of an energy source's environmental impact from 'well' (fuel source) to 'wheel' (tailpipe emissions). Thus, well-to-wheel analysis considers not only the emissions produced during the vehicle's use, but also those generated by extracting, processing and transporting the fuel used to power the vehicle.

Diesel buses have the highest well-to-wheel emissions due to the carbon-intensive nature of extracting, refining and transporting crude oil to produce diesel fuel. Additionally, burning diesel in the engine emits greenhouse gases, particulate matter and nitrogen oxides (NOx) during operation (Waka Kotahi, 2021).

The well-to-wheel emissions for BEB and repowered buses depend on the electricity generation mix in New Zealand. As approximately 82% of the energy sources in the New Zealand grid are renewable (Ministry of Business, Innovation and Employment, 2021a), the emissions factor is only 0.120 kgCO2e/kWh (Ministry for the Environment, 2022). In contrast, in Jamaica, where renewable energy sources in the national grid account for only 9%, the emissions factor is about 0.562 kgCO2e/kWh (IRENA, 2022). Consequently, BEB in New Zealand have very low well-to-wheel emissions during operation. However, even with a high percentage of fossil-fuel-based electricity generation, BEB generally emit significantly lower greenhouse gases compared to diesel buses (Ministry for the Environment, 2022).

Similarly, the well-to-wheel emissions for HFCB depend on the source of hydrogen production. There are three main types of hydrogen, each with different characteristics.

- Brown hydrogen is produced mainly from natural gas, coal or oil, and it contributes significant greenhouse gas emissions.
- Blue hydrogen is a cleaner option compared to brown hydrogen. It's also produced from fossil fuels like natural gas, coal or oil, but the emissions generated are captured, stored or reused, reducing its environmental impact.
- Green hydrogen is the cleanest type. It's generated using renewable energy sources like hydro, solar or wind power. This process, known as electrolysis, separates water into oxygen and hydrogen, and it doesn't produce any greenhouse gas emissions (Ministry of Transport, 2019).

The model assumes that HFCB are fuelled with green hydrogen, resulting in negligible well-to-wheel emissions (Hensher et al., 2021).

Renewable diesel offers a reduction in well-to-wheel emissions compared to conventional diesel (TriMet, 2021). The use of renewable feedstocks in production helps lower the carbon footprint, making it a cleaner option for public buses. However, the research on emission reduction is very limited and typically only considers carbon dioxide emissions reduction, rather than a full range of pollutants.

Buses using hydrogen-fuel-injection systems will generally have lower emissions than traditional diesel buses due to improved combustion efficiency. However, studies show that emissions such as nitrogen dioxide (NO2) are higher in hydrogen-fuel-injection buses than diesel buses (Bari, 2021).

It is important to note that the type of bus, terrain and speed also impact tailpipe emissions. For instance, fuel consumption for diesel buses on an undulating route is expected to increase by around 62% compared to a flat route. On a hilly route, fuel consumption is expected to increase by about 200% for diesel buses (Waka Kotahi, 2021). However, increases in energy consumption are not equal by fuel or energy type. For BEB with regenerative braking, some of the additional energy consumed on a hilly route will be recovered on the downhill sections and at other times during vehicle braking. As a result, BEB energy consumption only increases 7% on an undulating route and 15% on a hilly route.

The size of the bus (two-axle rigid, three-axle rigid, and three-axle double decker bus) also affects power consumption and emissions, with larger buses consuming more power and emitting more pollutants. Furthermore, the speed of the bus significantly impacts power consumption and emissions, with lower speeds resulting in higher power consumption and emissions. Note that at high speeds, wind resistance may also play a role in emissions. However, for simplicity, the ZEB Cost Model uses average emissions data gathered from NZTA for buses travelling at 10 km/h for urban routes, 25 km/h for suburban routes and 40km/h for rural routes. (Waka Kotahi, 2021)

For a detailed overview of the emissions associated with each bus technology used in the ZEB Cost Model, please refer to Appendix A.

2.2.3.2 Embedded emissions

The research on the emissions embedded in the manufacturing of different types of buses is limited.

A study conducted by Lie et al. (2021) focused on the carbon footprint of electrified city buses in Trondheim, Norway. According to their findings, the embedded emissions from manufacturing diesel and BEB varies based on factors such as the location of production, the type of bus, and the electricity mix used to charge the battery.

However, in general, BEB tend to have higher embedded emissions than diesel buses. This difference is mainly attributed to the process for manufacturing their batteries, which requires a significant amount of energy and resources. The battery alone constitutes one-third of embedded emissions in BEB.

Notably, the largest discrepancy in embedded emissions is observed between electric and conventional diesel buses. The study indicates that conventional buses result in embedded emissions of approximately 100 tonnes CO2e per bus. On the other hand, BEB result in embedded emissions of 147 tonnes of CO2e per bus. Thus, a BEB, has an additional 47 tonnes of embedded emissions due to its battery production compared to conventional buses.

In the case of HFCB, the available data on embedded emissions is scarce. A technical note from Ballard Power Systems (2021) suggests that the fuel cell module generates 5,600 kg of CO2e emissions during its production, from cradle to gate. However, detailed studies on the embedded emissions associated with producing HFCB are limited.

It is essential to consider that, in the overall life span of ZEB, the increased emissions associated with the manufacturing of the buses have a relatively small impact on their per kilometre emissions. Thus, the operational phase, where ZEB emit lower or zero emissions, plays a more significant role in determining the overall environmental impact and cost of emissions of these buses.

Therefore, while the manufacturing phase does contribute to the overall emissions of ZEB, it is crucial to focus on the long-term operational phase, where their environmental benefits become more prominent. Finally, as the transition to cleaner transportation progresses and technology improves, it is expected that the embedded emissions associated with producing ZEB will also decrease over time.

2.2.3.3 Costs of emissions

This section discusses the sources and approach used to evaluate the cost of different types of emissions, including CO2e, NOx and other pollutants. Additionally, it discusses the embedded costs associated with producing various types of buses.

Cost of CO2e emissions

The cost of CO2e emissions in the ZEB Cost Model is estimated based on the shadow price of carbon.[8] The New Zealand Government has a uniform shadow price of carbon ($ per tonne of CO2e), set out in the *Monetised Benefits and Costs Manual* (Waka Kotahi, 2023b), which should be used for calculating the economic impact of carbon for transport activities. This is used in the model.

Model users have a choice of three options for shadow price per tonne of CO2e – low, middle and high – which reflect the options in the *Monetised Benefits and Costs Manual* for the price path of the shadow price of carbon. Figure 2.5 provides an overview of prices under each option.

Figure 2.5 **Shadow price of carbon in New Zealand ($2022 per tonne of CO2e) (adapted from Waka Kotahi, 2023b, p. 59)**

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Low	$59	$65	$72	$78	$85	$91	$98	$104	$108	$112	$116	$120
Middle	$87	$97	$107	$116	$126	$136	$146	$155	$161	$167	$174	$180
High	$171	$182	$193	$203	$214	$219	$224	$230	$235	$241	$247	$253
Year	**2035**	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**
Low	$124	$129	$133	$137	$141	$145	$149	$153	$157	$161	$165	$169
Middle	$186	$192	$198	$204	$210	$216	$222	$228	$235	$241	$247	$253
High	$259	$265	$271	$278	$284	$291	$298	$305	$313	$320	$328	$336
Year	**2047**	**2048**	**2049**	**2050**	**2051**	**2052**	**2053**	**2054**	**2055**	**2056**	**2057**	**2058**
Low	$173	$178	$182	$186	$188	$189	$191	$193	$195	$197	$199	$201
Middle	$259	$265	$271	$277	$286	$294	$303	$312	$321	$331	$341	$351
High	$344	$352	$361	$369	$387	$407	$427	$448	$471	$494	$519	$545

Cost of NOx and other pollutants

The external impacts of air pollutants, such as NOx, are assessed using the damage-cost approach. This approach assigns a cost to each tonne of emitted pollutant, reflecting the harm caused to the environment, including people and ecosystems. The cost of damage from NOx and other pollutants is presented in Figure 2.6.

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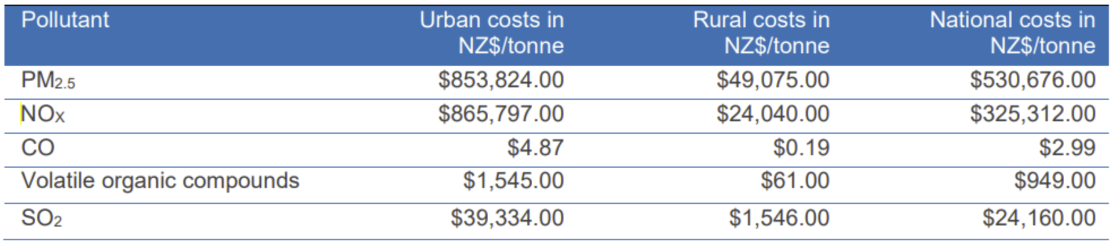
[8] Shadow prices are different from market-traded prices in the Emissions Trading Scheme. Market-traded prices do not currently reflect the full marginal cost of achieving New Zealand's emission targets.

Figure 2.6 Emissions damage costs ($/tonne – 2021)* (adapted from Waka Kotahi, 2023b, p. 57)



Pollutant	Urban costs in NZ$/tonne	Rural costs in NZ$/tonne	National costs in NZ$/tonne
$PM_{2.5}$	$853,824.00	$49,075.00	$530,676.00
NO_x	$865,797.00	$24,040.00	$325,312.00
CO	$4.87	$0.19	$2.99
Volatile organic compounds	$1,545.00	$61.00	$949.00
SO_2	$39,334.00	$1,546.00	$24,160.00

* In the model, the emissions damage costs were converted to 2023 dollar values.

Figure 2.6 shows that particulate matter 2.5 (PM2.5) and NOx have by far the highest cost by volume. In addition, the estimated impact and cost of NOx have significantly increased in recent years. In 2021, the estimated cost of NOx damage was $16,347 per tonne (Waka Kotahi, 2021). In 2023, this cost was reassessed following an update to the Health and Air Pollution in New Zealand study (HAPINZ 3.0) to be $325,312 per tonne at the national level (Waka Kotahi, 2023b).

This recent increase in the price of NOx illustrates the substantial impact of the cost update of NOx on the results of the TCO. The ZEB Cost Model has a switch to show the impact of the updated NOx cost: the old cost of $16,347 per tonne and the new cost of $325,312 per tonne. The purpose of this feature is to enable users to observe the significant impact of updated NOx costs on the TCO results.

2.2.4 Road-user chargers

Road-user charges in New Zealand are levies paid on vehicles not powered by petrol to contribute towards the maintenance and upkeep of the country's roads. While road users who drive vehicles powered by petrol pay levies when they purchase fuel, others, such as drivers of diesel vehicles like trucks, pay road-user charges directly.

At the time of preparing this report, pure electric vehicles were exempt from road-user charges if their motive power came wholly from an external source of electricity. An external source refers to the ability of the vehicle to be plugged into the electric grid or another electricity source for recharging[9].

The exemption was part of a policy to encourage the adoption of pure electric vehicles. As of now, heavy electric vehicles with a gross laden weight of more than 3,500 kg are exempt from road-user charges until 31 December 2025. As a result, the default setting of the ZEB Cost Model exempts BEB from road-user charges until 2025. After this exemption period ends, BEB would be required to pay road-user charges, which would add to the TOC for these vehicles (Waka Kotahi, 2023c). However, the ZEB Cost Model includes a switch to turn off road-user charges from 2026 for BEB to evaluate the impact that a policy choice to continue to exempt BEB from road-user charges would have on TCO.

