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# Emissions and Total Cost of Ownership for Diesel and Battery Electric Freight Pickup and Delivery Trucks in New Zealand: Implications for Transition

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**Abstract:** Road freight transport contributes to a large portion of greenhouse gas (GHG) emissions. Transitioning diesel to battery electric (BE) trucks is an attractive sustainability solution. To evaluate the BE transition in New Zealand (NZ), this study analysed the life-cycle GHG emissions and total cost of ownership (TCO) of diesel and BE trucks based on real industry data. The freight pickup and delivery (PUD) operations were simulated by a discrete-event simulation (DES) model. Spreadsheet models were constructed for life-cycle assessment (LCA) and TCO for a truck operational lifetime of 10 years (first owner), this being the typical usage of a tier-one freight company in New Zealand (NZ). The whole-of-life emissions from the diesel and BE trucks are 717,641 kg and 62,466 kg $CO_{2e}$, respectively. For the use phase (first owner), the emissions are 686,754 kg and 8714 kg $CO_{2e}$, respectively; i.e., the BE is 1.27% of the diesel truck. The TCO results are 528,124 NZ dollars (NZD) and 529,573 NZD (as of 2022), respectively. The battery price and road user charge are the most sensitive variables for the BE truck. BE truck transitions are explored for freight companies, customers, and the government. For the purchase of BE trucks, the break-even point is about 9.5 years, and straight-line depreciation increases freight costs by 8.3%. Government subsidy options are evaluated. The cost of emission credits on the emissions trading scheme (ETS) is not expected to drive the transition. An integrated model is created for DES freight logistics, LCA emissions, and TCO costs supported by real industry data. This allows a close examination of the transition economics.

**Keywords:** life-cycle assessment (LCA); total cost of ownership (TCO); greenhouse gas (GHG) emissions; battery electric (BE) truck; emission allocation; discrete-event simulation (DES); transition engineering; emissions trading scheme (ETS)



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## 1. Introduction

Decarbonising is necessary to mitigate climate change. The greenhouse gas (GHG) emissions could be reduced from different sectors. In New Zealand, the transport sector is the second major source of GHG emissions, which takes up 19.7% of total GHG emissions [1]. Much of the road, rail, shipping, and aviation freight industry is dependent on diesel and similar fossil fuels. Road transport is the most important mode in New Zealand, accounting for 75.1% of total freight tonne-kilometres. New Zealand plans to reduce freight transport emissions by 35% by 2035 [2]. A possible way to decarbonise this section is to replace diesel trucks. Battery electric (BE) trucks, hydrogen fuel cell (FC) trucks and biofuel trucks are options for reducing GHG emissions. The current analysis focuses on BE trucks as they are an established technology that is already available in New Zealand (NZ), whereas the other options are not yet operational realities. For New Zealand, BE trucks are suitable because most electricity comes from clean energy (approximately 80% renewables), while the costs of hydrogen trucks and biofuel truck development are predicted to be high in New Zealand [3]. Existing electric trucks in the market include Volvo, Mitsubishi, Freightliner, etc.

The potential of BE trucks has been analysed in many countries, such as Switzerland, Finland [4], Italy [5], the United States [6], Canada [7], China [8] and Singapore [9]. New Zealand is encouraging the development of BE trucks, including providing subsidies and exempting some of the road user charges (RUC). Consequently, some freight companies have set up trial routes for BE trucks. However, there are some challenges for different stakeholders.

There are many types of emissions and environmental impacts, but the present study focuses on greenhouse gases, which are measured in carbon dioxide equivalent ($CO_{2e}$). This is a weighted aggregation of various gases, including carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), and fluorinated gases comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3) by taking into account their global-warming potential.

Freight companies are becoming aware of their own responsibilities in this area, spurred on by consumer concerns. Thus, there is a need to develop a method whereby freight models are able to incorporate life-cycle considerations dedicated to New Zealand. These have the potential to be incorporated into new dashboards for both customers and freight company decision-makers. It is well known that BE trucks can greatly reduce emissions in the use phase. However, the emission of the whole life cycle is also important to be understood. The total cost of ownership (TCO) of BE trucks is important for wider sustainability considerations since freight companies need to do due diligence in their investment in this change. The government needs to know the status of BE transition and introduce strategies to support the transition. As will be shown, the matter is finely balanced as the total cost of ownership for a diesel truck and a battery-electric truck are very similar for the first owner.

The objective of the study is to analyse the BE transition in New Zealand. Hence, the life-cycle GHG emissions and TCO of a diesel truck and a BE truck were assessed based on the real case of freight logistics, and then several transition scenarios were evaluated. The freight pickup-and-delivery (PUD) operations were simulated by the discrete-event simulation (DES) method, and life-cycle assessment (LCA) models were developed for both trucks. The area under examination is a tier-one freight company, i.e., a large national carrier that purchases new trucks and retains them for about 10 years. We consider this timeframe the new owner/tier-one operational life. After this period, the trucks are sold into the second-tier freight operations, where they typically have another ten years of life at diminishing tonne-kilometre usage. Focusing on the first owner is important because these are the early adopters, and their investment needs to be sustainable.

## 2. The Literature Review

### 2.1. Life-Cycle Assessment (LCA)

LCA is a methodology to assess the whole life cycle of a product in terms of environmental and economic impacts. All processes related to the product, from cradle to grave, are involved. LCA has been applied to various fields, such as the agriculture [10], construction [11], and production [12], to evaluate environmental impacts. For example, GHG emissions of biofuels and petroleum were compared by applying LCA, involving the processes of feedstock, fuel handling, storage, and transportation for the US distribution infrastructure [13]. It is found that emission reduction is achievable through optimising transportation distances. LCA has been used to analyse the truck life cycle and compare trucks with different prime movers to reduce GHG emissions. TCO is sometimes involved in LCA models. It estimates the direct and indirect costs of the product over its lifespan. The life-cycle emissions and costs of heavy-duty trucks were compared regarding different types of fuels [6] for the United States, and it was found that battery electric trucks had the least total lifetime cost and GHG emissions over diesel, biodiesel, compressed natural gas, and hybrid trucks. An analysis of diesel trucks and BE trucks for Canada's situation showed that the total lifetime cost of BE trucks was higher than diesel trucks while the GHG emissions were reduced [7]. The truck payloads and operating temperatures were considered. The life-cycle GHG emissions for diesel, BE, and hydrogen fuel cell medium-duty urban delivery trucks were compared based on the Singapore situation [9]. The results indicated that hydrogen fuel cell trucks could produce the lowest GHG emissions for the life cycle. The life-cycle GHG emissions and TCO of light-duty and medium-duty diesel trucks, plug-in electric trucks, and battery-swap electric trucks (ETs) were analysed for China [8]. In terms of GHG emissions, light-duty ETs emitted 69% less than light-duty diesel trucks, whereas medium-duty electric trucks emitted 9.8% more than medium-duty diesel trucks. When it comes to TCO, plug-in electric trucks and battery-swap electric trucks had lower and higher costs than light-duty diesel trucks, respectively, while medium-duty electric trucks had lower and higher costs than medium-duty diesel trucks. A multi-region input–output analysis of trucks in the US [14] found that BE trucks consumed and generated the highest energy and GHG emissions. Moreover, the BE truck emissions were different in each region of the US, which was caused by the energy mix of electricity sources.

From the above pieces of literature, the results of life-cycle GHG emissions and TCO of diesel trucks and BE trucks vary in countries. There are several reasons for this. First, there are differences in life-cycle phases, such as the manufacturing and recycling of trucks and batteries in each country. Second, the energy mix of electricity sources is different in countries and regions, and this is especially significant for BE truck emissions. For example, coal is the dominant source of electricity in China [8], gas in Florida and USA [14], and hydropower in New Zealand [15]. Therefore, the GHG emissions from electricity generation vary, which is the most significant part of BE truck emissions. BE trucks also have other environmental issues. For example, there is a water-intensive issue since more cooling water was used for thermoelectric power plants in the US [16]. Third, traffic in regions can affect the performance of diesel trucks and BE trucks [8]. Last, the BE truck type is also a factor for GHG emissions since it relates to energy consumption and utilisation. Related to this, the battery weight detracts appreciably from the payload of BE trucks, so it is complex to determine truck equivalence.

### 2.2. Estimating GHG Emissions

Table 1 shows existing methods to analyse freight $CO_2$e emissions for diesel trucks with transport parameters used to determine $CO_2$e emissions.

**Table 1.** Existing $CO_2$e emissions models.

| Parameters | Study |
|---|---|
| Average speed | [17] |
| Fuel consumption | [18] |
| Fuel consumption and travel distance | [19] |
| Travel distance and time | [20] |
| Speed, distance, and time | [21] |
| Fuel consumption and vehicle parameters | [22] |

The literature provided several examples of emission calculations. A generic urban freight model was proposed to estimate overall freight emissions in a city [21]. Vehicle characters, engine exhaust and travel routes were included in the model. Analytical models were developed to improve the distribution planning and network flow of multimodal transportation by the selection of transportation mode and vehicle type and their impacts on the costs and emissions along the arcs and at transhipping nodes in the network. Models implementation and verification were conducted in the Cplex platform. A mixed integer nonlinear programming model (MINLP) was used to find the best solution [23]. The emissions of heavy-duty diesel trucks were analysed by using multiple transportation data combined with a bottom-up model [24]. The data included truck trajectories, road traffic conditions, and networks. The spatiotemporal distribution pattern was developed from spatial autocorrelation, high/low clustering, and outlier analysis. The road network was integrated with road segments.

