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Techno-economic Assessment of Battery Electric Heavy Vehicles

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TABLE OF CONTENTS

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EXECUTIVE SUMMARY

There is world-wide interest in mitigating the effects of climate change and reducing greenhouse gas emissions. International interest in reducing emissions from heavy-duty trucks is focused around three main areas; optimising routes to reduce energy consumption, improving truck and engine designs for heavy trucks that use diesel as an energy source, and using alternative energy sources to diesel.

Battery electric vehicles (BEVs) and battery electric heavy vehicles (BEHVs) are now beginning to see application in New Zealand by general freight, milk collection, supermarket, refuse collection, quarry, port, and mail delivery companies. No BEHV log trucks are being operated in New Zealand, but they are starting to see application in Europe. Regenerative braking allows an EV to collect electricity and partially recharge its battery as it decelerates.

This study analyses the energy consumption, required battery size and log transport costs of BEHV trucks with a gross weight of up to 50 tonnes. To calculate the energy consumption of the BEHV truck a techno-economic model was created and parameters for different truck and trailer configurations created. The model was applied to four log transport routes in New Zealand that had large changes in elevation. The resulting tank-to-wheel energy consumption for battery electric trucks varied between 0.68 and 3.06 kWh/km. Compared to the simulated diesel trucks the BEHV shows a 1.2 to 1.9 times higher energy efficiency.

For most of the scenarios evaluated battery pack size was determined by power (kW) demands rather than energy (kWh) demands due to limitations on the number of hours per day log trucks are operated and the number of times a route can be repeated in the available work time. Compared with diesel trucks payload was reduced by 4% to 18%.

The transport cost of operating heavy-duty trucks, including the charging infrastructure, was calculated. There was no consistent trend in cost reduction or cost increase from utilising a BEHV log truck on the routes and scenarios evaluated. BEHV trucks had higher costs for three routes and mixed cost changes for one route. Cost advantages and disadvantages of BEHV trucks were dependent on truck tare weights and battery management systems. Costs were also sensitive to the assumed road user charges, diesel prices, insurance costs, and battery cell-to-pack ratios.

Finally, cost gains for BEHV log trucks from lower fuel, repairs and maintenance, and road user charges were sometimes negated by higher depreciation, insurance, interest and infrastructure costs and lower payloads compared with diesel log trucks.

INTRODUCTION

There is world-wide interest in mitigating the effects of climate change and reducing greenhouse gas emissions[1].

Transport is one of New Zealand's largest sources of greenhouse gas emissions. It is responsible for 17 percent of NZ's gross emissions and 43 percent of carbon dioxide emissions. Heavy-duty vehicles, most of which are used for freight, emit almost a quarter of NZ's total transport emissions (Ministry for the Environment 2022). Log transport accounts for approximately 13 percent by weight of freight movement in New Zealand (Paling *et al.* 2019).

International interest in reducing emissions from heavy-duty trucks is focussed around three main areas; optimising routes to reduce energy consumption, improving truck and engine designs for heavy trucks that use diesel as an energy source, and using alternative energy sources to diesel. Hydrogen fuel cell electric heavy vehicles (FCEHV) and battery electric heavy vehicles (BEHV) are two types of vehicles that make use of alternative energy sources. This report focusses on BEHVs.

There are many debates about the current viability of electric vehicles, but more than a century ago Christchurch had a fleet of about 200 electric trucks[2], manufactured in Chicago with an "optimistic" range of 65 km. These were popular with department stores, grocery stores, dairy companies, bakers, and butchers for delivery of goods. The electric trucks were recharged overnight using renewable energy from the Lake Coleridge hydro station and electricity generated from an incinerator that burnt rubbish from all over Christchurch. Some electric vehicles, used in the US in the 1910's and in the UK in the late 1800's, were modified to facilitate a fast battery exchange[3] so that the operator did not have to wait for overnight charging. Improvements to internal combustion engine vehicles which, among other things, allowed longer travel distances between refuelling stops, saw the rapid decline in the use of electric vehicles by 1935.