It is important to note that HFCB are not considered electric vehicles and are not exempt from road-user charges. The Ministry of Transport specifies that vehicles generating electricity on board using a fuel cell must pay road-user charges (New Zealand Ministry of Transport, 2021).

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[9] This is based on the NZTA policy that was in place at the time of the report’s preparation in 2023.

2.2.5 Operational life of the buses

The expected operational life of new Diesel, BEB and HFCB is estimated to be 20 years. This provides a likewise comparison of the TCO for these use-cases.

For existing diesel buses, assuming they are either transitioned to use lower emissions fuel or repowered to electric buses, their expected operational life is estimated to be a maximum of 12 years, considering the average remaining life of a diesel bus to meet the target of decarbonising the bus fleet by 2035.

However, feedback from industry experts and Waka Kotahi has suggested the possibility of extending the operational life of repowered buses by certifying them as new vehicles. This would align their operational life with that of conventional buses, reaching up to 20 years. The decision to certify repowered buses as new is determined on a case-by-case basis by NZTA, considering various factors such as the bus's condition, the retrofitting process, and adherence to safety and environmental standards. As such, the ZEB Cost Model includes the ability to set the lifespan of a repowered bus to 20 years to allow the user to evaluate the impact on TCO.

2.3 Development of the ZEB Cost Model

This section explains the methodology for developing the ZEB Cost Model by first introducing the main building blocks of the model and then explaining the detailed formulae used to calculate each output.

2.3.1 Building blocks of the model

To calculate the TCO and the MAC for different use-cases displayed on its Dashboard, the ZEB Cost Model has three main components:

- **inputs –** these are the general assumptions and the assumptions that are specific to each use-case
- **calculations –** these are the computations that transform the inputs into outputs
- **outputs –** the outputs are the key indicators produced by the ZEB Cost Model.

Figure 2.7 provides an overview of the ZEB Cost Model and its main building blocks, while Table 2.1 provides a more detailed description.

Figure 2.7 Overview of the ZEB Cost Model

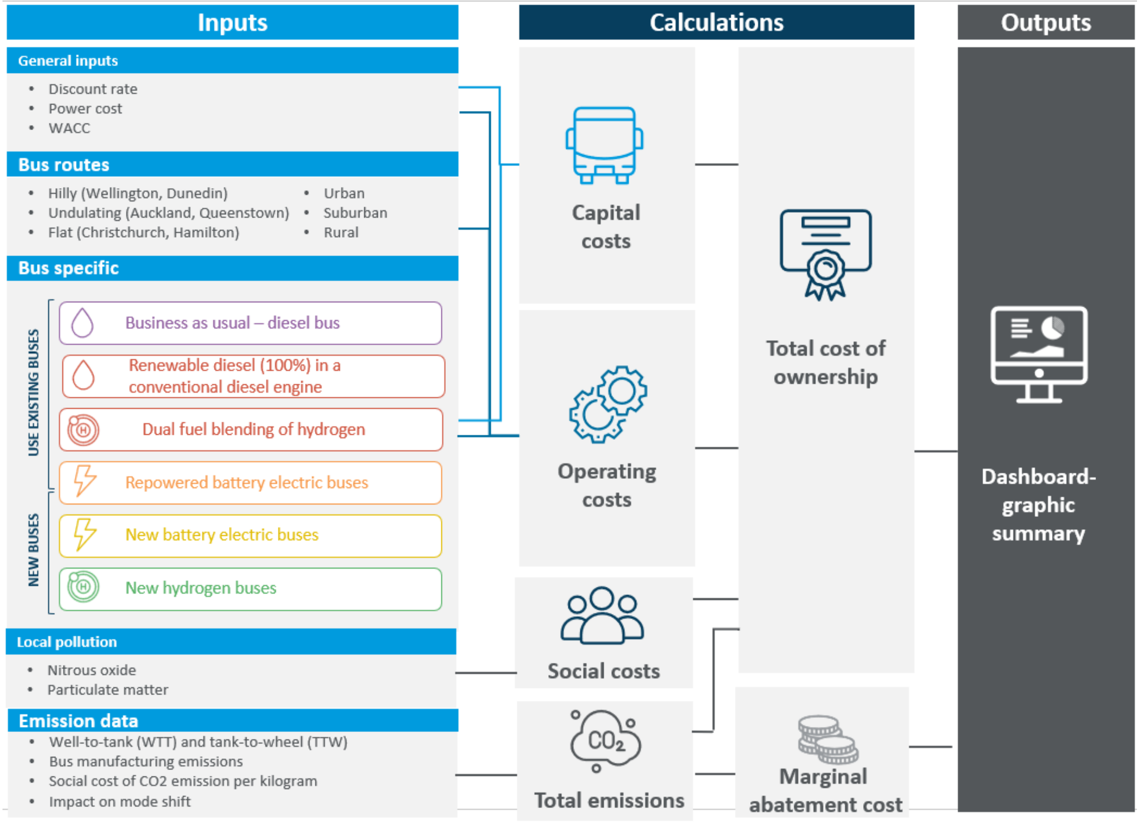


Table 2.1 The main building blocks of the ZEB Cost Model

Building block	Description
Inputs	
General model assumptions	General assumptions that are required for all use-cases – for example, the remaining service life of a diesel bus, and the cost of various power sources such as diesel, hydrogen, electricity and renewable diesel
Route assumptions	There are urban, suburban and rural routes, and an additional route used during the mode shift scenario. Each route requires the user to input assumptions on the route's length, number of trips per day, number of buses servicing the route, terrain, bus type and number of fast chargers (if any) expected to be used on the route
Bus technology assumptions	Assumptions specific to each use-case, including the cost of purchasing a bus and its corresponding infrastructure, operations and maintenance costs, power consumption etc.
Emissions assumptions	The assumptions are related to the cost and quantity per kilometre of each pollutant, including CO2e, CO, volatile organic compounds (VOC), NOx, NO2 and PM2.5.
Calculations	
Route	The calculation for a route includes the total annual distance travelled by a bus on a specific route.
TCO	The total cost of purchasing and operating a specific bus technology is calculated on a per kilometre basis over the entire lifespan of the bus. This is calculated with and without the cost of emissions on a per kilometre basis.
MAC	Calculates the incremental cost associated with reducing or avoiding one unit of greenhouse gas CO2e emissions compared to the BAU scenario.
Early scrapping of diesel buses	Calculates the cost of avoided emissions from retiring diesel buses early and the emissions from early manufacturing of new buses.
Mode shift	The per kilometre cost of reducing emissions from people switching from cars to buses, calculated by comparing the emissions generated by cars with the emissions produced by buses per kilometre. To compare the diesel buses used for mode shift and the avoided emissions resulting from cars taken off the road because of mode shift, the ZEB Cost Model uses the average bus occupancy to calculate the approximate number of cars taken off the road based on the average vehicle occupancy in urban areas in New Zealand.
Outputs	
Dashboard	All the outputs are presented on the Dashboard. This includes TCO and MAC graphs for each use-case and route type.
Sensitivity	Sensitivity analysis that examines the impact of selected variables that are likely to change over time, such as the cost of new buses or power prices. The results of this analysis are presented in the Sensitivity tab.

In addition to the input sheets, calculation sheets and output sheets, the ZEB Cost Model also contains several support sheets, such as background information on the ZEB Cost Model in the coversheet, the documentation sheet and bus research sheet. Table 2.2 categorises the sheets in the model by their function and describes their role.

Table 2.2 Descriptions of the sheets in the ZEB Cost Model and its functions

Function	Sheet	Role
Support	Cover	Background information on the model, its purpose, and developers
	Documentation	Instructions, resources and other information on the workbook
	Control panel	Settings for the ZEB Cost Model and Dashboard; mainly formula driven
Inputs	Data	Data and assumptions used in the ZEB Cost Model
	Bus research	Data and assumptions only related to buses
	Dashboard	Toggles to change inputs, assumptions and sensitivities
Calculations	Route	Calculations of annual distance and mode shift TCO
	Diesel (BAU)	Calculations of TCO of a diesel bus
	Renewable diesel	Calculations of TCO and MAC for a diesel bus using renewable diesel
	Hydrogen blending	Calculations of TCO and MAC for a diesel bus with hydrogen injection system
	Repowering	Calculations of TCO and MAC for a diesel bus repowered to an electric bus
	BEB	Calculations of TCO and MAC for BEB
	HFCB	Calculations of TCO and MAC for HFCB
Outputs	Dashboard	Results from the ZEB Cost Model
	Results	Results from the ZEB Cost Model
	Sensitivity	Sensitivity tests and results including payback period

For the convenience of users, the Dashboard serves a dual purpose by accommodating both inputting variables and displaying outputs. This design enables users to adjust assumptions directly on the Dashboard and instantly observe the impact on the outputs without switching between multiple sheets.

2.3.2 Total cost of ownership and marginal abatement cost methodology

This section explains the methodology used in the ZEB Cost Model to calculate the TCO and the MAC, emissions from operating buses and emissions reduction from mode shift, and early scrapping of diesel buses.

2.3.2.1 Total cost of ownership per kilometre

TCO analysis compares different bus technologies by calculating the total cost to own and operate each type of bus on a per kilometre basis. TCO analysis considers all costs associated with owning and operating a bus over its entire lifespan, including CAPEX costs, fuel or energy costs, OPEX costs, financing costs, residual value and emissions. TCO is presented on a per kilometre basis to account for differences in the lifespan of different bus technologies.

In the ZEB Cost Model, TCO is expressed as two different numbers.

- The TCO without considering the cost of emissions – this is the cost of each use-case only considering costs that a bus operator directly incurs, such as CAPEX and OPEX costs (ie, no externalities).
- The TCO including the cost of CO2e emissions and other harmful emissions – this is the cost of bus operations, including the cost to society as a whole.

The ZEB Cost Model first calculates the TCO per kilometre excluding emissions, and then separately calculates the social cost of emissions per kilometre. Once both are calculated they are summed to derive the TCO including emissions per kilometre.

Formula for calculating TCO per kilometre excluding emissions

The TCO excluding emissions considers factors such as CAPEX costs, OPEX costs and the salvage value of each bus. The present value of TCO is calculated using the following formula.

$$TCO\ per\ bus = \sum_{i=1}^{L} \frac{PMT}{(1+r)^i} + \sum_{i=1}^{L} \frac{O}{(1+r)^i} - \frac{S}{(1+r)^n} \qquad \text{(Equation 2.1)}$$

Where:

- PMT = annual CAPEX cost
- O = annual OPEX cost and any one-time battery replacement cost
- r = discount rate
- i = year i
- L= bus operational life
- n = year following the last operating year of a bus
- S = salvage value.

This formula provides the TCO of the bus as a lump sum. However, the TCO is then transformed to a per kilometre value using the following formula.

$$TCO\ per\ km = \frac{TCO\ per\ bus}{N} \qquad \text{(Equation 2.2)}$$

Where:

- N = total amount of kilometres over the lifespan of a bus, which is calculated by multiplying the daily expected distance travelled by 312 days, to get an annual amount, which is then multiplied by the total expected remaining life of the bus (years).