However, in stochastic models, fuel consumption is difficult to estimate. The freight industry tends to use the tonne-kilometre method to calculate $CO_2$e emissions. This is also used in regulatory frameworks such as in NZ. Equation (1) indicates $CO_2$e emissions calculated by the tonne-kilometre method.

$$\mathrm{GHG} = \sum_{i=1}^{n}((W_t + W_l(i)) \times D(i)) \times F_c \quad (1)$$

The total emissions are summed by emissions for n trips. Tonne-kilometre for each trip is determined by multiplying the truck weight $(W_t)$ and the truckload for the trip $(W_l(i))$ and trip distance $(D(i))$ for the number $i$ trip. $F_c$ denotes the $CO_2$e intensity factor.

### *2.3. Simulating Freight Transport to Obtain GHG Emissions*

Conventional approaches for simulating freight transport are called vehicle routing problems (VRPs). Freight transport direct emissions can be incorporated into VRP models. A last-mile model was built to evaluate emissions from an electric vehicle fleet [25]. Route distance was optimised by solving the VRP model. A dynamic last-mile delivery model was developed to simulate the loading bays [26]. Fuzzy k-means clustering and a routing algorithm were combined to optimise travel time and distance along with $CO_2$e emissions.

Moreover, there are some other techniques to evaluate GHG emissions. A freight transport agent-based model was developed to evaluate emissions in the supermarket distribution [27]. Several scenarios were simulated to find the best trade-off solution.

A stochastic Monte Carlo method was used to analyse service level, emissions footprint, and delivery cost therein and compared two last-mile delivery operations of direct delivery and mobile depot with tricycles [28]. They collected data from the operator and conducted a field collection by using a Global Positioning System (GPS). They listed a set of Key Performance Indicators to assess the eco-efficiency of Urban Freight Transport operations in environmental and economic categories.

A continuous approximation model using game theory was proposed to improve the design of a seaport–dry-port network and considered the carbon emissions [29]. The model also involved multimodal transport by rail and road. In addition, the carbon emission cost, social costs, accidents, and noise were taken into account.

A three-objective linear programming model was developed to optimise fresh food distribution networks, including operating cost, carbon footprint, and delivery time goals [30]. Time and cost functions were obtained from a market survey a. Transport time functions consist of vehicle loading and unloading times. The emission functions were from the Ecoinvent database v.2.0. Both the direct and indirect GHG emissions were included. The fuel consumption during the producing transportation activities accounted for the direct emissions. In comparison, the indirect emissions were from the manufacturing, the disposal of the vehicles, and the related infrastructures. GHG emissions were calculated based on transported weight and travelled km.

### *2.4. Discrete Event Simulation*

The challenge of modelling freight operations is that in a general freight situation, the consignments are highly variable from day to day. This variability extends to the customer address, the number of items, types of items (palletised, drums, cartons, loose goods, etc.), mass, and volume. It is then necessary from the modelling perspective to reduce a large set of addresses into clusters or suburbs. The simulation model is supposed to cater to real operations and provide corresponding results.

DES simulation benefits practical problem-solving for the following reasons. First, DES can be used to deal with a large number of stochastic values. Second, DES can mimic real operations, so it is able to support decision-making. Third, DES is traceable, comprehensible, and plausible for stakeholders [31]. Last, DES is capable of solving complex transportation systems. It has been combined with Geographic Information System (GIS) to simulate PUD operations. Furthermore, it allows various levels of complexity in modelling representation. For example, models may be relatively complex intersection-based models that represent route segments [32] or simple two-tier architecture models [33], depending on the purposes of the simulation.

However, modelling the architecture of DES is challenging due to the intricate information required and mimicking of practical operations. This can cause a long modelling period [34]. A Minimum Viable Model method was proposed to mitigate these issues [31].

### *2.5. Gaps in Analysis of Diesel and Electric Trucks*

There are several gaps in the existing literature. First, LCA for heavy electric trucks is absent in New Zealand from both environmental and economic perspectives [3]. Due to differences in truck production and the electricity energy mix in countries, LCA needs to be conducted for the New Zealand case specifically. Second, analyses in the existing literature assume overly simple truck operation cases where it is difficult to know how representative they are of actual industrial operations. There is a need to be explicit about the assumptions of truck operations, such as tonne-kilometre and kilometre inputs. Third, the structure of life-cycle emissions and costs could be more comprehensive to better understand the sustainability implications.

## 3. Methodology

### *3.1. Overview*

The boundary of the LCA model is defined in Figure 1. Main phases are the manufacturing and supply phase, the use phase and the end-of-life phase. GHG emissions and TCO of the diesel truck and the electric truck are considered in each stage. In accordance with the Greenhouse Gas Protocol, which defines scopes of GHG emissions, scope 1 incorporates direct GHG emissions produced by the company; scope 2 covers GHG emissions from the generation of purchased electricity, and scope 3 includes indirect GHG emissions [35]. Freight companies only need to undertake scope 1 emissions for carbon accounting.

In the manufacturing and supply phase, the diesel truck, the BE truck and the batteries were assumed to be produced and assembled in China based on the current New Zealand market and the investigated company business. The trucks were operated in New Zealand in the use phase. The fuel well-to-tank (WTT) supply is from the crude oil refinery. Electricity is generated in New Zealand mostly from renewable energy. In the end-of-life phase, the trucks and batteries are assumed to be shipped to the recycling industries in China.

### *3.2. Truck Specifications*

The situation under examination was a tier-one freight company in New Zealand, and the analysis models this context. The diesel truck in the analysis represents a typical urban PUD truck operated by the company. The BE truck was selected from the supplier [36]. The largest available BE PUD truck was selected, with a volume capacity of 48 $m^{3,}$ which was identical to the diesel truck. However, with freight, both volume and consignment weight are limits on consolidation. While the trucks have the same volume capacity, their payload capacity is different: 13.38 t for diesel vs. 8t for BE. This mismatch arises because the diesel truck is built heavier than the BE truck: Body weight is 4.37 t for diesel vs. 2.632 t for BE. Nonetheless, field observations suggest that in practice, the volume limit is the more important one, rather than the mass, for PUD. Hence, the two trucks are functionally comparable, at least for a volume-limited PUD environment. Truck specifications are presented in Table 2.

The focus of this study is a first-tier freight company that operates with high freight volumes and a preference for using trucks for 10 years before selling them to downstream second-tier freight operators. The truck life vehicle kilometres travelled are between 160,000 km and 320,000 km [7]. Hence, a conservative lifetime of 10 years was assumed based on this information and the estimated total travelled distance.

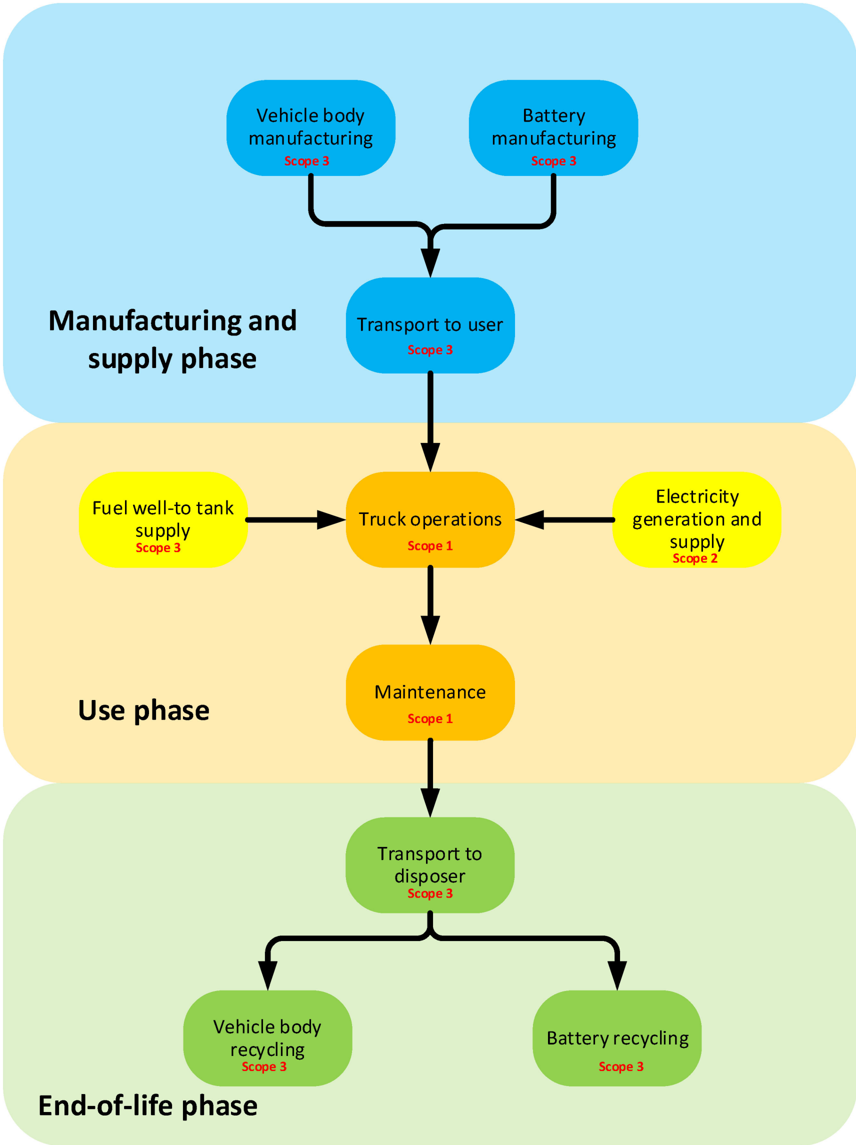


**Figure 1.** System boundary of LCA model.

**Table 2.** Truck specifications.

| | Diesel Truck | BE Truck [36] |
|---|---|---|
| Payload (t) | 13.38 | 8 |
| Tare weight (t) | 4.37 | 4 |
| Body weight (t) | 4.37 | 2.632 ^ |
| Gross weight (t) | 17.75 | 12 |
| Volume capacity ($m^3$) | 48 | 48 |
| Truck lifetime (year) | 10 * | 10 * |
| Battery weight (t) | - | 1.368 ^ |
| Battery capacity (kWh) | - | 120 |
| Battery type | - | Li-ion |
| Battery lifetime (year) | - | 5 * |
| Number of batteries for lifetime | - | 2 ^ |
| Electricity consumption (kwh/tkm) | - | 0.042 |
| Diesel efficiency (km/L) | 1.8 | - |
| Open road truck speed (km/h) | 56.140 ^ | 56.140 ^ |
| Urban road truck speed (km/h) | 23.279 ^ | 23.279 ^ |