Battery electric vehicles (BEVs) and battery electric heavy vehicles (BEHVs) are now beginning to see new application in New Zealand by general freight (Figure 1a), milk collection, supermarket, refuse collection, quarry, port, and mail delivery companies (Mostofi 2022).

Debate on the viability of electric trucks tends to centre around range limitations, battery size and its effect on load capacity, and costs (e.g., Forrest *et al.* 2020). Improvements in battery technology for BEHV's are rapidly overcoming some of these limitations (Nykvist and Olsson 2021).

For example, Scania recently announced the launch of its regional long-haul electric truck with a range of up to 350 km[4]. Scania also recently announced the development and delivery of a new BEHV log truck with an 80-tonne capacity to SCA (Europe's largest private forest owner)[5]. The Scania log truck will be used for short distance transporting of logs between a rail terminal and a paper mill which are about 14 km apart (Figure 1b).

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[1] https://www.un.org/sustainabledevelopment/climate-change/
[2] https://my.christchurchcitylibraries.com/electric-truck/
[3] https://en.wikipedia.org/wiki/History_of_the_electric_vehicle
[4] https://electrek.co/2022/06/13/scania-regional-long-haul-electric-truck/
[5] https://electrek.co/2022/07/07/electric-timber-truck-sweden/

Regenerative braking allows an EV to collect electricity and recharge its battery as it decelerates. For a given battery size, it adds up to 30% more range in urban environments for heavy goods vehicles (Odhams *et al.* 2010 cited in Midgley and Cebon 2012).

Sessions and Lyons (2018) have shown, for a limited set of conditions, that recovery braking energy from log trucks descending from high elevation forests to lower elevation manufacturing facilities can reduce the size of the battery required to run a log truck. They also showed that adding level highway hauls after descending from the higher elevation forests quickly increases the required battery capacity.

As of the time of preparing this report there are no BEHV trucks used for log transport in New Zealand but interest in evaluating their potential has been expressed by some forest companies. In 2021 the New Zealand Forest Growers Levy Trust funded a project to “investigate the feasibility of using electric trucks for hauling logs …. from forests located on hillsides where there is the potential to use regenerative braking to charge the battery on the downhill journey, thereby overcoming the range limitations of electric transport”.

This report assesses the economic feasibility of using BEHV log trucks for selected routes using a techno-economic model developed by the author and compares the economics with equivalent powered diesel log trucks.

Figure 1. BEHV freight truck operating in New Zealand (A) and log truck operating in Sweden (B)

STUDY METHODS AND MATERIALS

Model Description

The techno-economic model has been constructed within two spreadsheets; one containing the technical assessment and the other containing the economic assessment (Figure 2). Routes and truck travel speeds are common inputs to both spreadsheets. Net payloads (tonnes) and energy requirements (kWh per 100 km) are outputs from the technical spreadsheet and inputs to the economic spreadsheet. The main output from the economic spreadsheet is the cost for the route ($/t). The annual cost of energy can also be extracted from the economic spreadsheet. The techno-economic model was used to evaluate both diesel and BEHV truck configurations.