Formula for calculating the social cost of emissions per kilometre

The social cost of emissions per kilometre, which is the cost of emissions generated by a bus technology on a per kilometre basis, is calculated using the following formula.

$$Social\ cost\ of\ emssions\ (SCE)\ per\ km = \frac{E_{em} * C_{CO2e}}{N} + \frac{\sum_{i=1}^{L} \frac{N_a * E_k * C_E}{(1+r)^i}}{N} \qquad \text{(Equation 2.3)}$$

Where:

- E_{em} = embedded emissions during the manufacturing
- C_{CO2e}= cost of CO2e
- N_a = total annual distance travelled by the bus
- E_k = emissions produced per kilometre travelled by the bus
- C_E = cost associated with a specific type of emission. It is important to note that cost of emissions is also discounted, which allows users to convert future damages into their present-day value and add them up to determine total damages.

2.3.2.2 Calculating the impact of diesel bus retirement choices

This section provides a simplified version of the formulae used to calculate the impact of different options for retiring diesel buses, and provides an overview of the methodology used in assessing the impact of retiring diesel buses.

Option 1: End-of-life diesel bus replacement with BEB/HFCB

The end-of-life diesel bus replacement with BEB/HFCB (or TCO 1) is calculated by summing the costs of the diesel bus over the rest of its useful life to the costs of a new BEB/HFCB over its lifetime, and then dividing those costs by the total kilometres that both buses will operate using the following formula.

$$TCO1\ per\ km = \frac{TCO\ per\ bus_{Diesel} + TCO\ per\ bus_{BEB/HFC} + SCE_{BEB/HFC} + SCE\ _{Diesel}}{N_{BEB/HFC} + N_{Diesel}} \qquad \text{(Equation 2.4)}$$

Where:

- $TCO\ per\ bus_{Diesel}$ = TCO of an existing diesel bus until the end of its operational life
- $TCO\ per\ bus_{BEB/HFC}$ = TCO of BEB or HFC over its entire lifespan
- $SCE\ _{BEB/HFC}$ = TCO of emission associated with operating a BEB or HFCB over its operational life
- SCE_{Diesel} = TCO of emission associated with operating a diesel bus until the end of its operational life
- $N_{BEB/HFC}$ = total distance travelled by BEB or HFCB over its operational life
- N_{Diesel} = total distance travelled by an existing diesel bus over its remaining operational life.

Option 2: Immediate diesel to BEB/HFCB replacement

Under this option – early scrapping of diesel buses (or TCO 2) – new BEB or HFCB are purchased immediately, and existing diesel buses are retired. TCO 2 includes the cost of purchasing and operating a new BEB or HFCB, while also accounting for the impact of avoided emissions from retiring a diesel bus early. Early scrapping of diesel buses is calculated using the following formula.

$$TCO2\ per\ km = \frac{TCO\ per\ bus_{BEB/HFC} + SCE_{BEB/HFC}}{N_{BEB/HFC}} - \frac{SCE_{Diesel}}{N_{Diesel}} \qquad \text{(Equation 2.5)}$$

Option 3: Immediate diesel to BEB/HFCB replacement with diesel bus used for mode shift

Option three is for immediate diesel to BEB/HFCB bus replacement, with the diesel bus then used for mode shift purposes (TCO 3). Under TCO 3, the emissions avoided by passengers switching from cars to buses are deducted from the TCO associated with running the BEB/HFCB together with a diesel bus using the formula below.

$$\begin{aligned} &TCO\ 3\ per\ km \\ &= \frac{TCO\ per\ bus_{Diesel\ mode\ shift} + TCO\ per\ bus_{BEB/HFC} + TCO\ of\ emisions_{BEB/HFC} + TCO\ of\ emissions_{Diesel\ mode\ shift}}{N_{BEB/HFC} + N_{Diesel\ mode\ shift}} \\ &- \frac{TCO_{emissions\ cars}}{N_{diesel\ mode\ shift}} \end{aligned} \qquad \text{(Equation 2.6)}$$

Where:

- $TCO\ per\ bus_{Diesel\ mode\ shift}$ = TCO of existing diesel bus used for mode shift purposes until the end of its operational life
- $TCO\ of\ emissions_{Diesel\ mode\ shift}$ = TCO of emissions associated with operating a diesel bus used for mode shift purposes until the end of its operational life
- $TCO_{emissions\ cars}$ = TCO of emissions associated with operating cars on a route that is targeted for mode shift
- $N_{diesel\ mode\ shift}$ = the total distance travelled by a diesel bus over its remaining operational life on a mode shift route.

To calculate the avoided emissions from cars, the ZEB Cost Model estimates the number of cars that would be displaced from the road as more buses operate during peak hours and their emissions. This requires four steps.

1. First, the average occupancy of a bus offering an expanded bus service, which varies depending on the bus size, is computed using data from Auckland Transport (2019).
2. Second, the model makes an assumption about which passengers would have otherwise driven. Data on what percentage of passengers on an expanded bus service would have otherwise driven is not available. For the purposes of our analysis, the ZEB Cost Model's baseline assumption is that 70% of the people on the expanded bus offering would have otherwise been car users. However, the model allows for easy adjustment of the proportion of people switching from cars to buses, enabling users to assess the impact of the change on the TCO as explained in section 3.7.
3. Third, the number of passengers that would have otherwise driven is divided by the average occupancy of a car on urban roads.

4. Finally, the model estimates the annual reduction in car kilometres resulting from mode shift using average passenger kilometre data. By applying the per kilometre emissions specific to cars, the model can calculate the annual cost of avoided emissions.

2.3.2.3 Marginal abatement cost

The MAC evaluates the cost-effectiveness of different bus technologies in reducing greenhouse gas emissions. It measures the incremental cost of reducing or avoiding one unit of emissions compared to a baseline scenario. Using the MAC allows for a simple ‘bang for your buck’ comparison of different bus technologies and their ability to mitigate environmental impacts. Thus, it can help decision-makers identify the most cost-efficient way to reduce CO2 emissions.

MAC compares the costs of adopting and operating alternative bus technologies with the costs of conventional buses. The formula to calculate the MAC is as follows.

$$MAC = \frac{C_{ZEB} - C_{diesel}}{E_{ZEB} - E_{diesel}} \qquad \text{(Equation 2.7)}$$

Where:

- C_{ZEB} = TCO of ZEB
- C_{diesel} = TCO of a diesel bus
- E_{ZEB} = average CO2e emissions from an alternative bus technology
- E_{diesel}= average CO2e emissions from a diesel bus.

Overall, the approach is to first estimate the emissions and costs associated with conventional diesel buses (baseline scenario). This serves as a benchmark against which the emissions and costs of ZEB are compared. Next, the ZEB Cost Model calculates the emissions reduction achieved by adopting an alternative bus technology compared to the baseline scenario. This involves considering the specific use-case and the corresponding reduction in emissions. Then, the model calculates the incremental costs associated with implementing and operating ZEB, without considering the cost of emission. Finally, the model divides the incremental costs of adopting and operating ZEB by the emissions reduction achieved.

This provides the MAC per unit of emissions reduced. It represents the additional cost incurred to achieve one unit of emissions reduction compared to the baseline scenario. However, in some cases, the cost of implementing ZEB may be lower than the baseline scenario, resulting in a negative MAC. This indicates that reducing one unit of emissions leads to cost savings for the bus operator.

The model is available at www.nzta.govt.nz/resources/research/reports/718.

3 Results and findings

This section provides an overview of the key outputs of the model and provides the results of the TCO and MAC for different bus use-cases based on an example route to illustrate how to understand the model results. To be clear, this section does not provide definitive results on which use-case is least cost, because the model results are dependent on the user's inputs – which must include customisation of routes and can include customised assumptions for CAPEX or OPEX of use-cases.

This section also identifies the key drivers of the TCO, analyses payback period and conducts a sensitivity analysis to see how changes in bus cost and energy cost impact the TCO. Finally, it discusses how users can customise the model by adjusting different variables on the Dashboard and the Data sheet.

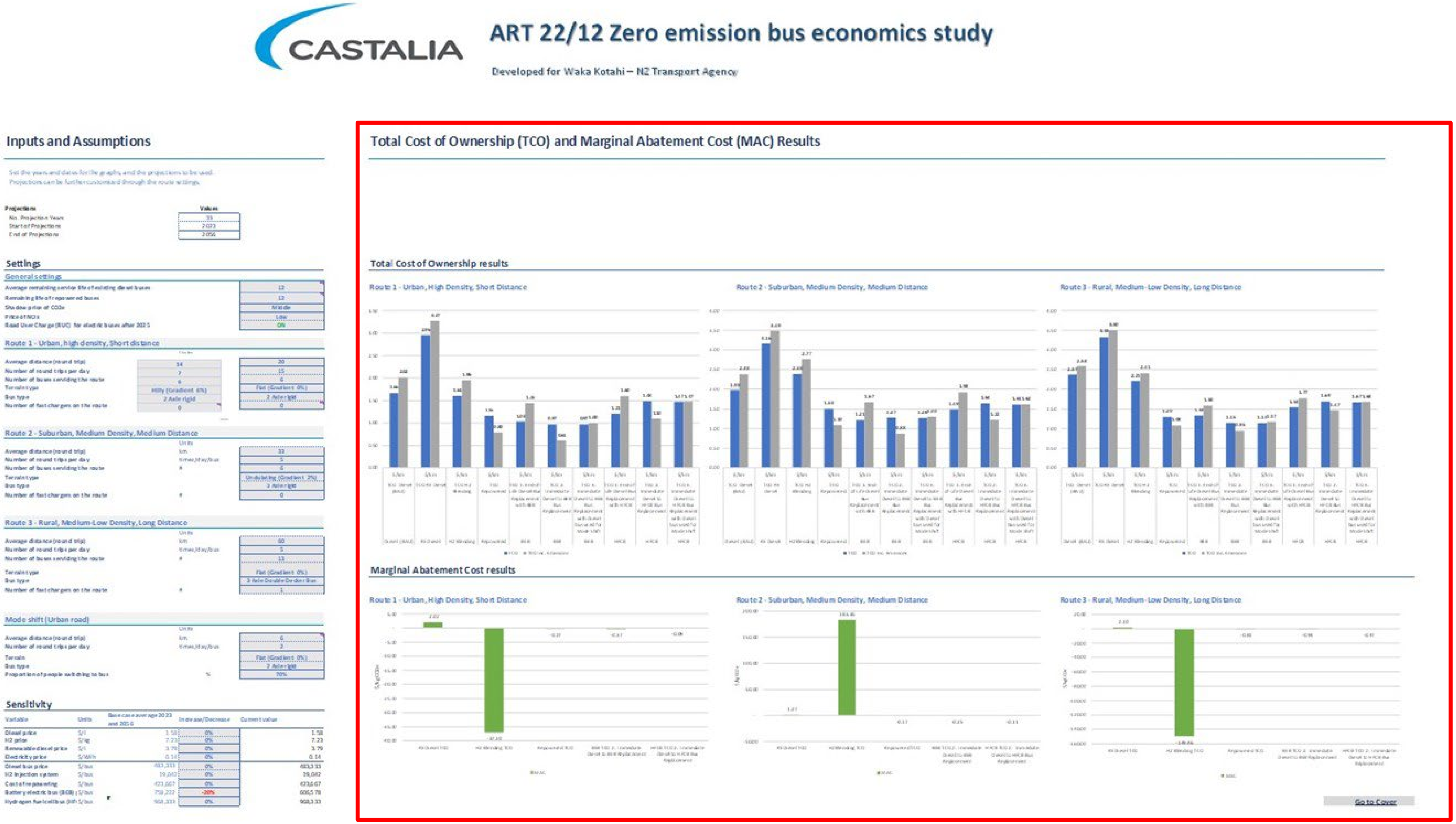
3.1 Overview of the ZEB Cost Model outputs

The outputs of the model are a TCO and MAC for each use-case on three different route types: urban, suburban and rural. The TCO and MAC outputs allow the user to compare different bus technologies comprehensively based on capital, operating and external costs, including greenhouse gas and other harmful emissions, on routes that are customised to the route on which the user is considering replacing a diesel bus.