* Assumed value, ^ calculated value.

The mean diesel truck efficiency is 2.7 km/L in New Zealand [37]. However, during city operations, pickup and delivery (PUD) trucks often experience idling periods due to frequent freight loading and unloading as well as traffic stops. This idling period results in a decrease in diesel engine efficiency to approximately 20% of the efficiency recorded during highway operations [38]. The truck idling time is about 40% of the total operating time. Freight company data indicates that a more realistic diesel efficiency is 1.8 km/L, and this forms the basis of the current analysis.

Truck speeds were obtained from GPS data. Acceleration speed, deceleration speed, and the 0 km/h speed for stops on the road were considered in the analysis [32]. The ratio of battery weight to capacity was 11.4 kg/kWh [39]. The battery life was assumed to be 5 years [40], this being the extent of the warranty period. Batteries in electric cars tend to last longer, but trucks have a higher utilisation, and their owners are sensitive to degraded range performance.

## *3.3. DES Simulation*

### 3.3.1. Logistics Data

Industry data were obtained under permission from the partner organisation under a confidential agreement via Callaghan Innovation New Zealand grant MAIN1901/PROP-69059-FELLOW-MAIN, and under ethical approval HEC 2020/65/LR-PS from the University of Canterbury, New Zealand. One year of operational data were available for the route under examination.

### 3.3.2. Model Architecture

A DES model was constructed for the use phase of the truck operations with stochasticity in operations. An intersection-based DES model was created in Arena for the route comprising Harewood, Airport, Papanui, etc. (see Figure 2). This model can accommodate random truck routes for a sequence of consignment addresses with the driver's route decision. Freight consignments with stochastic weight, volume, and numbers were delivered to suburbs in an area by a specific truck. Tables 3 and 4 present consignment parameters and consignment numbers for suburbs. The model development process can be found in [32]. The pickup consignments were considered the same as the delivery consignments. A freight consolidation module was included to implement stochastic truckloads. The model was based on one year of real data from the industry, which included consignment details (weight, volume, address). Raw data are not presented here for reasons of commercial confidentiality.

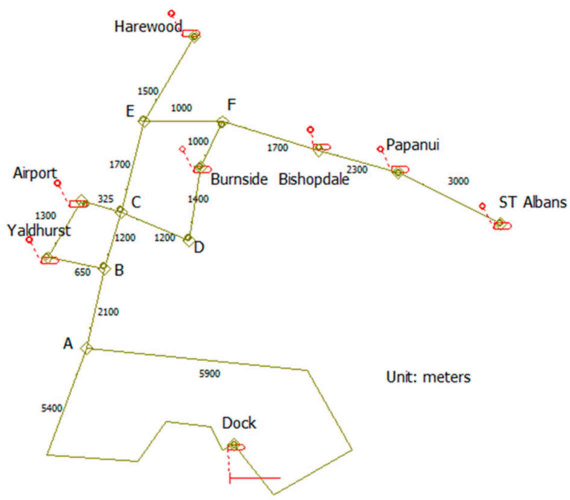


**Figure 2.** Intersection-based freight model. Image adapted from [32].

**Table 3.** Consignment parameters.

| Parameters | Values |
| --- | --- |
| Consignment weight (kg) | 0.999 + LOGNORMAL(533, $1.64 \times 10^3$) |
| Consignment volume ($m^3$) | −0.001 + WEIBULL(1.24, 0.89) |

**Table 4.** Consignment numbers for suburbs.

| Suburbs | Consignment Numbers |
| --- | --- |
| Airport | POISSON (1.03) |
| Bishopdale | POISSON (0.973) |
| Burnside | POISSON (1.34) |
| Harewood | POISSON (0.981) |
| Papanui | POISSON (7.21) |
| ST Albans | POISSON (0.441) |
| Yaldhurst | POISSON (0.697) |

## *3.4. LCA*

### 3.4.1. Life-Cycle GHG Emission Analysis

The LCA model was developed using a spreadsheet. Table 5 summarises emission factors in each LCA stage for diesel trucks and BE trucks. For the use phase, factors were obtained from NZ sources as indicated.

**Table 5.** GHG emission factors for each phase.

| | Diesel Trucks | BE Trucks | Source |
| --- | --- | --- | --- |
| Body manufacturing emissions (kg $CO_{2e}$/kg) | 8.180 | 8.180 | [39] |
| Battery manufacturing emissions (kg $CO_{2e}$/kWh) | – | 150 | [41–44] |
| Tailpipe emissions (kg $CO_{2e}$/tkm) | 0.390 | 0.004 ^ | [45] |
| Emission factor for purchased grid-average electricity (kg $CO_{2e}$/kWh) | – | 0.101 | [45] |
| Body recycling emissions (kg $CO_{2e}$/kg) | −1.390 | −1.390 | [39] |
| Battery recycling emissions (kg $CO_{2e}$/kWh) | – | −20 | [41–44] |

^ Calculated value.

Negative values are the carbon credits gained from the activities. The maintenance emissions were obtained from the GREET model version 2021, developed by Argonne National Laboratory.

The fuel cycle was included in the model. Factors for fuel WTT emission calculation are shown in Table 6.

**Table 6.** Factors for fuel WTT emission calculation.

| | Diesel Truck | Source |
| --- | --- | --- |
| Energy consumption for diesel (MJ/kg) | 42.9 | [46] |
| Diesel density (kg/L) | 0.83 | [47] |
| Diesel WTT GHGs (kg $CO_{2e}$/kJ) | 0.018 | [48] |

The trucks and batteries were assumed to be transported from China, so the shipping emissions were added to the model. The shipping emission factor was sourced from the NZ database, and the distance from Shanghai to Auckland was defined, see Table 7.

**Table 7.** Factors for shipping emission calculation.

| | Diesel Truck | BE Truck | Source |
|---|---|---|---|
| Shipping emission factor ($kg\ CO_{2e}/tkm$) | 0.012 | 0.012 | [45] |
| Shipping distance between China and New Zealand (km) | 11,579 | 11,579 | [49] |

3.4.2. TCO Analysis

The TCO analysis incorporates costs over the lifetime of trucks. It includes the initial cost, the annual use cost and the end-of-life cost, see Figure 3.

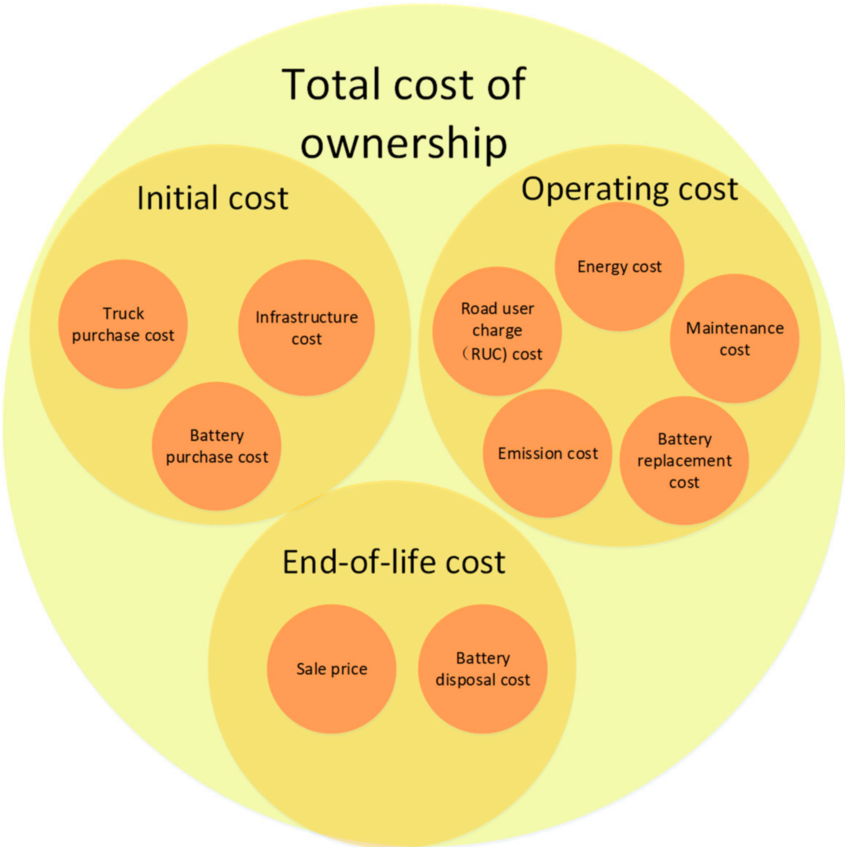


**Figure 3.** TCO composition.

Table 8 indicates cost parameters for diesel and BE trucks for the optimistic case, the base case and the pessimistic case based on literature and company estimation. The base case describes the expected value, while the optimistic case and the pessimistic case represent extreme situations. Optimistic is defined as when all the underpinning factors simultaneously take favourable outcomes, and pessimistic as them all taking unfavourable values. However, in aggregating these estimates from multiple sources, it is not always clear how the original sources have defined this. For example, some sources provide a 'minimum' and 'maximum' value, whereas, for diesel prices, the estimates were based on historical values. Generally, the sources do not state standard deviations. These various sources of data have been aggregated in the table.