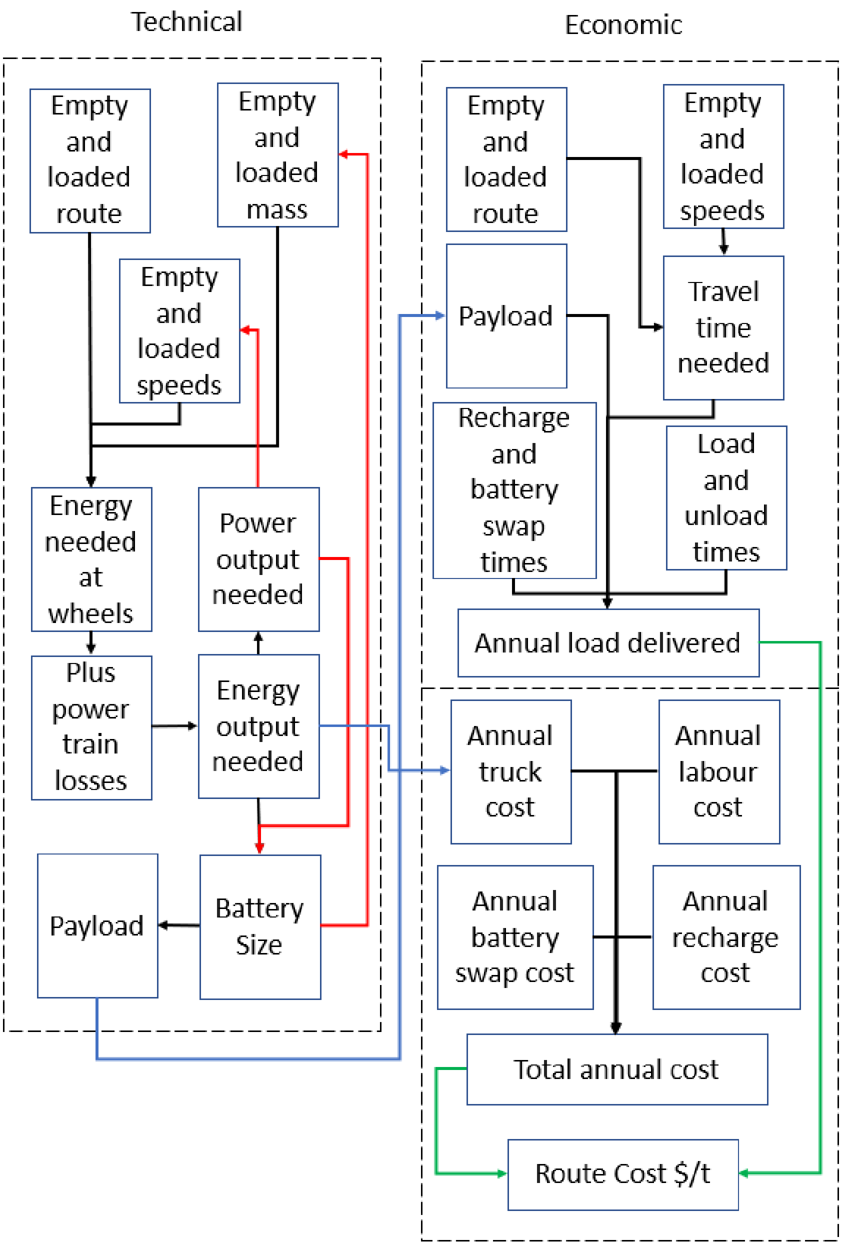


Figure 2. Flowchart of BEHV Log Truck techno-economic model

Routes

Four routes were assessed; two were from forests to ports, one was from forest to a mill, and one was from a forest to a potential sort yard within the forest. Routes were split into segments of similar grade, alignment, and road type (on-forest gravel, rural paved, motorway, and urban). The length of each segment varied from 20 to 7360 m. The smallest route evaluated had 232 segments for a return trip and the largest had 2078 segments.

Route A

Route A started at the Napier Port, went to a forest stand near Kuripapango in the Kaweka Ranges and then returned to the port. The Route was 167.54 km in length. Figure 3 shows a vertical profile of the route from the port to the forest. The maximum grade was 15%. The elevation difference between the port and forest stand was 696 m. The profile, from port to forest stand, included 1166 m of ascents and 460 m of descents. It also included 5% forest roads, 62% paved rural roads, 22% urban roads and 11% motorways. Alignment on the rural roads was rated as approximately 25% predominantly straight, 50% transitional and 25% winding.