3.2 Model Dashboard shows key outputs

The model Dashboard is depicted in Figure 3.1. It shows the calculated TCO and MAC for 10 use-cases, which represent the six bus technologies and four additional use-cases for retaining diesel buses when new BEB or HFCB are added to a PTA's fleet (red box). To customise the outputs, users can modify route and bus-related settings (left-hand side). Additionally, users can adjust key assumptions to test the sensitivity of outputs to changes in those assumptions (bottom-left corner). This is explained in detail in section 3.7.

Figure 3.1 Dashboard



CASTALIA

ART 22/12 Zero emission bus economics study

Developed for Waka Kotahi – NZ Transport Agency

Inputs and Assumptions

Settings

General settings

Route 1 - Urban, high density, Short distance

Route 2 - Suburban, Medium Density, Medium Distance

Route 3 - Rural, Medium-Low Density, Long Distance

Mode shift (Urban road)

Sensitivity

Total Cost of Ownership (TCO) and Marginal Abatement Cost (MAC) Results

Total Cost of Ownership results

Route 1 - Urban, High Density, Short Distance

Route 2 - Suburban, Medium Density, Medium Distance

Route 3 - Rural, Medium-Low Density, Long Distance

Marginal Abatement Cost results

Route 1 - Urban, High Density, Short Distance

Route 2 - Suburban, Medium Density, Medium Distance

Route 3 - Rural, Medium-Low Density, Long Distance

Go to Cover

3.3 Comparison of total cost of ownership and marginal abatement cost for different bus use-cases

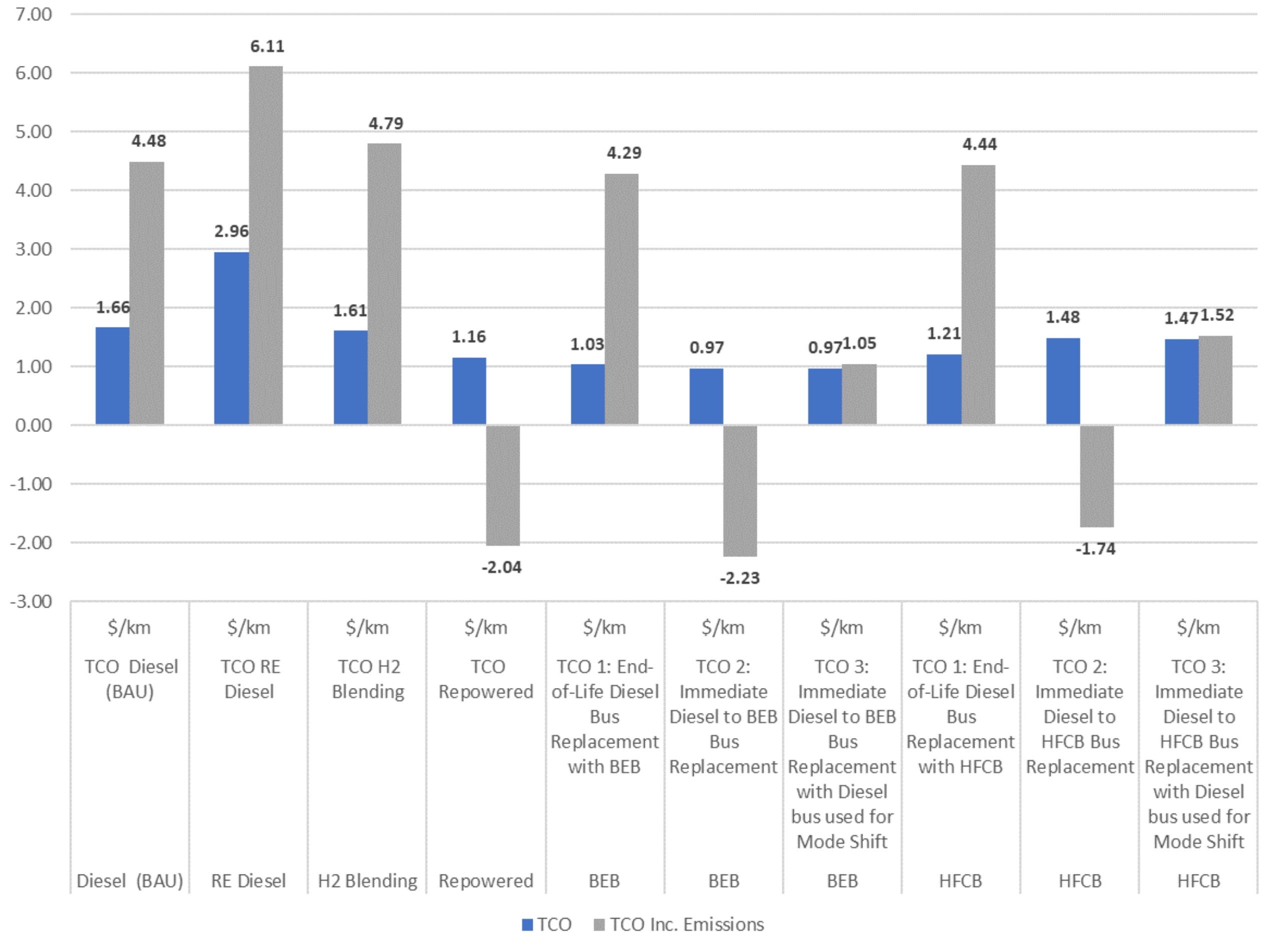
This section compares and analyses the outputs of the model for TCO and MAC across different bus use-cases, considering a set of predefined assumptions. This allows users to gain insights into the cost implications and MAC associated with the use-cases. This section discusses 10 use-cases based on the following assumptions.

- **General default settings**:
  - average remaining service life of existing diesel buses – 12 years
  - remaining life of repowered buses – 12 years
  - shadow price of CO2e is based on the middle price level
  - new price of NOx
  - road-user charges for electric buses are reinstated after 2025.
- **Route settings:**
  - route 1 – urban, high-density, short distance
  - average distance (round trip) – 20 km
  - number of round trips per day – 15
  - number of buses servicing the route – six
  - terrain type – flat (gradient 0%)
  - bus type – two-axle rigid
  - number of fast chargers on the route – zero.
- **Mode shift:**
  - average distance (round trip) – 6 km
  - number of round trips per day – two times/day/bus
  - terrain – flat (gradient 0%)
  - bus type – two-axle rigid
  - proportion of people switching to bus – 70%.

3.3.1 Example of total cost of ownership outputs

The TCO output provides a simple diagram with two columns so users can easily identify the most cost-effective way to transition to ZEB from the perspective of the bus operator and from the perspective of society as a whole. The blue column in Figure 3.2 indicates the TCO excluding emissions costs, while the grey column indicates the total TCO including the cost of emissions. An example of the TCO output on the ZEB Cost Model's Dashboard, based on the assumptions listed above, is illustrated in Figure 3.2.

Figure 3.2 Example of the model output for TCO



In this example, the outputs show that immediately replacing diesel buses with BEB and scrapping the diesel buses is the most cost-efficient approach from the perspective of society as a whole and the bus operator. This is because the TCO, including emissions for immediately replacing diesel buses with BEB (BEB:TCO 2), is significantly lower than the TCO of using the diesel buses until the end of their operational life (BEB:TCO 1). The TCO excluding emissions for these two use-cases is practically equal. However, it is important to remember that the bus operator does have to pay for emissions costs through the carbon component of the diesel fuel. The model excludes this cost from the analysis to avoid double counting. However, under New Zealand's Emissions Trading Scheme, it is an expense they will have to bear, and it will likely increase over time.

In contrast, the most expensive way to transition to ZEB is the use-case of replacing diesel with renewable diesel.

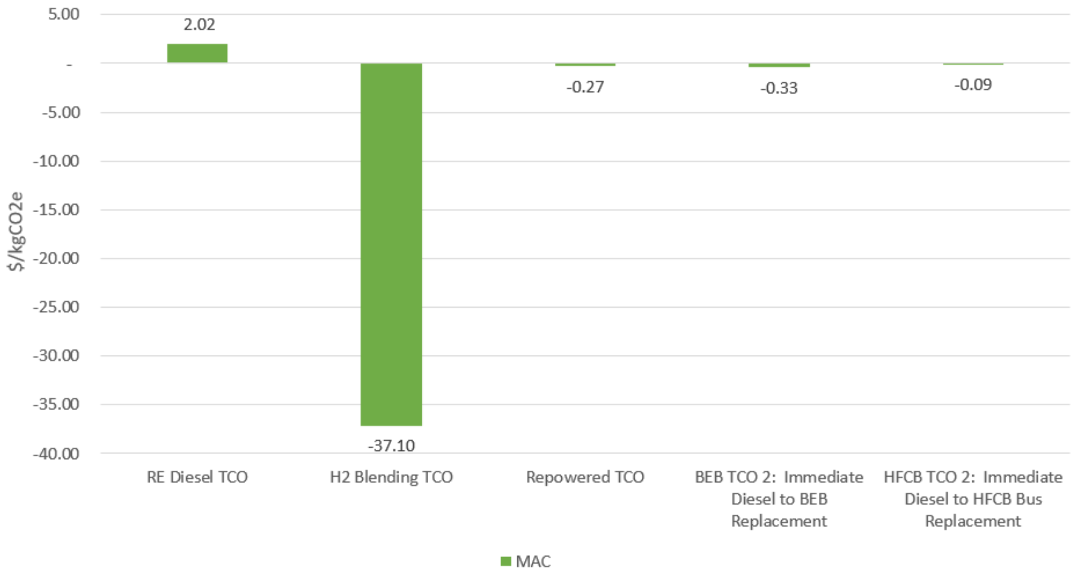
To answer the question about the emissions impact of retiring diesel buses early, the TCO analysis weighs the trade-off between avoided tailpipe emissions from scrapping diesel buses early and the emissions from earlier-than-necessary manufacturing of new buses. Figure 3.2 shows that the emissions benefits from early retirement outweigh the emissions from constructing buses earlier, because TCO 2 (which retires the diesel bus immediately) is lower than TCO 1 (which allows the diesel bus to serve out its remaining useful lifespan) when the impact of emissions is included in the TCO. It also shows that under the assumptions used for mode shift, TCO 3 including emissions is higher than TCO 2 for both BEB and HFCB. Thus, the emissions benefits from mode shift do not outweigh the emissions of continuing to run the diesel bus under the assumptions used for mode shift.

3.3.2 Example of marginal abatement cost outputs

An example of the MAC results for the six use-cases is presented in

Figure 3.3.

Figure 3.3 Example of the model output for MAC



As illustrated in

Figure 3.3, MAC outputs can be either positive or negative.

- A positive MAC indicates that the alternative technology is more expensive than the BAU. This means that reducing emissions would come at a cost. For instance, using renewable diesel would incur a cost of $2.02 per kilogram of reduced CO2e emissions.
- A negative MAC indicates that adopting the new technology would cost less than the BAU. This occurs when the TCO of the ZEB is lower than the TCO of BAU. For example, while the initial investment in BEB is higher than the diesel (BAU), its lower operational cost would lead to a lower TCO compared to a diesel bus, resulting in negative MAC. However, when the MAC curve turns negative the resulting ranking sometimes favours measures that produce low emissions savings and is therefore unreliable (Taylor, 2012).