**Table 8.** Cost parameters.

| | Optimistic | Base | Pessimistic | Source |
|---|---|---|---|---|
| Diesel price ($/L) | 2.450 | 2.660 | 2.990 | [50] |
| Electricity price ($/kWh) | 0.150 | 0.185 | 0.209 | [51] |
| BE truck battery price per unit ($/kWh) | 452 | 546 | 780 | [52] |
| Battery overhead cost factor | 1.15 | 1.3 | 1.5 | [53] |
| Diesel truck maintenance cost ($/km) | 0.150 | 0.180 | 0.200 | Commercial estimation |
| BE truck maintenance cost ($/km) | 0.080 | 0.10 | 0.120 | Commercial estimation |
| Road user charge (RUC) for diesel truck ($/km) | 0.340 | 0.434 | 0.630 | [54] |
| Road user charge for BE truck ($/km) | 0 | 0.434 | 0.630 | [54] |
| Diesel truck purchase cost ($) | 186,134 | 195,519 | 209,597 | [46] |
| BE truck purchase cost ($) | 234,623 | 258,086 | 281,548 | [16] |
| Gun charger cost for one truck ($) | 34,000 | 37,650 | 40,000 | Commercial estimation |
| Diesel truck value rate after 10 years age | 0.370 | 0.350 | 0.300 | [55] |
| BE truck value rate after 10 years age | 0.260 | 0.250 | 0.210 | [55] |
| BE truck battery dispose cost ($/kg) | 6.160 | 6.190 | 8.670 | [56] |

The trucks were assumed to be brand new in the market. A gun charger was selected rather than a battery-swapping facility because the gun charger is considerably cheaper. PUD trucks can be sufficiently charged during the night. The gun charger can serve two BE trucks, so the above gun charger cost is for one BE truck. The annual cost factors were applied in accordance with the New Zealand situation. The batteries were assumed to be recycled in China. Battery end-of-life cost consists of collection and transport cost, removal cost, disassembly cost and recycling cost [56]. The base case and the optimistic were considered to use the hydrometallurgical recycling method, whereas the pessimistic case applied the direct recycling method. The company prefers to use trucks for 10 years. The average age of freight trucks is 23 years in 2020 in New Zealand [57]. Therefore, the trucks can be placed on the market after the 10-year age.

The total cost of ownership model was developed using a spreadsheet.

The applied GHG emissions price was obtained from New Zealand Climate Change Commission [58]; see Table 9.

**Table 9.** Emission price forecast. Trajectory A is adapted from [58]. Trajectory B was derived retrospectively based on the transition analysis presented later in the paper.

| | Emission Price ($/t $CO_{2e}$) for Trajectory A | Emission Price ($/t $CO_{2e}$) for Trajectory B |
|---|---|---|
| 2022 | 76.883 | 220 |
| 2023 | 87.123 | 240 |
| 2024 | 97.362 | 260 |
| 2025 | 107.602 | 280 |
| 2026 | 117.842 | 300 |
| 2027 | 128.081 | 320 |
| 2028 | 138.321 | 340 |
| 2029 | 148.560 | 360 |
| 2030 | 158.800 | 380 |
| 2031 | 163.564 | 400 |

## 4. Results

### *4.1. DES Simulation Results for Route*

The simulation in Arena® was performed by 248 replications representing operational days in 2022. The results are shown in Table 10.

**Table 10.** DES results.

| | Diesel Truck | Electric Truck |
|---|---|---|
| Total km per year | 15,489 | 18,437 |
| Total tkm per year | 161,355 | 162,465 |
| Fuel consumption per year (L) | 8605 | - |
| Electricity consumption per year (kWh) | - | 6824 |

Tonne-kilometre results were used to calculate energy consumption and then evaluate GHG emissions. Tonne-kilometre is endorsed by the NZ government for the purpose of carbon accounting.

### *4.2. Life-Cycle GHG Emissions*

GHG emissions for each stage were calculated by inputting truck specifications and simulation results using spreadsheets. The emission composition is shown in Table 11.

**Table 11.** Emission composition.

| | GHGs Category | Diesel Truck | BE Truck |
|---|---|---|---|
| Manufacturing | Vehicle body manufacturing (kg $CO_{2e}$) | 35,747 | 21,530 |
| | Battery manufacturing (kg $CO_{2e}$) | - | 36,000 |
| Supply chain | International shipping of truck (kg $CO_{2e}$) | 607 | 760 |
| | International shipping of battery (kg $CO_{2e}$) | - | 380 |
| Use phase (first owner—10 years) | Fuel TTW (direct) (kg $CO_{2e}$) | 629,284 | - |
| | Electricity (kg $CO_{2e}$) | 0 | 6960 |
| | Maintenance (kg $CO_{2e}$) | 2317 | 1754 |
| | Fuel WTT (kg $CO_{2e}$) | 55,153 | 0 |
| | Subtotals for use phase | 686,754 | 8714 |
| End of life | Vehicle body recycling (kg $CO_{2e}$) | −6074 | −3658 |
| | Transport truck to recycling country (kg $CO_{2e}$) | 528 | 662 |
| | Transport battery to recycling country (kg $CO_{2e}$) | - | 331 |
| | Battery recycling (kg $CO_{2e}$) | - | −2400 |
| Total life-cycle $CO_{2e}$ emissions (kg $CO_{2e}$) | | 717,641 | 62,466 |

Electrical energy mix for New Zealand is dominated by hydroelectric. This results in small electricity emissions in the use phase.

### *4.3. Total Cost of Ownership for Tier-One Freight Company*

Table 12 indicates the TCO composition.

**Table 12.** TCO composition. Financial currency is the New Zealand dollar (NZD).

| | Diesel Optimistic ($c_{1,d}$) | Diesel Base Case ($c_{2,d}$) | Diesel Pessimistic ($c_{3,d}$) | $c_{mean,d}$ | $c_{std,d}$ | BE Optimistic ($c_{1,BE}$) | BE Base Case ($c_{2,BE}$) | BE Pessimistic ($c_{3,BE}$) | $c_{mean,BE}$ | $c_{std,BE}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Initial cost ($) | 186,134 | 195,519 | 209,597 | 196,301 | 3910 | 330,999 | 380,912 | 461,948 | 386,099 | 21,825 |
| Operating cost ($) | 363,759 | 401,037 | 462,891 | 405,133 | 16,522 | 87,368 | 196,247 | 268,992 | 190,224 | 30,271 |
| End-of-life cost ($) | −68,870 | −68,432 | −62,879 | −67,579 | 998 | −44,148 | −47,586 | −35,404 | −44,982 | 1457 |
| Total cost ($) | 481,024 | 528,124 | 609,609 | 533,855 | 21,431 | 374,219 | 529,573 | 695,536 | 531,341 | 53,553 |

For the diesel truck, the operating cost is greater than the initial cost in all cases. In comparison, the initial cost is much higher than the initial cost in all BE truck cases.

As the optimistic and pessimistic values are not related to standard deviations, PERT is applicable rather than statistical analysis, see Equations (2) and (3) [59].

$$c_{mean} = \frac{1}{6}(c_1 + 4c_2 + c_3) \quad (2)$$

$$c_{std} = \frac{1}{6}(c_3 - c_1) \quad (3)$$

Sensitivity analysis was conducted with Palisade @Risk version 8.3.2 to determine regression coefficients.

Figures 4 and 5 show that for the diesel truck, the variables that most affect the TCO are diesel price and road user charges, while battery price unit and road user charge are the most sensitive variables for the BE truck.