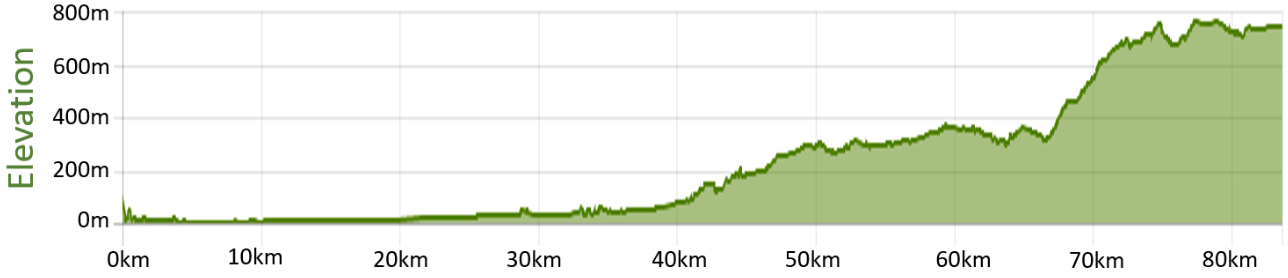


Figure 3. Route A profile from port to forest

Route B

Route B started at the Port Nelson, went to a forest stand south of Belgrove in the Spooners Range and then returned to the port. The Route was 95.28 km in length. Figure 4 shows a vertical profile of the route from the port to the forest. The maximum grade was 26%. The elevation difference between the port and forest stand was 457 m. The profile, from port to forest stand, included 914 m of ascents and 457 m of descents. It also included 10% forest roads, 48% paved rural roads, 42% urban roads and 0% motorways. Alignment on the rural roads was generally predominantly straight.

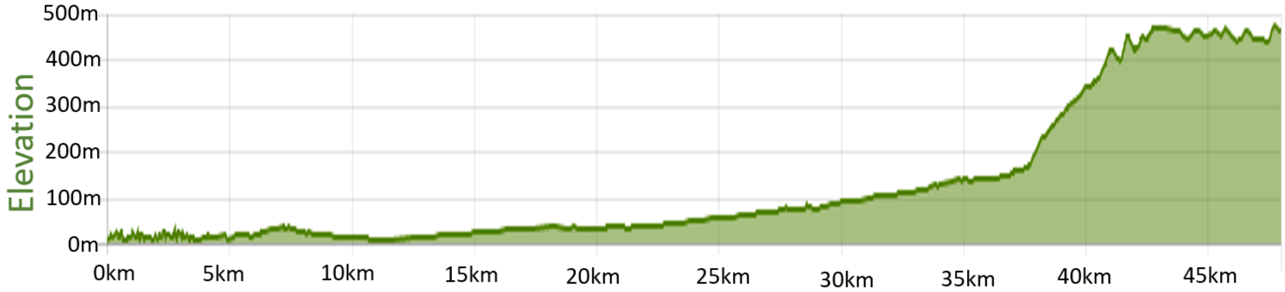


Figure 4. Route B profile from port to forest

Route C

Route C started at a mill near Tangiwai in the central North Island, went to a forest stand near Kuripapango in the Kaweka Ranges and then returned to Tangiwai. The Route was 210.2 km in length. Figure 5 shows a vertical profile of the route from the mill to the forest. The maximum grade was 27%. The elevation difference between the mill and forest stand was 32 m. The profile, from mill to forest stand, included 2320 m of ascents and 2288 m of descents. It also included 4% forest roads, 79% paved rural roads, 1% urban roads and 16% motorways (SH1). Alignment on the rural roads was rated as approximately 45% predominantly straight, 35% transitional and 20% winding.

Figure 5. Route C profile from mill to forest

Route D

Route D started at a potential sort yard location near Whatatutu west of Gisborne, went to a forest stand in the Raukumara Ranges and then returned to the sort yard. The Route was 65.4 km in length. Figure 6 shows a vertical profile of the route from the potential sort yard location to the forest. The maximum grade was 21%. The elevation difference between the sort yard and the forest stand was 650 m. The profile, from sort yard to forest stand, included 1472 m of ascents and 822 m of descents. All roads were unpaved gravel roads. Alignment on the roads was rated as approximately 55% predominantly straight and 45% winding.