The challenge of a negative MAC has been noted in several research papers (Levihn, 2016; Taylor, 2012; Ward, 2014). The literature suggests that when actions produce a positive financial benefit, specifically a negative MAC, using MAC curves for ranking purposes should be avoided. As such, users should revert to the TCO to determine the preferred technology for implementation when multiple technologies have a negative MAC.

3.4 Identifying cost drivers

This section identifies which of the components of TCO – CAPEX, OPEX and emissions costs – have the largest impact on TCO overall, as illustrated in Figure 3.4. This analysis offers insights into the extent of influence that changes in CAPEX, OPEX and emission costs have on the overall TCO. The analysis is based on the assumptions listed in the previous section.

Figure 3.4 Example of the cost stack, NZ$

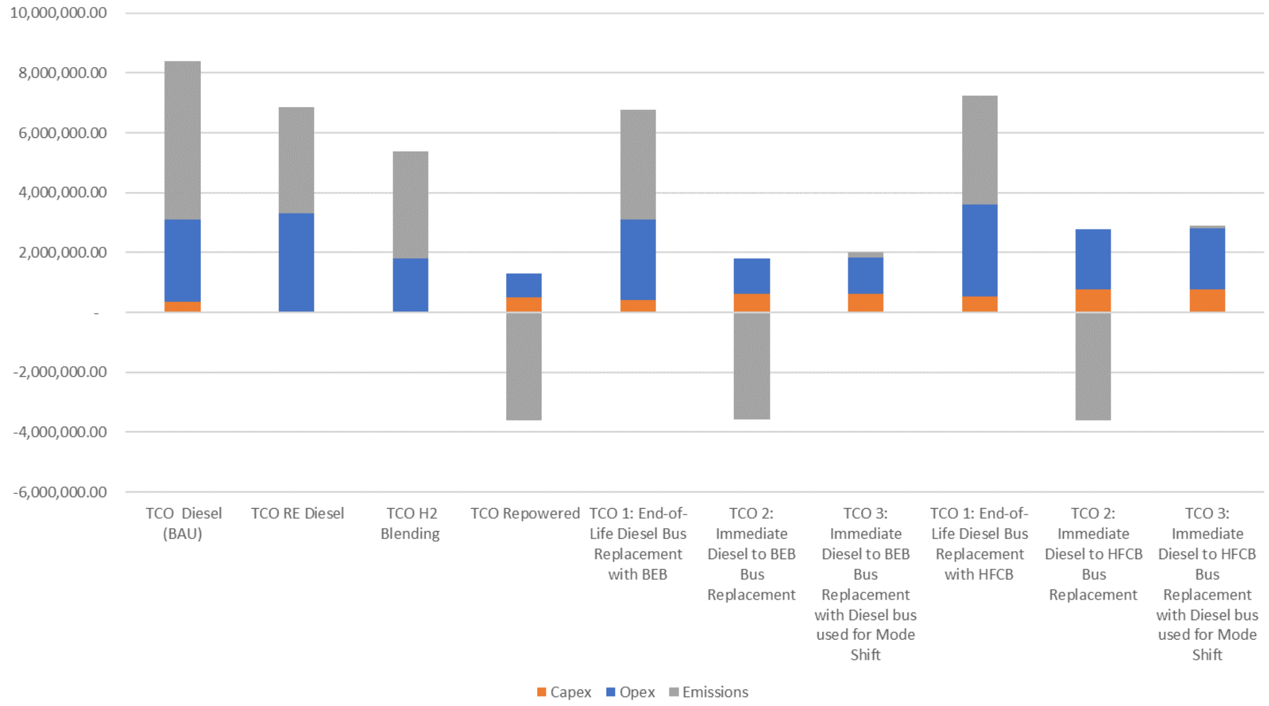


Figure 3.4 shows that CAPEX represents a low proportion of the total cost over a bus's lifecycle. This is because it is a one-time investment at the beginning of the bus's service life, while other cost factors continue to accumulate throughout its operational years. CAPEX costs represent less than 40% of the TCO of BEB and less than one-third of the total TCO of HFCB.

Figure 3.4 also shows that OPEX forms a significant portion of the total cost stack. These expenses continue to accumulate throughout the bus's service life, exerting a substantial impact on the overall TCO. This is especially notable in the diesel (BAU), renewable diesel and hydrogen blending use-cases, where OPEX costs constitute the vast majority of all expenses. However, in the case of BEB and HFCB, OPEX costs represent a smaller proportion of the total cost stack due to their lower energy and maintenance costs relative to conventional diesel buses.

OPEX includes the energy source (diesel, electricity or hydrogen), maintenance, routine servicing and repairs; however, the energy source is the largest component of OPEX. Thus, the most important driver of TCO is fuel cost. This explains why HFCB is more expensive than BEB. It also indicates that without significant reductions in the cost of hydrogen relative to the electricity cost for BEB, HFCB is unlikely to become competitive with BEB on many routes, even with incremental changes in CAPEX for both BEB and HFCB.

The impact of GHG emissions costs is small compared to the CAPEX and OPEX cost components. However, NOx emissions costs, contributing over 90 percent to the total emissions cost, are significant and exceed OPEX costs. Consequently, the emissions' impact is substantial enough to influence the least-cost use-case in various instances. In addition, the cost of emissions is negative in cases where diesel buses are retired immediately. This is because ZEB are used to replace diesel buses, directly reducing total emissions and associated costs. This explains how the TCO including emissions is lower than the TCO excluding emissions for several use-cases.

In summary, NOx costs are significant drivers of the total cost of owning and operating a bus over its lifecycle (TCO). The next highest cost component is OPEX, which drive significant differences in the TCO. Therefore, small changes in CAPEX, due to things such as needing additional depot space for chargers, are unlikely to have a large impact on TCO.

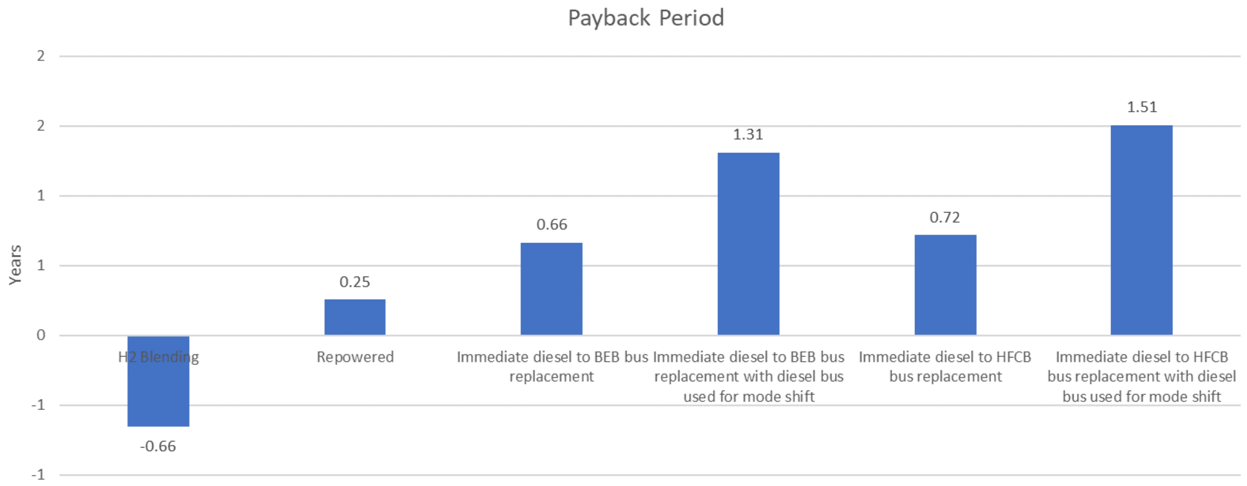
3.5 Payback period

This section explains how the ZEB Cost Model estimates the payback period of various use-cases based on the assumptions listed in section 3.3 The payback period is the number of years required to recover the additional CAPEX of alternatives to diesel (BAU) cost. The payback period analysis is limited to use-cases where diesel buses are replaced immediately, rather than at a later time. This approach allows for a fair comparison of options and enables a clear evaluation of their cost-effectiveness.

The payback period is calculated by dividing the additional capex by the amount of annual savings for each use-case. The additional CAPEX represents the difference between the alternative use-case and diesel (BAU), while the savings are the difference between the annual TCO *including emissions* of the alternative use-case and diesel (BAU).

Figure 3.5 illustrates that H2 blending has an immediate payback, followed by repowered buses relative to other use-cases. This is because repowered buses have lower additional CAPEX, which allows them to recover additional CAPEX quicker. For example, while the TCO for immediate diesel to BEB replacement (BEB:TCO 2) is lower than the TCO of repowered buses, leading to higher annual savings, BEB:TCO 2 also has a significantly higher CAPEX. When this higher Capex is divided by the annual savings, the calculation of payback period for BEB:TCO 2 results in a slower recovery of investment than the repowered buses. Fortunately, for the new BEB, the longer bus life of 20 years means that more savings accumulate over time, resulting in the lower TCO.

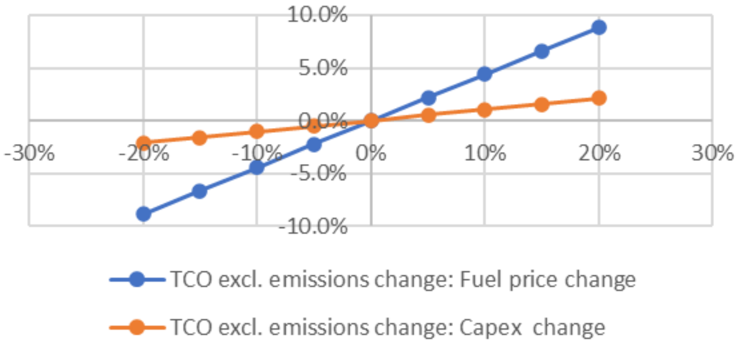
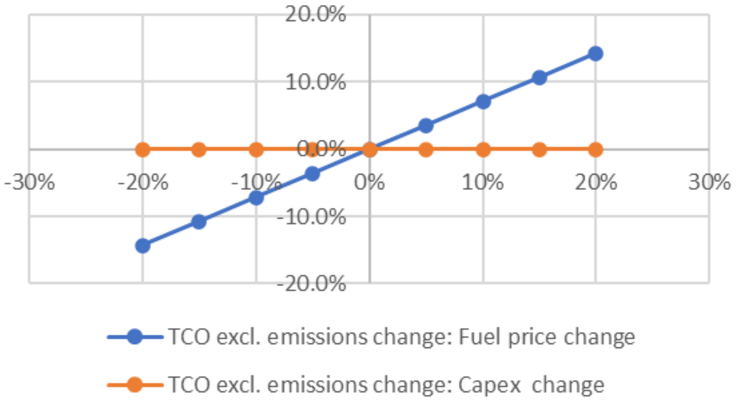
Figure 3.5 Payback period including emissions costs



3.6 Sensitivity analysis

This section provides insight into how changes in the cost of fuels/energy and the cost of a bus affect the TCO excl. emissions for each use-case. Thus, the purpose of this section is to provide the user with context on how key cost drivers impact use-cases differently. Table 3.1 discusses the impact of these variables on the TCO excl. emissions of each use-case, with the impacts shown in Figure 3.6 to Figure 3.11. Note that for all use-cases, except BEB and repowered buses, the energy cost has a higher impact on TCO than the cost of the bus. This is because electricity is relatively cheap compared to diesel or hydrogen on a per kilometre basis.