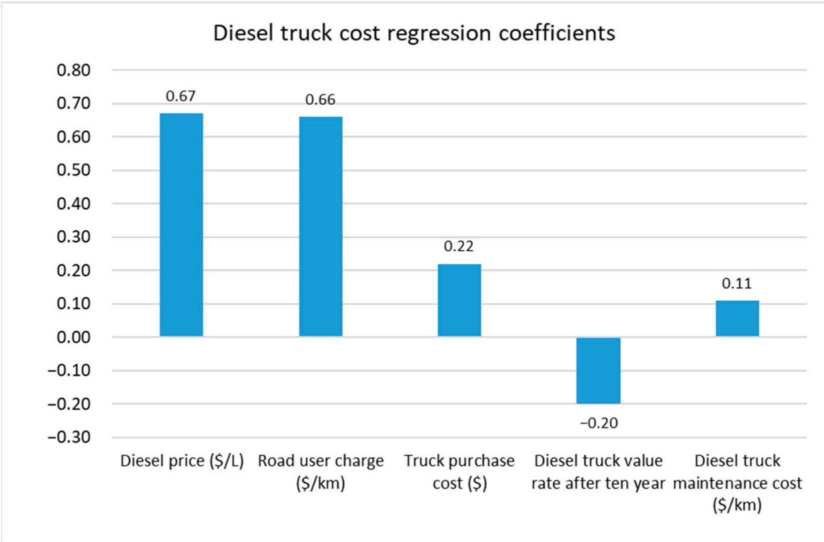


**Figure 4.** Diesel truck cost regression coefficients.

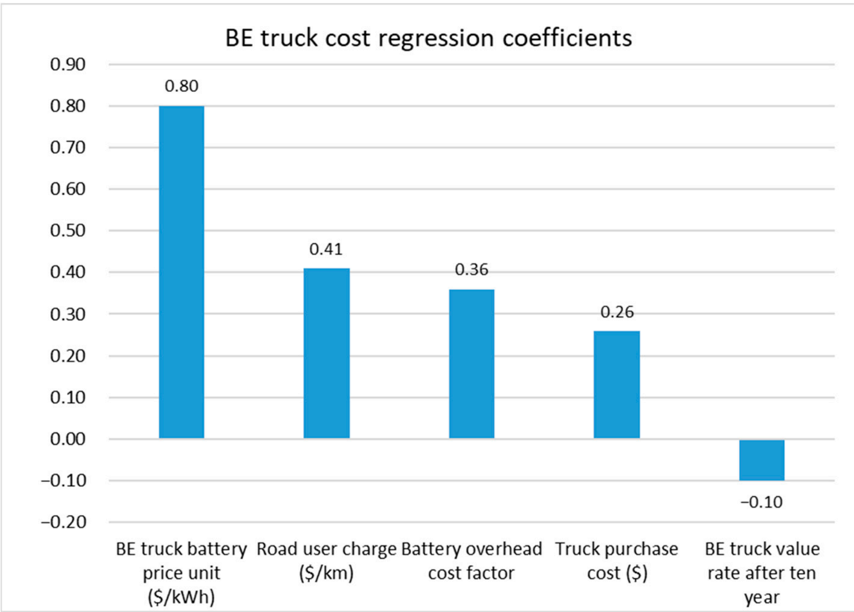


**Figure 5.** BE truck cost regression coefficients.

### 4.4. Mean Emission and Cost Units

Emission and cost factors for the diesel truck and the BE truck are obtained averaged over a 10-year life, see Table 13.

**Table 13.** Emission and cost units for the diesel truck and the BE truck.

| | Diesel Truck | BE Truck |
|---|---|---|
| Life-cycle GHG emissions per tkm(kg/tkm) | 0.445 | 0.038 |
| Optimistic case truck operational cost per tkm ($/tkm) | 0.298 | 0.230 |
| Base case truck operational cost per tkm ($/tkm) | 0.327 | 0.326 |
| Pessimistic case truck operational cost per tkm ($/tkm) | 0.378 | 0.428 |
| Optimistic case truck operational cost per consignment unit ($/kg) | 0.030 | 0.024 |
| Base case truck operational cost per consignment unit ($/kg) | 0.033 | 0.034 |
| Pessimistic case truck operational cost consignment unit tkm ($/kg) | 0.039 | 0.044 |

The life-cycle GHG emission unit indicates the BE truck is competitive for freight customers regarding sustainability while the cost metrics are unexceptional.

### 4.5. Emission Allocation to Freight Customers

There is another issue for diesel trucks regarding the emission cost. Most freight consignments are consolidated on trucks which are known as less-than-truckload (LCL) transport. Freight companies may transfer the use phase emissions to their customers; hence a need to obtain a fair emission allocation method.

The allocated emissions for customers could be calculated by the following methods. The cooperative game theory (CGT) has been used to solve the pollution routing problem and evaluate the emission allocation [19]. Three scenarios were compared, including a vehicle routing problem, a transhipment network flow model, and a model mixed with the travelling salesman problem and the network flow model. The Shapley value was used as a benchmark for GHG contribution. EN 16,258 is established by European Standard and suggests that emissions should be allocated proportionally. In compliance with EN 16258, there are several existing approaches for allocating emissions to consignments, including Egalitarian allocation, Distance-based allocation, payload-based allocation combination allocation, and performance-based allocation (tonne-kilometre) [22].

The Star method is a widely applied distance-based allocation method. It is also known as a dedicated distance proportional allocation method in compliance with the equal profit method, the CEN EN16258 standard, and the Greenhouse gas protocol [60]. The norm prescribes that the travel distance can be either direct distances (bird flight) or road travelled distances. Direct distances have been proved fairer than travelled distances since the consignment sequence is excluded by direct distances [61]. Moreover, the great circle distance is suggested rather than the shortest feasible distance from the perspective of customer geographic coordinates. The Star method was proposed to allocate emissions [62]; see Equation (4).

$$E_i = \frac{e_i}{\sum_{i \in N} e_i} e_n \quad i \in N \tag{4}$$

For $n$ consignments, individually allocated emissions $(E_i)$ is calculated by the total emissions $e_n$ and the proportion of the stand-alone emissions $e_i$. This method is more perceptive for all stakeholders [62]. It has been applied with a stochastic simulation [60].

The cooperative game theory examines the interaction of coalitions when all payoffs are applicable. It focuses on the game between coalitions of players rather than between individuals and decides how to allocate payoffs. The most common method is the Shapley value, as Equation (5) shows.

$$E_i = \sum\nolimits_{s \subseteq \mathrm{N(i)}} \frac{|S|!(n - |S| - 1)!}{n!} m_i(S) \quad i \in N \quad 1 \leq N \leq n \quad S \subsetneqq N \tag{5}$$

where $m_i(S)$ indicates the marginal emissions for the number $i$ shipment. $S$ is the collation of all shipments.

The Star method is simpler and more easily understood. The Star method is the best allocation method in terms of stability, consistency, and computation time [62]. In comparison, the Shapley value presents the average contribution for each player, but the method is complicated in practice [62,63]. The Star method is widely used due to its simplicity and fairness.

Based on the simulation model, GHG emissions were allocated to customers by the Star method; see Table 14.

**Table 14.** Emission allocation results.

| Destination Suburb | Consignment Weight (kg) | Tonne-Kilometer Proportion | Allocated Emissions (kg $CO_{2e}$) | Allocated Emission Cost (2022 Trajectory A) ($) | Allocated Emission Cost (2022 Trajectory B) ($) |
|---|---|---|---|---|---|
| Christchurch airport | 500 | 11.434% | 8.494 | 1.39 | 3.40 |
| Bishopdale | 899 | 31.498% | 23.400 | 1.80 | 5.15 |
| Burnside | 48 | 1.451% | 1.078 | 0.08 | 0.24 |
| Papanui | 1200 | 49.426% | 36.719 | 2.82 | 8.08 |
| Backhaul pickup in Yaldhurst | 284 | 6.191% | 4.599 | 0.35 | 1.01 |
| Total | 2931 | 100% | 74.290 | 6.45 | 17.87 |

By using diesel trucks, freight customers are allocated GHG emissions in accordance with EN 16258. However, customers will not need to undertake this part of emissions when electric trucks are used since they have almost zero emissions in the use phase. Application of the emission allocation plan may help freight customers understand sustainable goals and encourage them to adopt low-carbon changes.

## 5. Discussion

### *5.1. Lifetime Predictions*

Cumulative costs and GHG emissions for both the diesel truck and the BE truck used by the tier-one freight company are presented in Figures 6 and 7.