Figure 6. Route D profile from sort yard to forest

Log Trucks

Two on-highway truck configurations were included in the model; a four-axle truck with a five-axle trailer with a maximum gross mass of up to 50,000 kg (referred to as 50MAX in this report), and a four-axle truck with a four-axle trailer with a maximum gross mass of 46,000 kg (referred to as 46T in this report). Off-highway "stems" trucks were out-of-scope for this study. In the model, both truck types were assumed to have gross masses, when loaded, that were 500 kg less than the maximum allowed.

Average tare weights for diesel-powered log trucks and trailers were supplied by a forest company. For the 50MAX trucks these were approximately 11,500 kg for the truck and 6,300 kg for the trailer. For the 46T trucks these were approximately 11,500 kg for the truck and 5,400 kg for the trailer.

Average tare weights for the trailers towed by BEHV trucks were assumed to be the same as those towed by diesel-powered trucks. Tare weights for the BEHV trucks (minus batteries) were calculated as follows:

BEHV log truck tare weight = DTW – DPT + EPT + BOL

where: DTW = tare weight of base diesel truck without fuel and prior to outfitting for log transport
DPT = weight of diesel powertrain components
EPT = weight of electric powertrain components
BOL = weight of bolsters, etc. for log transport

DTW for a diesel day cab was assumed to be 7500 kg (Ricardo 2021)
DPT was assumed to be 2200 kg (Basma *et al.* 2021)
EPT was assumed to be 650 kg (Basma *et al.* 2021)
BOL was assumed to be 3450 kg (based on forest industry tare weights less weight of the pre-outfitted truck).

BEHV truck tare weights (without batteries) were, therefore, assumed to be 9,400 kg (referred to as Medium Tare hereon). Alternative derivations, by the author, of a BEHV log truck tare weight ranged between 8,830 kg and 11,320 kg. The higher figure, referred to as High Tare hereon, was used in this report to determine the sensitivity of the outcomes to the assumed 9,400 kg tare weight.

Both diesel-powered log trucks and BEHV log trucks were assumed to have power sources capable of supplying up to 400 kW.

Trailers were assumed to ride "piggy-back" on the return empty trip to the forest.

Truck Travel Speeds

The assumed truck travel speeds varied with load condition (loaded or unloaded), grade, road type, and alignment (Byrne *et al.* 1960, Jackson and Sessions 1987, Moll and Copstead 1996). Speeds ranged from as low as 8 kph to as high as 85 kph for a given section of road. Speeds were lower for loaded than unloaded conditions, decreased as grade (favourable or unfavourable) increased, and decreased as alignment (related to number of curves per km) became poorer. For different road types, speeds were greatest for motorways, then decreased for rural paved roads, urban, and forest roads. Acceleration and deceleration between road segments with different characteristics were accounted for in the assumed average travel speeds. Lower speeds at road junctions were handled by assigning a winding alignment to a short road segment.

Energy Needed at Wheels

The approach for estimating the energy needed at the wheels was similar to that described by Sessions and Lyons (2018) and Earl *et al.* (2018).

For each segment on the route energy is required at the wheels (E_W) to overcome rolling resistance, air resistance and grade resistance assuming constant velocity in the segment.

$$E_W \text{ (joules)} = \text{Rolling Resistance} + \text{Air Resistance} + \text{Grade Resistance}$$

and

$$\text{Rolling Resistance (joules)} = L*m*cos(\theta)*g*C_{RR}$$

$$\text{Air Resistance (joules)} = L*A*V^2*C_{AR}$$

$$\text{Grade Resistance (joules)} = m*g*\Delta H$$

where: L is the length of the segment (m), m is the mass of the truck, trailer and load (kg), θ is the slope of the road segment (degrees), g is the gravitational constant 9.81 (ms^{-2}), C_{RR} is the coefficient of rolling resistance (0.0080 for paved roads[6] and 0.0112 for gravel roads[7]), V is the velocity of the truck (ms^{-1}), A is the frontal area of the truck (m^2)[8], C_{AR} is the coefficient of air resistance (0.5989),[9] and ΔH is the change in elevation (m).