Table 3.1 Sensitivity analysis

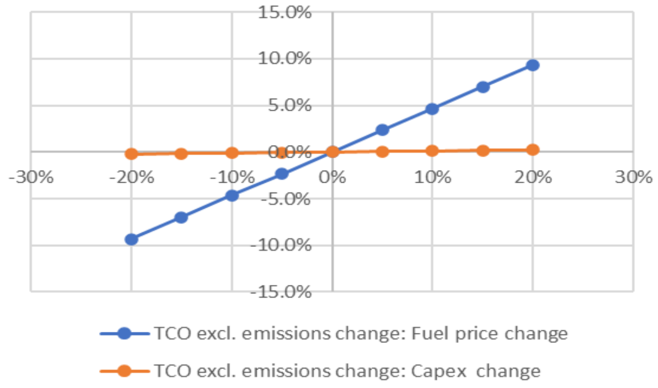
Use-case	Sensitivity analysis
Diesel (BAU)	
The impact of a change in diesel price has a significantly higher effect on the TCO compared to the variation in the cost of a bus. Specifically, a 20% increase in fuel prices would lead to a substantial 8.8% increase in the TCO, whereas the same 20% increase in the cost of the bus would only result in a modest 2% rise in the TCO. This highlights the critical role that fuel prices play in shaping the overall TCO of diesel buses.	**Figure 3.6 Impact of fuel and bus cost on the per km TCO for diesel (BAU)** 
Renewable diesel	
Using renewable diesel implies that there are no additional capital costs since it is assumed to be used on existing diesel buses. Consequently, the cost of the bus itself has no implication on the TCO. However, an increase in the cost of renewable diesel by 20% would result in a significant 14% increase in the TCO. This highlights the significant impact that fuel prices, particularly for renewable diesel, can have on the overall cost of operating and maintaining the buses, even without considering the initial capital investment.	**Figure 3.7 Impact of fuel and bus cost on the per km TCO for renewable diesel** 

Use-case	Sensitivity analysis

Hydrogen blending

In the case of hydrogen blending, the capital cost also has an insignificant impact on the TCO since the cost of the injection system is relatively small. However, an increase in diesel prices by 20% would lead to a notable 9.3% increase in the TCO.

Figure 3.8 **Impact of fuel and bus cost on the per km TCO for hydrogen blending**

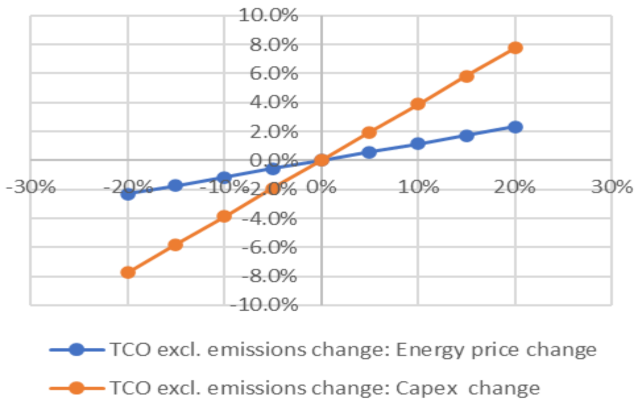


Repowered

In the case of repowered buses, the cost of the bus has a more significant impact on the TCO compared to the cost of electricity. This is because the cost of electricity is substantially lower relative to the cost of diesel. Therefore, even with a 20% increase in electricity prices, the resulting impact on the TCO would be relatively modest, at only 2% higher.

In contrast, a 20% increase in the cost of repowering the bus would lead to a substantial 7.8% higher TCO.

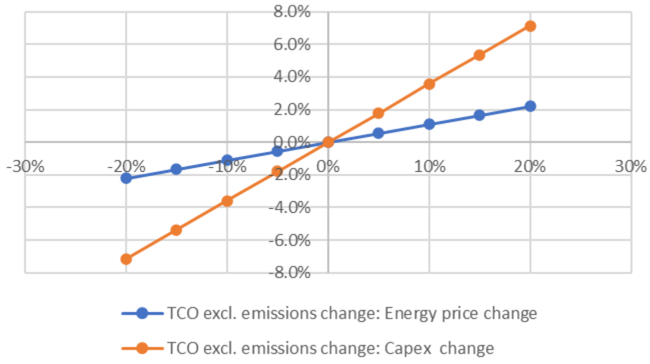
Figure 3.9 **Impact of fuel and bus cost on the per km TCO for repowered buses**

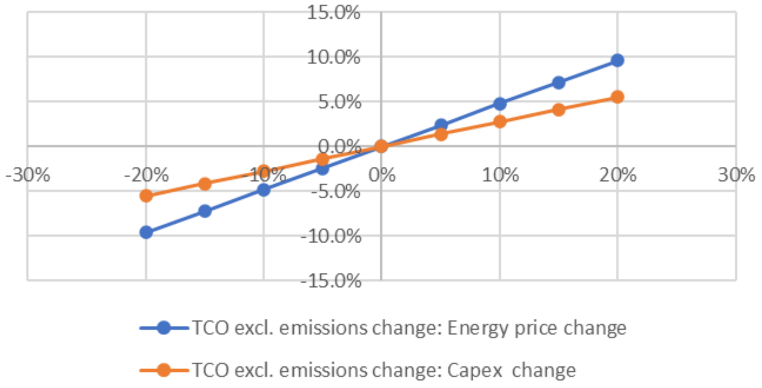


BEB (TCO 2)

Similarly, the TCO of BEB is more responsive to changes in the cost of a bus rather than fluctuations in electricity prices. Specifically, a 20% increase in the price of electricity would result in a modest 2% increase in the TCO, whereas a similar 20% increase in the cost of the bus would lead to a more significant 7% increase in the TCO.

Figure 3.10 **Impact of fuel and bus cost on the per km TCO for BEB (TCO 2)**



Use-case	Sensitivity analysis
HFCB (TCO 2)	
For HFCB, the discrepancy between the impact of fuel and bus costs is smaller compared to other use-cases. A 20% increase in the cost of hydrogen would result in a 9% increase in TCO, while a similar increase in the cost of the bus would lead to approximately a 5.5% increase in TCO. This indicates that both fuel and bus costs play significant roles in determining the overall TCO for HFCB, with fuel costs having a slightly more substantial effect on the TCO compared to the cost of the bus.	**Figure 3.11 Impact of fuel and bus cost on the per km TCO for HFCB (TCO 2)** 

3.7 Model application

The ZEB Cost Model can be used by PTA to make an informed investment decision when choosing the most suitable ZEB technology for their fleet.

One of the key advantages of the ZEB Cost Model is its ability to be tailored to the specific circumstances of a bus route or PTA. Different PTA may have varying operating conditions, capital and energy prices, all of which can significantly impact the overall TCO of each use-case. By customising the tool's parameters, PTA can obtain precise estimates that align with their unique context, ensuring that their investment decisions are relevant and well-informed.

On the model’s Dashboard, users can adjust assumptions in three setting sections:

- general settings
- route settings
- sensitivity settings.

To access and modify the assumptions that are not listed on the Dashboard, users can navigate to the Data sheet in the ZEB Cost Model.

3.7.1 General settings

General settings include parameters that are applicable to all use-cases, as follows.

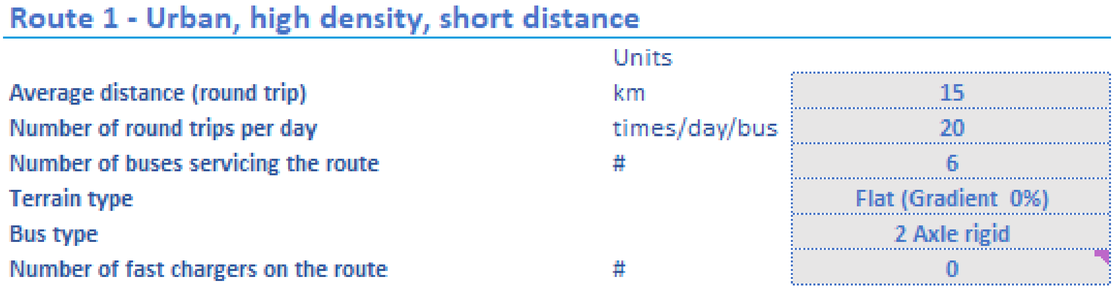
- Average remaining service life of diesel buses that are set to be replaced—NZTA’s *Requirements for Urban Buses* (2022a) specifies that by 2028, over 25% of the national bus fleet will be 10 years old or younger. Given that different PTAs would have different average remaining service lives for diesel buses, users can change the average remaining life of diesel buses across a range of 1 to 12 years. This variable impacts the emissions benefits of early retirement and mode shift.
- Remaining life of repowered buses – the ZEB Cost Model’s default assumption is that the remaining life of repowered buses is the same as the average remaining service life of diesel buses. However, as discussed in section 2.2.5, it may be possible to certify repowered buses as new buses with a 20-year lifespan. This variable allows users to do that.

- Shadow price of CO2e – this parameter allows users to choose between the low, medium and high cost of CO2e emissions provided by Waka Kotahi (2023b), as discussed in section 2.2.3.3.
- New price of NOx – this allows users to see between the impact of the new social cost of NOx emissions calculated in 2023 compared to the significantly lower old estimate as discussed in section 2.2.3.3.
- Road-user charges for electric buses after 2025 – as discussed in section 2.2.4, this switch allows users to turn off road-user charges for BEB in perpetuity instead of allowing the road-user charges exemption for BEB to expire in 2025.

3.7.2 Route settings including mode shift

Users can customise the characteristics of the routes on which diesel buses will be replaced. Figure 3.12 provides an example of route settings on the Dashboard.

Figure 3.12 Route settings on the Dashboard



Route 1 - Urban, high density, short distance

	Units	
Average distance (round trip)	km	15
Number of round trips per day	times/day/bus	20
Number of buses servicing the route	#	6
Terrain type		Flat (Gradient 0%)
Bus type		2 Axle rigid
Number of fast chargers on the route	#	0

Users can assess the TCO and MAC on three types of routes:

- route 1 – urban, high density, short distance
- route 2 – suburban, medium density, medium distance
- route 3 – rural, medium-low density, long distance.

The main difference between these three routes is the expected speed of the bus. On route 1, the average speed is assumed to be around 10 km/h, as the bus moves slowly on congested urban roads with multiple stops. On route 2, a suburban route, the speed is expected to increase to 25 km/h. Lastly, on long-distance rural roads, route 3, the speed is anticipated to be 40 km/h. The speed of the bus significantly impacts power consumption and emissions. Specifically, lower speeds result in higher power consumption and emissions (Waka Kotahi, 2022b).

For each of the three route types, users can customise the following characteristics.