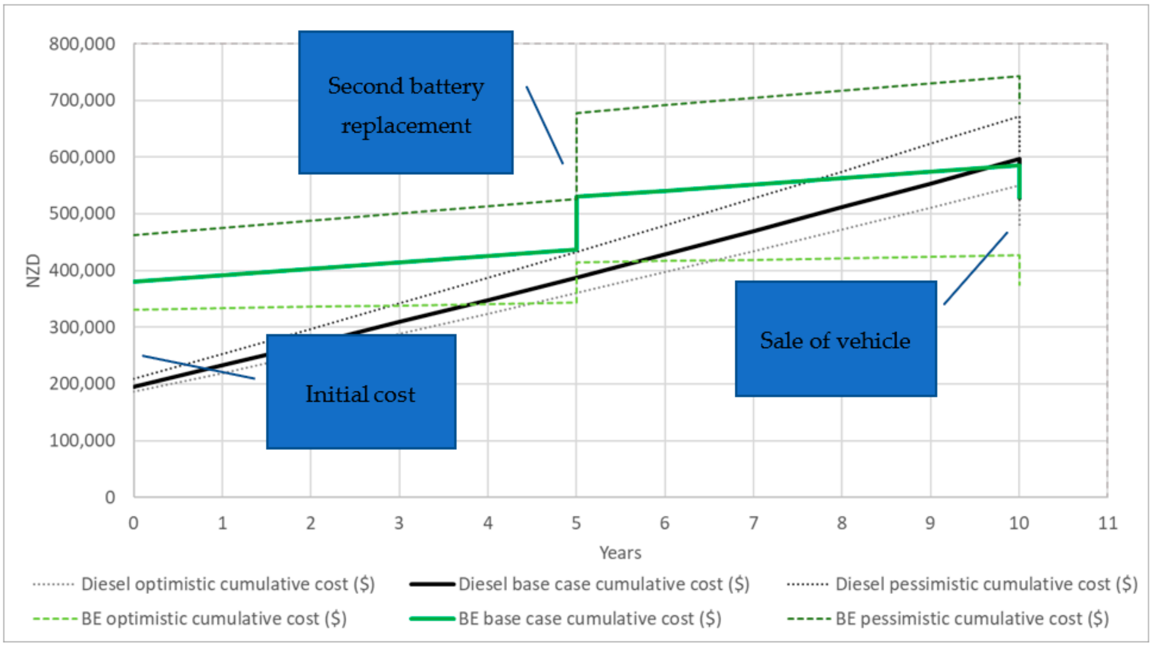


**Figure 6.** Cumulative costs for all cases.

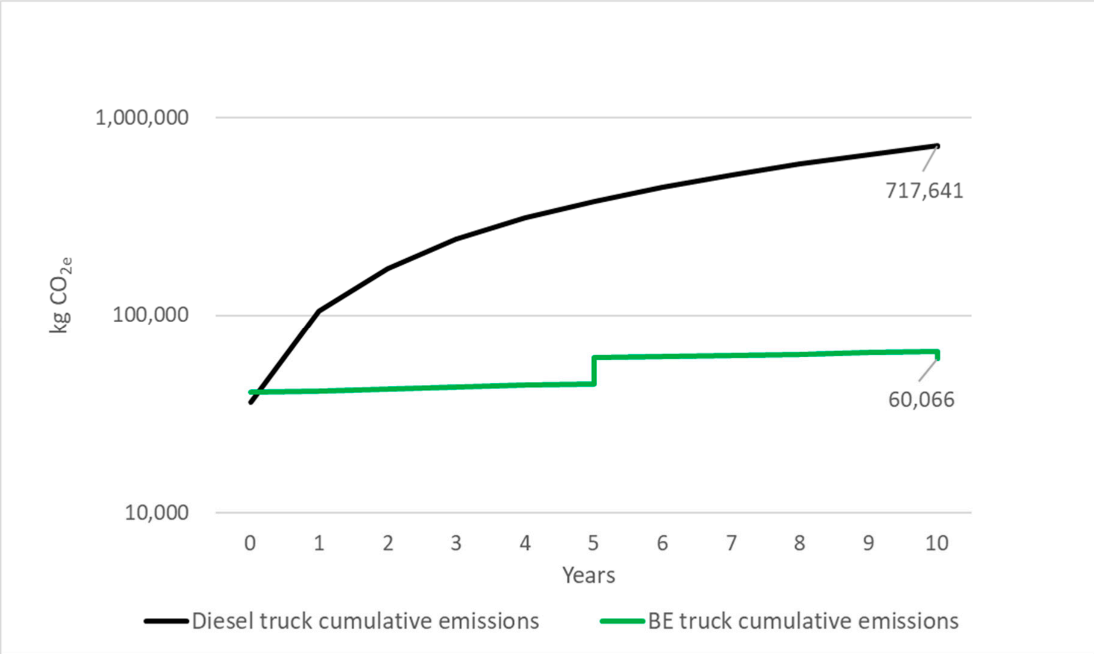


**Figure 7.** Cumulative GHG emissions.

The TCO of diesel and BE trucks is about the same at 10 years, at least for the base cases. What this indicates is that the cost structures do not strongly support the transition to BE PUD freight. The main variables for the diesel truck and the BE truck are the truck purchase cost, the energy cost, and the battery cost. All analyses assume present values.

The optimistic and pessimistic results are for assuming that all parameters simultaneously take optimistic or pessimistic values. While this might not be very likely in a system that is statistically random, in practice, the correlation of these parameters is unknown. Hence, the results shown here represent conservative assumptions.

A break-even point is where the total cost of a diesel truck equals the total costs of a BE truck in this study. This metric provides crucial insights into the relative profitability of these two types of trucks for a freight company, enabling informed decisions to be made about fleet replenishment. For the BE truck, under extremely optimistic assumptions, the break-even period is 4 years (which is perhaps commercially acceptable). The pessimistic extreme is that BE does not break even at all but rather has a TCO of $167k more than the base-case diesel at 10 years.

The main benefit of the BE truck is reduced carbon production. The cost of this carbon is included in the TCO model. Thus, there is a potential brand value in running electric trucks, even if the economics are not compelling.

The model developed here can readily be adjusted to different operations. Take a growth scenario where the PUD area expands with the increase of the business. For example, assume a 1.5 times increase in the annual travelled distance and the tonne-kilometres, hence 23,234 km and 242,032 tkm for the diesel truck and 27,656 km and 243,698 tkm for the BE truck. The results of this scenario are shown in Figures 8 and 9.

The results show that the BE trucks are both economically and environmentally more competitive than the diesel truck for a larger PUD area, with the break-even point shifting forward to 4.5 years. Hence, sustainability (emissions and financial cost) depends on precise operational parameters.

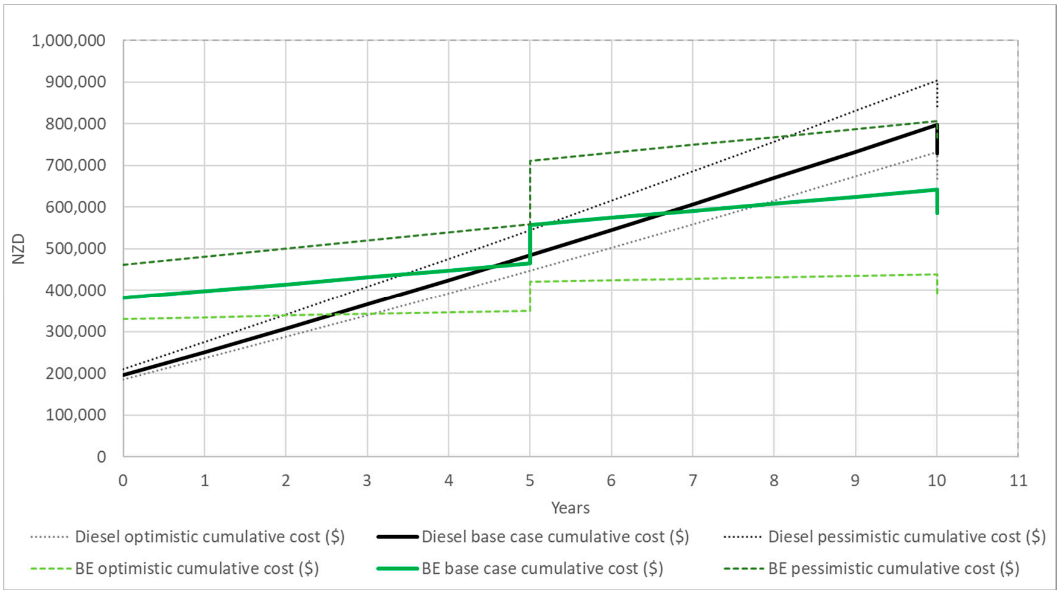


**Figure 8.** Cumulative costs for larger distances.

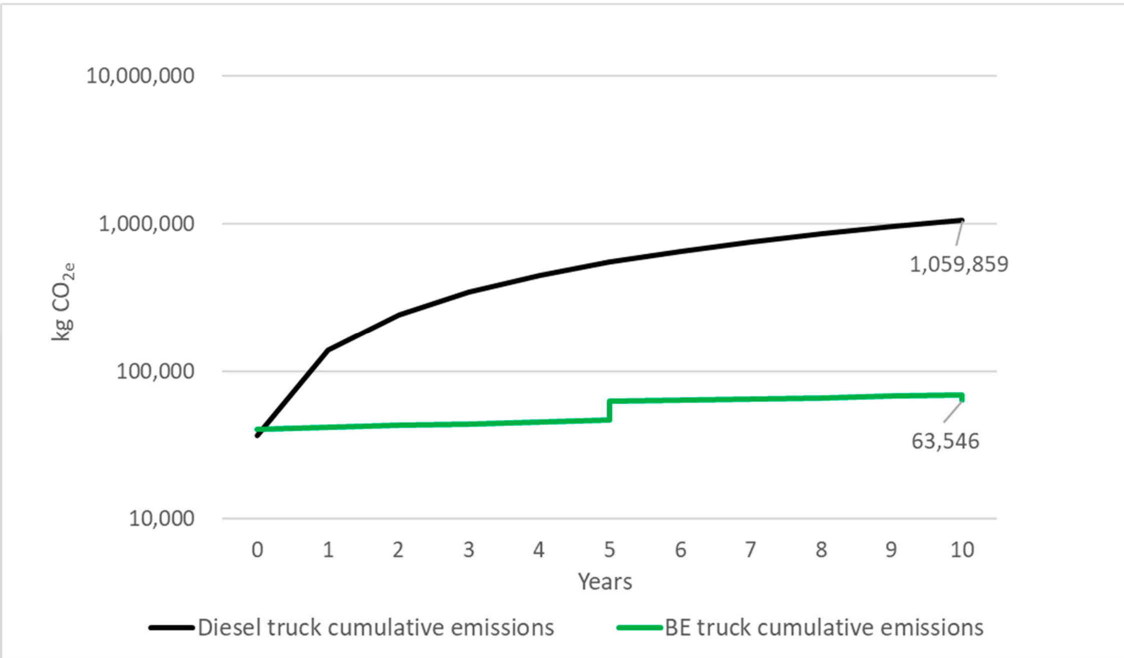


**Figure 9.** Cumulative GHG emissions for larger distances.

### *5.2. Transitioningfreight to Lower GHG Emissions*

Figure 7 shows that the development of the BE truck in New Zealand could significantly reduce GHG emissions in the use phase, which emits 1.27% of the GHG emissions of the diesel truck for the whole life cycle. The main reason is that most of the electricity in New Zealand is generated from renewable energy. However, manufacturing BE trucks and batteries could cause more GHG emissions than diesel trucks. In other words, countries that manufacture BE trucks and batteries will produce more GHG emissions. As NZ does not have a truck or battery manufacturing industry, this is not its problem in terms of the international agreements, but nonetheless, the emissions do affect the world climate—this is the well-known problem of translocation of emissions.