Four situations will determine the sign of the value for E_W.

- If the truck is traveling uphill, E_W will be positive since all three resistances will be positive.
- If the truck is traveling downhill, grade resistance will be negative and E_W will be positive if grade resistance is not large enough to overcome the sum of rolling resistance and air resistance.
- If the truck is traveling downhill and grade resistance is larger than the sum of rolling resistance and air resistance, then E_W will be 0 if the truck does not have a regenerative braking system. Excess grade resistance will largely be expended as heat generated by the traditional braking system.
- If the truck is traveling downhill and grade resistance is larger than the sum of rolling resistance and air resistance, then E_W will be negative if the truck has a regenerative braking system that can store energy in a battery.

It is convenient to express E_W in terms of kWh (1 kWh = 1 Mj/3.6).

[6] Source: The Engineering Toolbox (https://www.engineeringtoolbox.com/rolling-friction-resistance-d_1303.html) shows values ranging between 0.006 and 0.010. A midpoint value was used in the model.

[7] Various references indicate that rolling resistance on gravel roads is 25 to 60% higher than that for paved. A 40% increase was used in the model.

[8] Frontal areas were scaled from photos of loaded and unloaded trucks commonly used in New Zealand. These were 6.90, 6.74, 6.90, and 7.45 m^2 for empty 50MAX, loaded 50 MAX, empty 46T and loaded 46T trucks respectively.

[9] Source: Sessions and Lyons (2018).

Energy Needed at Engine

The amount of energy that needs to be supplied by the engine (E_E) depends on the power losses that are incurred through the drive train.

For diesel drive trains, efficiencies range between 70 and 85%. The engine to wheel efficiency was assumed to be 75% for diesel HVs in the model.

E_E for diesel HVs = E_W / 0.75

The energy contained within diesel fuel in the tank prior to combustion is 10.6 kWh per litre. Heavy-duty diesel engines convert less than 40% of fuel energy to usable energy output (~4.14 kWh). Most of the fuel energy is lost as heat in various forms (Thiruvengadam *et al.* 2014).

For electric drive trains, efficiencies range between 64% and 86% with an average of around 68% (Huang and Zhang 2011, Cunanan et al, 2021). The engine to wheel efficiency was assumed to be 68% for BEHVs in the model.

E_E for BEHVs = E_W / 0.68

If excess energy is created at the wheels through regenerative braking it is assumed that the same drive train efficiency will reduce the amount of energy that can be used to recharge the battery; i.e.,

E_E returned to the battery for BEHVs = E_W * 0.68.

For a given segment of road the engine not only has to provide sufficient energy to keep the vehicle moving at constant velocity, but it also needs to provide that energy at the rate, or power, required. If the power required for a given segment was greater than the maximum power available from the engine (i.e., the 400 kW that was assumed in the model) travel speed was reduced and new E_W and E_E values calculated.

The minimum amount of energy required to complete a single route (MESR) can be calculated as the maximum value of the cumulative energy function over the route from the first segment, i = 1, to the last segment, i = N. For a diesel truck without regenerative braking the maximum value will occur on the last segment, N. For a BEHV truck with regenerative braking this may occur on an earlier segment, M.

$$\text{MESR} = \max_{1 \le M \le N} \sum_{i=1}^{M} E_{E_i}$$

Battery Size

The minimum battery size (kWh) will depend on the number of times the route is repeated (***rep***) and the fraction (***f***) of the available battery energy that is used.