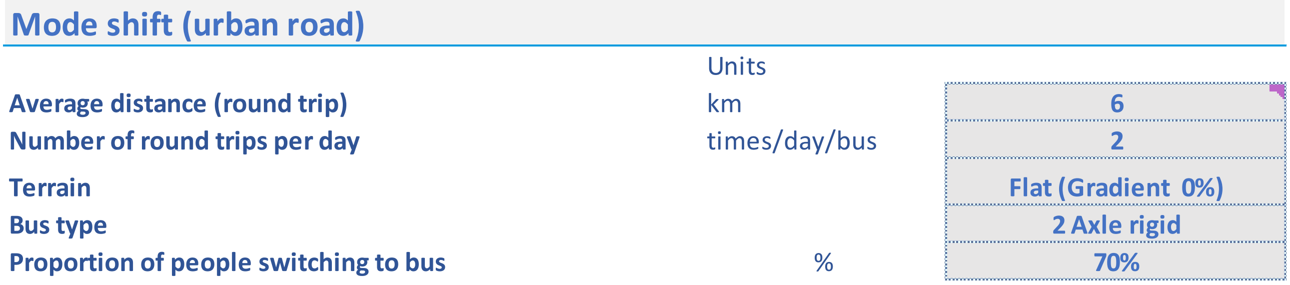
- **Average distance (round trip)**: This is the distance in kilometres that a bus travels on one round trip. It is used to calculate the total annual distance travelled by one bus.
- **Number of round trips per day:** This refers to the number of times a bus operates on a route per day. It is also used to calculate the annual distance travelled by the bus.
- **Number of buses servicing the route:** This indicates the number of buses operating on a specific route. It is used to determine the cost of shared infrastructure, such as the use of fast-charging stations.
- **Terrain type:** Users can choose the terrain type for each route, including flat (0% gradient), undulating (2% gradient) or hilly (6% gradient). The choice of terrain has a significant impact on power consumption and emissions. For instance, fuel consumption on an undulating route is expected to increase by around 67% compared with a flat route, while on a hilly route it is expected to increase by 200% (Waka Kotahi, 2021)

- **Bus type:** Users can select the type of bus used on each route. Users can choose between two-axle rigid, three-axle rigid and three-axle double decker Bus. The size of the bus affects power consumption and emissions, with larger buses consuming more power and emitting more pollutants
- **Number of fast chargers on the route:** If users anticipate using fast chargers on the route, they can specify the number of chargers required. It's important to note that the cost assumptions for the buses are based on the use of a larger battery size, typically between 350kWh and 440kWh,[10] allowing for a range of around 370km (Energy Matters, 2023). However, if a bus operator plans to use fast chargers on a shorter route, the capacity of the battery can be reduced, which would result in a lower cost per bus. In this case, users can adjust the cost of the bus in the Sensitivity section on the Dashboard. Similarly, if the user intends to use BEB on a route that would require operating more than 370km in a day, the use-case should add at least one fast charger to the route to extend the range of the BEB.

For the mode shift scenario, the ZEB Cost Model assumes that the bus will operate during peak hours and predominantly in urban settings with low speeds. Consultation between the steering group and Castalia revealed that there are many potential uses for retained diesel buses by PTAs, or by other parties if PTAs were not to retain them, but they remained in use in New Zealand. However, Castalia and the steering group determined that the ZEB Cost Model would assume that diesel buses with a remaining service life are retained by PTAs and used to expand public transit options and induce mode shift during peak hours on urban roads as this is viewed as the most likely and most efficient use of diesel buses retained by PTAs.

Thus, under the mode shift scenario, it is assumed that the bus will operate on an urban road. However, as shown in Figure 3.13, users can customise average distance, number of round trips per day, number of buses servicing the route, terrain type and bus type, the same as for the other route types. In addition, users can also make an assumption about what percentage of people riding the diesel bus retained for mode shift would have otherwise driven a car.

Figure 3.13 Mode shift settings on the Dashboard



Mode shift (urban road)

	Units	
Average distance (round trip)	km	6
Number of round trips per day	times/day/bus	2
Terrain		Flat (Gradient 0%)
Bus type		2 Axle rigid
Proportion of people switching to bus	%	70%

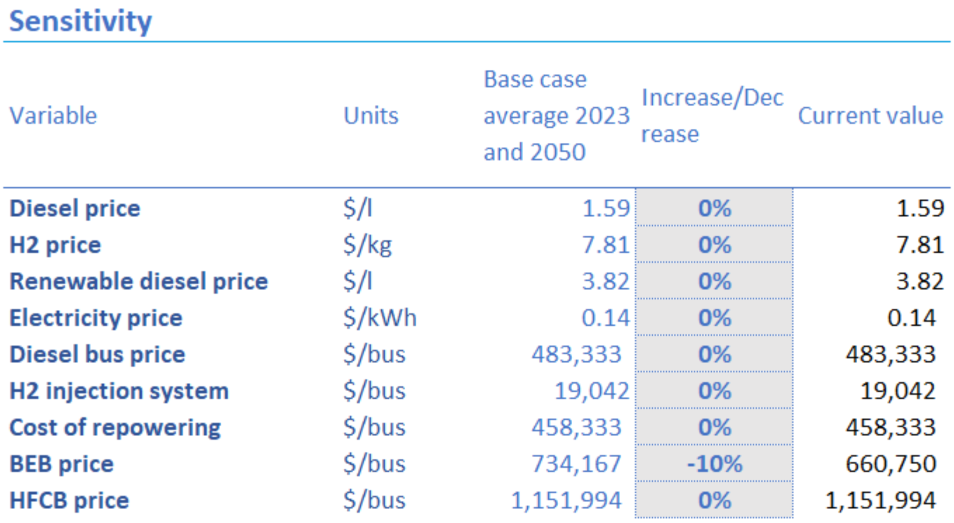
3.7.3 Sensitivity settings

Users also can adjust the cost of energy for different bus technologies and the price of a specific bus technology by increasing or decreasing relevant variables. This can be done through the Sensitivity box on the Dashboard, as illustrated in Figure 3.14.

---

[10] Note that the range is only approximate and highly depends on the outside temperature, driving behavior, and other factors that should be accounted for when estimating the range.

Figure 3.14 Sensitivity analysis on the Dashboard



Sensitivity

Variable	Units	Base case average 2023 and 2050	Increase/Decrease	Current value
Diesel price	$/l	1.59	**0%**	1.59
H2 price	$/kg	7.81	**0%**	7.81
Renewable diesel price	$/l	3.82	**0%**	3.82
Electricity price	$/kWh	0.14	**0%**	0.14
Diesel bus price	$/bus	483,333	**0%**	483,333
H2 injection system	$/bus	19,042	**0%**	19,042
Cost of repowering	$/bus	458,333	**0%**	458,333
BEB price	$/bus	734,167	**-10%**	660,750
HFCB price	$/bus	1,151,994	**0%**	1,151,994

For instance, if users wish to decrease the cost of BEB by 10%, they can input "-10%" in the Increase/Decrease section of the Sensitivity box. This adjustment will result in a reduced cost for all three sizes of BEB. The average cost of these three bus sizes will be displayed in the Current Value section of the Sensitivity box.

3.7.4 Modifying other assumptions

To access and modify the assumptions that are not listed on the Dashboard, users can navigate to the Data sheet in the ZEB Cost Model. Within this sheet, they can find a detailed list of assumptions categorised by relevant parameters, such as bus technology, power cost, emissions, and other factors. Users can update the values of these assumptions based on their own data, research or specific requirements. Appendix A provides a full list of assumptions made in the ZEB Cost Model. These assumptions are up to date based on Castalia’s research and interviews with industry players. However, users are encouraged to update the assumptions with information specific to their circumstances, for example, by inputting a different price for a particular bus that has been offered.

4 Research limitations

Several limitations were encountered during the research phase of this project. These limitations offer opportunities for further research and improvements to enhance the model's robustness and accuracy.

Analysis of embedded emissions is constrained due to limited data availability, especially concerning different types of buses. To improve the analysis, future research should focus on gathering comprehensive data on embedded costs associated with various bus technologies. Expanding this aspect of the model would enable a more holistic evaluation of the environmental impacts and economic feasibility of transitioning to ZEB.

Analysis of the emissions impact of renewable diesel is limited by the lack of comprehensive information on emissions reduction for emissions other than carbon dioxide, such as NOx, PM2.5 and other pollutants. To strengthen the model, it would be beneficial to incorporate more data on the emissions reduction potential of renewable diesel compared to traditional diesel.

Data for estimating maintenance costs for all bus types is limited. Moreover, different operators include different cost components when calculating operations and maintenance costs. As a result, to enhance the accuracy of the analysis, future research should endeavour to obtain actual maintenance cost data from different operators. Collecting data from diverse operators would enable a more comprehensive understanding of maintenance expenses for different ZEB technologies, contributing to a more robust TCO assessment.

To address the limitations mentioned above, opportunities for collaboration and data sharing among various stakeholders, including PTAs, operators, bus manufacturers and research institutions, should be explored. By pooling resources and data, researchers can build a more comprehensive database, enabling more accurate assessments of TCO and emissions reduction potential. Collaboration could also foster standardising data collection methods, leading to more consistent and comparable results across different studies.

In conclusion, while the ZEB Cost Model offers valuable insights into the TCO of different bus use-cases, acknowledging and addressing the research limitations presented here could lead to a more robust and comprehensive analysis. Seizing the opportunities for further research and data collaboration might enhance the model's utility and contribute to the successful and sustainable decarbonisation of public transport in New Zealand.

5 Conclusion

By allowing users to evaluate 10 bus use-cases, the ZEB Cost Model facilitates informed decision-making, aiding PTAs in their commitment to decarbonising their bus fleets and contributing to New Zealand's transition towards sustainable and environmentally responsible public transportation. However, this report does not give definitive answers on which use-case is least cost. Instead, it directs users on how to use the ZEB Cost Model to determine which use-case is least cost based on their specific circumstances.

In the process of making and testing the model, a couple of things became clear.

- The additional emissions from retaining and operating existing diesel buses until the end of their lifespan or for mode shift are greater than the additional emissions from constructing new ZEB earlier.
- The TCO analysis reveals that OPEX costs are the most important driver of TCO for all bus technologies. This emphasises that minor changes in CAPEX are unlikely to exert a substantial impact on TCO. Instead, the most important driver of TCO is energy cost.

While the analysis has provided valuable insights, there are certain limitations that need to be addressed for further improvement. Expanding information on embedded emissions from constructing different bus technologies, improving and standardising information about OPEX costs for different bus technologies, and obtaining comprehensive data on emissions reduction from renewable diesel would enhance the accuracy and comprehensiveness of future analyses. Collaboration and data sharing among PTAs, operators, bus manufacturers and research institutions can overcome these limitations and strengthen the model's reliability. By pooling resources and data, researchers can build a more comprehensive and standardised database, leading to more precise TCO assessments.

Overall, the TCO analysis provides a comprehensive framework for PTAs to make informed investment decisions and navigate the complexities of transitioning to ZEB. By leveraging the insights from this analysis, PTAs can foster a cleaner, greener and more sustainable future for public transportation in New Zealand, promoting environmental stewardship and enhancing the quality of life for its citizens.

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Appendix A Assumptions

A.1 Use-cases

This appendix presents the assumptions made in the ZEB Cost Model related to each of the six use-cases. The assumptions are grouped into:

- capital cost – capital cost is the cost of purchasing a bus, required infrastructure or a technology that reduces emissions
- operations and maintenance cost – the operations and maintenance cost of each bus technology type, excluding the cost of energy
- power consumption – the amount of energy consumed by the bus during its operation
- salvage value – the estimated value of the bus at the end of its useful life, which can be recovered through its sale or disposal
- embedded emissions – the greenhouse gas emissions associated with manufacturing buses
- road-user charges – a fee imposed on vehicles based on their usage of the road network
- operational emissions – the greenhouse gas emissions and other pollutants generated during bus operation.

All values are in New Zealand dollars.

A.1.1 Diesel (BAU)

The diesel (BAU) assumptions are as follows.