The present study examines the new vehicle purchasing decision by comparing a new diesel versus a new BE truck. The TCO for diesel and BE trucks are very similar according to the present analysis, and there is no compelling free-market economic reason to make the switch. However, the initial capital investment is much higher for the BE. Hence, it is interesting to examine the question of how to transition from an existing diesel fleet to something more environmentally friendly. That is a difficult problem because an existing diesel truck still has many more potential miles that it can serve at no further capital cost. A number of hypothetical scenarios can be anticipated and examined with the model.

#### 5.2.1. Scenario 1: Status Quo with Purchase of Carbon Credits

The company stays with current diesel PUD trucks, and there are no implications for capital spending. Company purchases emission credits for Scope 1 diesel usage (0.390 kg $CO_{2e}$/tkm [45]). The cost to the customer for emission price (2022 Trajectory A) is $0.03/tkm.

The cost of this is economically irrelevant. For example, for a typical consignment of 500 kg to Christchurch Airport on the round under examination, this would mean an additional cost of $0.65 for the GHG emissions.

If this scenario continued for ten years, then under Trajectory A carbon pricing, this cost would eventually be $1.39, and under the more aggressive pricing regime of Trajectory B, it would be $3.40.

The Trajectory A costs are insignificant and not worth establishing more precisely or specifically invoicing to the customer. They could instead be included in the charge-out rate.

However, the line-haul (long-distance city-to-city freight) component may be different. While the present study does not examine line haul in any detail, it may be approximated as follows: assume 500 kg over 1000 km entirely by line-haul truck (0.105 kg $CO_{2e}$/tkm [45]); hence, the result is 50.25 kg $CO_{2e}$. Then, for Trajectory A, the carbon cost is $3.86 in 2022 and $8.21 in 2032. This also may not be significant to warrant specific invoicing.

We conclude that the NZ emissions trading scheme is unlikely to materially sway a movement to BE trucks, not with the NZ Climate Commission's forecasted carbon price (Trajectory A) nor even with our much more aggressively priced Trajectory B.

#### 5.2.2. Scenario 2: Freight Company Depreciate Transition Costs to Customers

In this scenario, freight companies gradually abandon current diesel trucks at the end of ten years, sell them overseas to a jurisdiction without GHG carbon accounting requirements, and purchase new BE trucks. Assuming no government subsidy, this capital investment is depreciated back to customers, causing an increase in the freight cost.

We assume a freight company needs to expand/replace a truck in its fleet. If it purchases a BE rather than a diesel vehicle, then the initial cost differential with straight-line depreciation over 10 years is $18,539/yr. For the route under examination, a truck does 161,355 tkm/yr based on the simulation results; hence, the additional cost to the customer is about $0.12/tkm.

For a typical consignment of 500 kg to Christchurch Airport on the round under examination, this would mean an additional cost of $2.50, assuming the star method is applied for depreciation. Compared to the usual freight cost (1.45 $/tkm [64]), this represents an 8.3% increase. This is an appreciable increase and would put up prices of foods and consumer goods, with implications for national economics, cost of living, and inflation.

#### 5.2.3. Scenario 3: Government Subsidy on BE Truck Purchase and Battery

The nominal analysis (Figure 6) shows a break-even point of about 9.5 years. This is unattractive and may hinder the transition. For most commercial organisations, a typical break-even period is 2–3 years. Figure 10 presents the proportion of costs in each phase for the diesel truck and the BE truck. The initial cost of the BE truck is considerably greater than the diesel truck. If this cost could be reduced, the TCO would be improved for BE trucks. A possible mechanism is government subsidy. There are many ways this might be obtained. One is reducing the initial cost of a BE truck to the same as a diesel truck, i.e., $185,392.

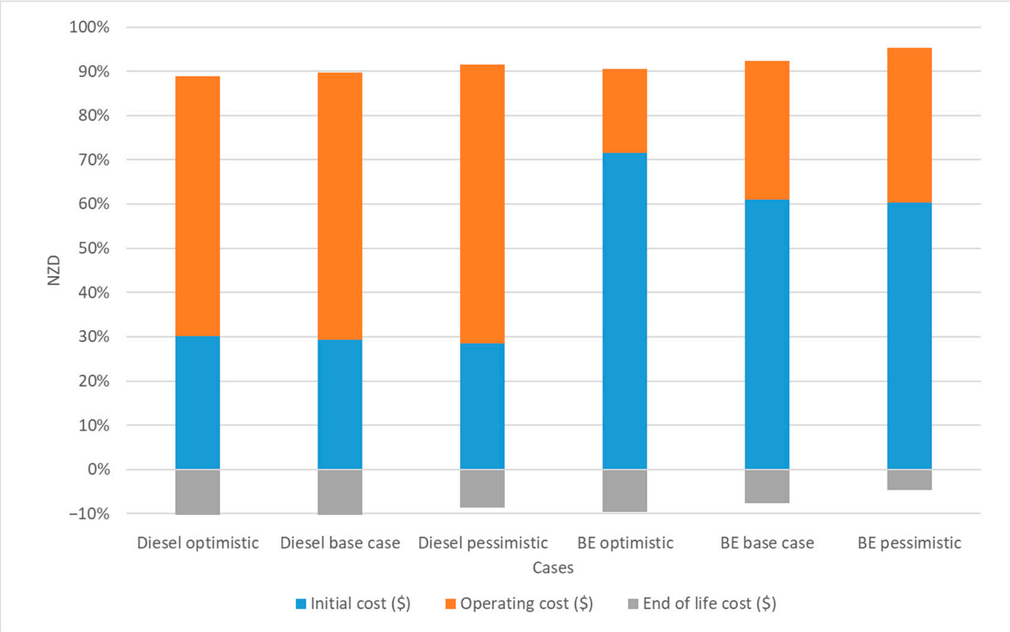


**Figure 10.** Proportion of costs.

It is probably unreasonable to expect the state to subsidise trucking to this extent, given the many other demands on the fiscus, and a period of 4–5 years might be more reasonable. This would require a subsidy of $60,000 per BE truck purchased. See Figure 11 for TCO for this scenario. The total number of medium trucks in NZ is 77,252 [1]; hence, the total cost to the state would be $0.464 billion.

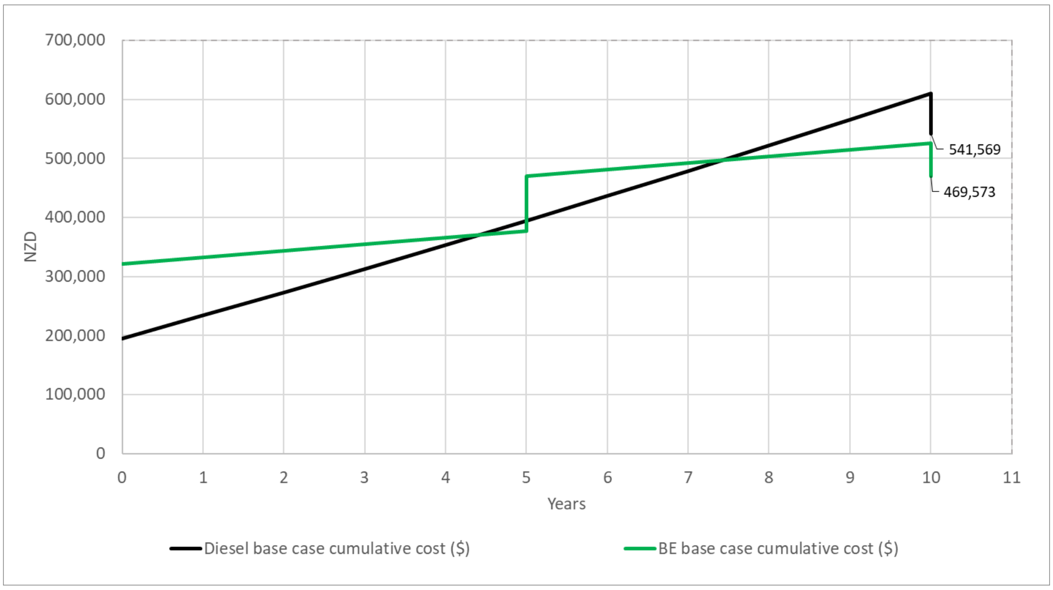


**Figure 11.** Cumulative costs with government subsidy.

5.2.4. Scenario 4: Government Interventions

New Zealand desires to reduce its carbon emissions, and freight makes up a large component thereof [2], so there may be political will to assist the transition. In this case, the question is what might be performed to facilitate the move away from diesel and towards BE trucks. A number of possibilities stand out. One government intervention could be increasing the GHG emission price. In examining these, we assume that the BE TCO needs to be 80% of the diesel TCO at 10 years.