Minimum battery size = ***rep****MESR/***f***

Batteries are often operated in a small fraction of their total energy storage range (some only between 55% to 60%) because of large excursions from optimal charging and discharging efficiencies, and to prolong the service life of the battery (Midgley and Cebon 2012). Two battery operating conditions were evaluated in this assessment, $\boldsymbol{f}$ = 60% and $\boldsymbol{f}$ = 80%. The former represents a situation where a battery could be discharged to 20% and charged to 80% of its total energy storage capacity (referred to as 80% charge hereon). The latter represents a situation where a battery could be discharged to 20% and charged to 100% of its total energy storage capacity (referred to as full charge hereon).

The minimum battery size (kg) will depend on both the energy density and power density of the battery. Nykvist and Olsson (2021) report that conservative and state-of-the-art values for energy densities for lithium-ion batteries are 125 and 175 Wh/kg, respectively. Campanari et al (2009), cited in Sessions and Lyons (2018), reports that energy density is correlated with power density (W/kg) for lithium-ion batteries – as energy density increases power density decreases. At an energy density of 165 Wh/kg, power density is approximately equal to energy density (165 W/kg). An energy density of 165 Wh/kg and a power density of 165 W/kg were used in the model.

The minimum battery size (kg) will depend on what is limiting - the power demand or the energy storage requirements. It should be noted that the energy storage requirements depend on the battery weight which, in turn, affects the energy storage requirements. An iterative process was sometimes required to settle on the minimum battery size.

As well as the energy cells, battery packs include housing, cooling systems, electronics, etc. Cell-to-pack ratios depend on battery chemistry and range between 55% and 90% (Basma *et al.* 2021). Based on information supplied by a NZ supplier of a BEHV for a 282 kWh battery, and an assumed 165 Wh/kg energy density, a value of 790 kg was calculated for the housing and attachments. This would indicate a cell-to-pack ratio of 75%. The minimum battery pack size (kg) was the sum of the minimum battery size (kg) and 790 kg. Sensitivity of costs to the calculated weight for housing and attachments was carried out by halving the value to 390 kg.

For the purposes of these techno-economic analyses it is assumed that battery sizes are completely variable. In practice they are likely to be modular, stepping up in increments. For example, one truck manufacturer producing electric trucks describes a BEHV that utilises up to six battery modules operated in parallel that each provide up to 90kWh[10].

Payload

Payloads for the routes modelled were calculated as:

$\text{Payload}_{\text{Diesel Log Trucks}}$ (kg) = Gross mass – Truck tare weight – trailer tare weight

$\text{Payload}_{\text{BEHV Log Trucks}}$ (kg) = Gross mass – Truck tare weight – trailer tare weight – minimum battery pack weight

[10] https://www.volvogroup.com/en/news-and-media/news/2022/may/battery-packs-for-electric-vehicles.html

Truck Productivity and Costs

A spreadsheet model, developed by Murphy and Wimer (2007) to estimate diesel logging truck productivity (tonne-km per year) and costs under different configurations and operating conditions, was modified to allow the economic evaluation of BEHV trucks as well as diesel trucks.

Using an engineering economics approach, ownership costs associated with the purchase of the vehicle and its accessories if applicable, labour costs, the fuel costs and consumption rates, road user charges, tyre costs, maintenance costs, overhead costs, and recharging and battery swap infrastructure costs are calculated. The costs are reported on a per annum basis and a per tonne basis.

Productivity related inputs to the model are payload (derived from the technical model), travel speeds (loaded and unloaded) for the four road types, loading and unloading times, distances travelled on each road type for a single route, the number of times per day a route could be completed, and the refuel time. A maximum operating day-length of 11 hours was set in the analyses. For example, if a single route required 4 hours to complete, the number of loads per day was limited to 2. The number of working days per year was assumed to be 235. A maximum machine time utilisation rate of 85% was assumed in the model.