Table A.1.1 Diesel bus assumptions

Assumption	Bus type	Unit	Data	Source/Comment
Capital cost	Two-axle rigid	$/bus	350,000	Industry experts
	Three-axle rigid	$/bus	400,000	
	Three-axle double decker	$/bus	700,000	
Operations and maintenance	Two-axle rigid	$/bus/km	0.75	Johnson, et al., 2020
	Three-axle rigid	$/bus/km	0.86	Scaled based on the capital cost
	Three-axle double decker	$/bus/km	1.71	Consultation with industry experts suggests that double decker buses have a significantly higher maintenance cost due to their weight. We do not have an estimate of the increase in maintenance cost. We use a bus purchase price difference to adjust the maintenance cost.
Road-user charge	All buses	$/km	0.3604	Industry experts

Assumption	Bus type	Unit	Data	Source/Comment
Power consumption	Two-axle rigid	l/km	0.45	Industry experts
	Three-axle rigid	l/km	0.45	
	Three-axle double decker	l/km	0.7	
Salvage value	All buses	%	15	Johnson, et al., 2020
Embedded emissions	All buses	kgCO2/ bus	100,000	Lie et al., 2021
Operational emissions	CO	g/km	4.82	Emission levels will vary according to the route, terrain and bus technology. The emissions presented in this table are derived from the assumption of route 1, featuring a flat gradient of 0%, and utilizing a three-axle double decker bus. Waka Kotahi, 2022b
	CO2e	g/km	1345.39	
	VOC	g/km	0.51	
	NOx	g/km	14.03	
	NO2	g/km	1.55	
	PM2.5 E	g/km	0.34	

A.1.2 Renewable diesel (100%) in a conventional diesel engine

The renewable diesel in conventional diesel engine assumptions are as follows.

Table A.1.2 Renewable diesel bus assumptions

Assumption	Bus type	Unit	Data	Source/Comment
Capital cost	Two-axle rigid	$/bus	0	N/A
	Three-axle rigid	$/bus	0	N/A
	Three-axle double decker	$/bus	0	N/A
Operations and maintenance	Two-axle rigid	$/bus/km	0.75	Same as diesel buses
	Three-axle rigid	$/bus/km	0.86	Same as diesel buses
	Three-axle double decker	$/bus/km	1.71	Same as diesel buses
Road-user charge	All buses	$/km	0.3604	Industry experts
Power consumption	Two-axle rigid	l/km	0.45	Same as diesel buses
	Three-axle rigid	l/km	0.45	Same as diesel buses
	Three-axle double decker	l/km	0.7	Same as diesel buses
Salvage value	All buses	%	15	Johnson, et al., 2020
Embedded emissions	All buses	kgCO2/bus	0	N/A

Assumption	Bus type	Unit	Data	Source/Comment
Operational emissions	CO	%	0	No data on the potential reduction
	CO2e	%	63%	Emissions reduction TriMet, 2021
	VOC	%	0	No data on the potential reduction
	NOx	%	0	No data on the potential reduction
	NO2	%	0	No data on the potential reduction
	PM2.5 E	%	0	No data on the potential reduction

A.1.3 Dual fuel blending of hydrogen

The dual fuel blending of hydrogen assumptions are as follows. Note that these assumptions are somewhat uncertain because dual fuel blending is not yet available at a commercial scale.

Table A.1.3 Hydrogen blending in a diesel bus assumptions

Assumption	Bus type	Unit	Data	Source/Comment
Capital cost	Two-axle rigid	$/bus	19,042	HYDI
	Three-axle rigid	$/bus	19,042	
	Three-axle double decker	$/bus	19,042	
Operations and maintenance	Two-axle rigid	$/bus/km	0.75	Same as diesel buses
	Three-axle rigid	$/bus/km	0.86	Same as diesel buses
	Three-axle double decker	$/bus/km	1.71	Same as diesel buses
Road-user charge	All buses	$/km	0.36	Same as diesel buses
Power consumption	Two-axle rigid	l/km	0.396	HYDI
	Three-axle rigid	l/km	0.396	HYDI
	Three-axle double decker Bus	l/km	0.616	HYDI
Salvage value	All buses	%	0	N/A
Embedded emissions	All buses	kgCO2/bus	0	Sunk cost

Assumption	Bus type	Unit	Data	Source/Comment
Operational emissions	CO	%	4%	HYDI
	CO2e	%	-0.2%	HYDI
	VOC	%	0%	HYDI
	NOx	%	0%	HYDI
	NO2	%	-4%	HYDI
	PM2.5 E	%	33%	HYDI

A.1.4 Electric repowered

The electric repowered bus assumptions are as follows.

Table A.1.4 Electric repowered bus assumptions

Assumption	Bus type	Unit	Data	Source/Comment
Capital cost	Two-axle rigid	$/bus	372,500	Industry experts/ Global Bus Ventures
	Three-axle rigid	$/bus	398,500	
	Three-axle double decker Bus	$/bus	500,000	
Battery replacement cost		%	N/A	The model assumes no battery replacement will take place. The bus is expected to operate until the end of its service life, which is estimated to be 12 years or less. Considering the cost-effectiveness, it was determined that replacing the battery would not be a viable option.
Infrastructure cost	Cost of depot charger	$/charger	55,113	Industry experts/ Yutong
	Cost of depot charger installation and depot upgrade	$/charger	65,667	Industry experts/ Yutong
	Cost of fast charger	$/charger	400,000	Industry experts
	Cost of fast charger installation	$/charger	163,677	Scaled based on data from the National Renewable Energy Laboratory relative to the cost of the fast charger
Operations and	Two-axle rigid	$/bus/km	0.49	Hensher et al., 2021; Johnson et al., 2020; Yutong, 2023
	Three-axle rigid	$/bus/km	0.49	

Assumption	Bus type	Unit	Data	Source/Comment
maintenance bus	Three-axle double decker Bus	$/bus/km	0.51	
Road-user charges	All buses	$/km	$0/km up to 2025 $0.36/km after 2025	Electric vehicles are exempt from road-user charges until 31 December 2025. Waka Kotahi, 2023c
Operations and maintenance infrastructure	Depot charger maintenance cost	$/year	0.00	National Renewable Energy Laboratory/ Yutong
	Fast charger maintenance cost	$/year/charger	26,042.40	National Renewable Energy Laboratory
Power consumption	Two-axle rigid	kWh/km	0.976	Industry experts
	Three-axle rigid	kWh/km	0.976	
	Three-axle double decker	kWh/km	1.220	
Salvage value	All buses	%	0	Assumed to be 0
Embedded emissions	All buses	kgCO2/bus	0	Sunk cost
Operational emissions	CO	kg/km	0	Emission levels will vary according to the route, terrain and bus technology. The emissions presented in this table are derived from the assumption of a route 1, flat gradient 0% and two-axle rigid bus. Ministry of Business, Innovation and Employment
	CO2e	kg/km	0.16	
	VOC	kg/km	0	
	NOx	kg/km	0	
	NO2	kg/km	0	
	PM2.5 E	kg/km	0	

A.1.5 New BEB

The new BEB bus assumptions are as follows.

Table A.1.5 New BEB assumptions

Assumption	Bus type	Unit	Data	Source/Comment
Capital cost	Two-axle rigid	$/bus	605,000	Industry experts/ Yutong/ Global Bus Ventures
	Three-axle rigid	$/bus	716,333	Industry experts/ Yutong / Global Bus Ventures
	Three-axle double decker	$/bus	953,333	Industry experts/ Yutong/ Global Bus Ventures

Assumption	Bus type	Unit	Data	Source/Comment
Battery replacement cost	Two-axle rigid 350kWh Three-axle rigid 350kWh Three-axle double decker 440kwh	%	156,000 180,000 235,000	Global Bus Ventures
Battery annual cost reduction	All buses	%	3.8	Yutong/ Environment + Energy Leader, 2021.
Battery replacement year	All buses	year	9	Global Bus Ventures/ Yutong
Infrastructure cost	Cost of depot charger	$/charger	62,335	Yutong/ Global Bus Ventures and other industry experts
	Cost of depot charger installation and depot upgrade	$/charger	70,445	Yutong/ Global Bus Ventures and other industry experts
	Cost of fast charger	$/charger	164,000	Yutong/ Global Bus Ventures and other industry experts
	Cost of fast charger installation	$/charger	180,267	Yutong/ Global Bus Ventures and other industry experts
Operations and maintenance bus	Two-axle rigid	$/bus/km	0.49	Hensher et al., 2021; Johnson et al., 2020; Yutong, 2023
	Three-axle rigid	$/bus/km	0.49	
	Three-axle double decker	$/bus/km	0.51	
Road-user charges	All buses	$/km	$0/km up to 2025 $0.36/km after 2025	Electric vehicles are exempt from road-user charges until 31 December 2025. Waka Kotahi, 2023c
Operations and maintenance infrastructure	Depot charger maintenance cost	$/year	0	National Renewable Energy Laboratory/ Yutong
	Fast charger maintenance cost	$/year/charger	26,042.40	National Renewable Energy Laboratory
Power consumption	Two-axle rigid	kWh/km	0.80	Global Bus Ventures and other industry experts
	Three-axle rigid	kWh/km	0.80	Global Bus Ventures and other industry experts
	Three-axle double decker	kWh/km	1.22	Industry experts
Operational life	All buses	years	20	Yutong

Assumption	Bus type	Unit	Data	Source/Comment
Number of depot chargers needed per bus	All buses	#	1	The baseline assumption in the model is that the number of chargers is on a 1:1 ratio, meaning one charger for each bus, which is the assumption used by National Renewable Energy Laboratory. However, depending on the battery capacity of the bus, it can be adjusted to a 1:0.5 ratio, where one charger is shared between two buses. Yutong
Salvage value	All buses	%	15	Johnson, et al., 2020
Embedded emissions	All buses	kgCO2/bus	147,000	Lie et al., 2021
	Battery	kgCO2/battery	47,000	
Operational emissions	CO	kg/km	0	Emission levels will vary according to the route, terrain and bus technology. The emissions presented in this table are derived from the assumption for route 1, flat gradient 0% and a two-axle rigid bus
	CO2e	kg/km	0.16	
	VOC	kg/km	0	
	NOx	kg/km	0	
	NO2	kg/km	0	
	PM2.5 E	kg/km	0	

A.1.6 New HFCB

The new HFCB assumptions are as follows.

Table A.1.6 New HFCB assumptions

Assumption	Bus type	Unit	Data	Source/Comment
Capital cost	Two-axle rigid	$/bus	820,000	Global Bus Ventures
	Three-axle rigid	$/bus	890,000	Global Bus Ventures
	Three-axle double decker	$/bus	1,195,000	Global Bus Ventures
Operations and maintenance	Two-axle rigid	$/bus/km	0.57	Johnson, et al., 2020; Eudy & Post, 2020; Hensher et al., 2021; Johnson et al., 2020
	Three-axle rigid	$/bus/km	0.57	
	Three-axle double decker	$/bus/km	0.83	
Road-user charge	All buses	$/km	0.36	Industry experts
Power consumption	Two-axle rigid	kg/km	0.076	National Renewable Energy Laboratory
	Three-axle rigid	kg/km	0.076	Apply the same difference as for BEB

Assumption	Bus type	Unit	Data	Source/Comment
	Three-axle double decker	kg/km	0.116	Apply the same difference as for BEB
Salvage value	All buses	%	15	Johnson, et al., 2020
Operational life	All buses	Years	20	For a likewise comparison to other use-cases
Embedded emissions	All buses	kgCO2/bus	105,600	Ballard Power Systems, 2021
Operational emissions	CO	kg/km	0	Assumes use of green hydrogen
	CO2e	kg/km	0	
	VOC	kg/km	0	
	NOx	kg/km	0	
	NO2	kg/km	0	
	PM2.5 E	kg/km	0	