A much higher cost of GHG emissions could also drive change. The difficulty with this approach is that the cost of GHG emissions is not directly controlled by the NZ government but rather through an emissions trading scheme (ETS). The government has control over the number of carbon units supplied to the market (cap). Price control settings are, therefore, via supply. For example, scarcity could be used to drive the price of carbon upwards. The government already plans to decrease the number of units available from 17.6 NZU million in 2024 to 13.5 NZU million in 2027, which relates to the initial assumption in our model [58].

An aggressive carbon price, the assumptions of which are shown in Trajectory B Table 8., would drive the TCO of the BE truck to about 80% of the diesel truck, and the break-even occurs in the fifth year, see Figure 12.

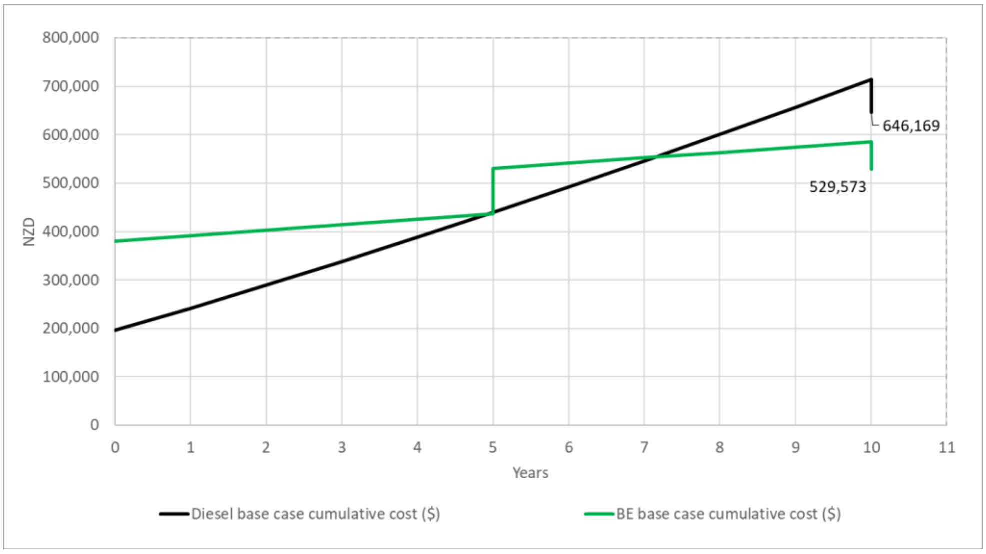


**Figure 12.** Cumulative costs with aggressive GHG emission price.

Another possible invention is to adjust RUC for both trucks. Assuming that RUC for medium diesel trucks is raised to 1.5 times the current value and RUC for BE trucks is completely exempted. The cumulative costs are shown in Figure 13. In this scenario, it also costs 20% less to run an electric truck than a diesel truck.

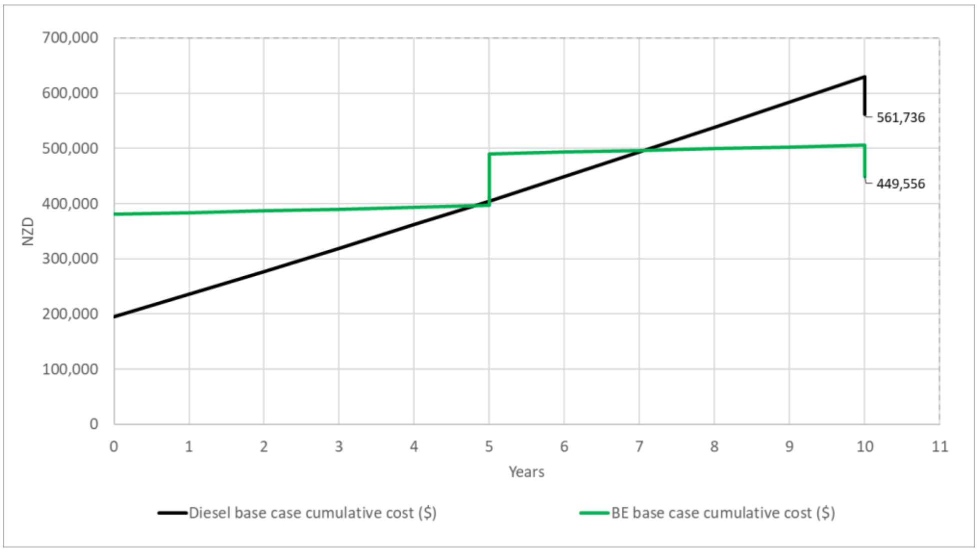


**Figure 13.** Cumulative costs with RUC adjustment.

The effect of this increase in the cost of GHG emissions and RUC would increase the cost of freight, as shown in Scenario 1. This cost would likely be passed on to consumers and, therefore, affect the economic activities of the whole country, i.e., cost of living increases, with attendant problems of inflation and potential political disaffection.

A further government invention could be increasing the diesel tax. It may have the same effect as the examples above. Nevertheless, this invention is sweeping since it would affect a wide range of diesel vehicles. Simultaneous application of multiple scenarios is possible.

As the above scenarios show, the transition from diesel to battery electric trucks is not straightforward. From a free market perspective—which tends to be the approach taken by NZ governments—the economics are not compelling for freight companies.

There are other possible ways to reduce the TCO of BE trucks. One way could be improving battery lifetime. In the analysis, the BE truck battery lifetime was assumed to be 5 years. If the battery life could be enhanced to 10 years, which means the truck only needs one battery for the first owner's use thereof, the cost of battery replacement would be reduced. New Zealand has to wait for the change since there is no local battery production line. In addition, early selling of diesel trucks would involve selling existing trucks while they still have life and buying BE trucks instead. However, there are two problems with this. First, there is no particular economic value for the freight company. Second, it translocates the emissions elsewhere (assuming the truck is still in use), so the worldwide GHG emissions are not reduced. The trucks may have residual service life beyond the 10-year period assumed for the tier-one company. In addition, if the trucks are sold to a second-tier user, there may be a slightly higher $CO_{2e}$ emission during the use phase compared to the primary user considered in this study.

### *5.3. Limitations and Future Work*

There are also other emissions and fine particles that are of potential concern. Air pollutant emissions can be another index, including carbon monoxide (CO), nitrogen oxides ($NO_X$), PM10, PM2.5, sulfur oxides ($SO_X$), and volatile organic compounds (VOC). According to Sen et al.'s study, air pollutant emissions from a diesel truck is about twice that from a BE truck for the entire life cycle [6]. Some of the fuels also have high sulphur content, particularly in shipping, which is a concern. There are also less commonly recognised effects, such as dust from tyre wear, oil leakage, plastic waste from packaging, etc.

The trucks may have residual service life beyond the 10-year period assumed for the tier-one company. In addition, if the trucks are sold to a second-tier user, there may be a slightly higher $CO_{2e}$ emission during the use phase compared to the primary user considered in this study. Several factors, such as the tailpipe emission factor and the diesel price, are for the New Zealand case, so if the models developed in this study were to be applied to other contexts, it would be necessary to account for relevant local factors.

## 6. Conclusions

This study examines the life-cycle GHG emissions and TCO for a diesel truck and a BE truck based on a real urban freight case in New Zealand. The study found that the total emissions over the lifespan of the diesel truck and the BE truck were 717,641 kg and 62,466 kg of $CO_{2e}$, respectively. During the use phase, the emissions were 686,754 kg and 8714 kg of $CO_{2e}$ for the diesel and BE trucks, respectively, meaning that the BE truck emitted only 1.27% of the emissions produced by the diesel truck. With 2022 data, the TCO analysis revealed that the diesel truck incurred costs of 528,124 NZD, whereas the BE truck's costs were slightly higher, totalling 529,573 NZD. The sensitivity analysis showed that the price of batteries and the road user charge were the most important variables affecting the TCO of the BE truck.

Consequently, the study reveals that the present situation is not favourable for freight companies to transition into BE trucks due to the higher initial costs, even though BE trucks are a more environmentally sustainable option.

There are some recommendations for future work. First, some factors could be considered as time-varying factors, such as the diesel price. Second, it is suggested that different classes of trucks be analysed under specific company operations to gain a more comprehensive understanding of their energy use and emissions. Last, additional BE truck transition scenarios could be investigated.

This work is original in the provision of integration of DES models and LCA models, use of real operations data, applicability to the New Zealand situation, and consideration of various sustainability transition scenarios.

**Author Contributions:** Conceptualization, Z.L. and D.P.; methodology, Z.L. and D.P.; software, Z.L.; validation, Z.L. and D.P.; formal analysis, Z.L.; investigation, Z.L.; resources, Z.L. and D.P.; data curation, Z.L.; writing—original draft preparation, Z.L.; writing—review and editing, Z.L., D.P., and Y.Z.; visualisation, Z.L. and D.P.; supervision, D.P. and Y.Z.; project administration, Z.L. and D.P.; funding acquisition, Z.L. and D.P. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** This study was conducted in accordance with the Declaration of Helsinki and approved by the University of Canterbury Human Ethics Committee (protocol code HEC 2020/65/LR-PS, 9 November 2020).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Not applicable.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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