Trucking cost related inputs to the model were obtained by contacting truck suppliers (diesel and electric), trailer manufacturers, and tyre suppliers, gathered from appropriate websites (e.g., road user charges for trucks and trailers, fuel prices ($/litre or $/kWh)), and truck costing literature. Selected cost inputs, with GST included, were as follows along with some key values:

- Capital costs for a fully rigged truck unit; $511,750 (50MAX and 46T diesel), $396,750 (50MAX and 46T electric)
- Capital costs for a fully rigged trailer; $207,000 (50MAX) and $184,000 (46T)
- Capital costs for a single electric battery[11]; $100 per kg – if battery swapping is utilised, two batteries are included in the capital costs
- Truck and trailer lives (550,000 and 775,000 km) and battery life (= 3000 charges)
- Residual values as a percent of purchase price (20% for truck and trailer, and 0% for battery)
- Interest rate for borrowing; 7%
- Fuel costs[12]; diesel - $2.35 per litre, electricity - $0.20 per kWh
- Fuel consumption (litres per 100 km or kWh per 100 km); estimated in technical model.
- Labour cost; $29 per hour
- Driver's company supplied vehicle to get to truck depot; $1.23/km
- Road user charges; exempt on BEHVs tractor units (but not trailers) until 2025, otherwise $658 to $691/1000km for tractor units and $179 to $238/1000km for trailers.
- Trailer maintenance costs; $0.32/km (50MAX), $0.27/km (46T)
- Diesel truck maintenance costs: $0.23/km (50MAX), $0.20/km (46T)

[11] The cost for a 2500 kg battery was quoted as approximately $253000. This equates to approximately $100 per kg.
[12] Fuel costs can account for a significant proportion (10 to 30%) of the costs of owning and operating a heavy vehicle. Diesel fuel prices in 2021 and 2022 have fluctuated by more than 75%. Sensitivity to the assumed price of $2.35 per litre for diesel and $0.20 per kWh was carried out by including scenario based on $2.00 per litre and $0.23 per kWh.

- Electric truck maintenance costs[13]: $0.14/km (50MAX), $0.12/km (46T)
- Insurance costs[14]; 2.5% of capital costs
- Overheads; 5% of total costs
- Profit allowance; 8% of total costs
- Chargeout rate for battery charging facility; $71/hour
- Time for battery charging; 0.67 hours for “fast charge” to 80% capacity and 2.2 hours for “full charge” to 100% capacity.
- Chargeout rate for battery swapping facility; $73/hour
- Time for battery swapping[15]; 0.25 hours per occasion.

Cost related outputs were annual depreciation, interest, insurance, registration, fuel, oil, tyres, repairs and maintenance, and road user charges for the truck and trailer unit, annual labour costs, annual overhead costs, annual company supplied vehicle costs, annual infrastructure costs for BEHV’s, and annual profit. A cost per tonne for a single completion of the route was also calculated.

[13] Nykvist and Olsson (2021) report a 40% reduction in maintenance costs for BEHVs compared with diesel heavy vehicles.
[14] Lithium-ion batteries are known to be a fire risk. Some forest owners have expressed a concern that insurance costs may rise as a result of this risk. Sensitivity to this assumed risk was evaluated by including a scenario where insurance costs were doubled to 5% of capital costs.
[15] Note that, although the model allowed evaluation of the impacts of battery swapping on route economics, none of the four routes had sufficient time available for carrying out a battery swap and adding in an extra trip for the day.

RESULTS

Energy consumption

The energy consumed per kilometre of travel and that needed to be supplied by the motor depended on the route and truck configuration (Table 1). Route C, which had little overall difference in elevation between the forest and mill but lots of ascents and descents, had the highest energy consumption. Route D, which was entirely on gravel roads and included a large ascent from the sort yard to the forest, had the second highest energy consumption. Route A, which also had a large ascent from the port to the forest but included only a small proportion of the travel on forest and urban roads, had the lowest energy consumption.

Table 1. Energy consumption (kWh per km) at engine (E_E) for selected routes and truck configurations.

Scenario	Energy Consumption (kWh/km)			
	Route			
	A	B	C	D
Diesel 50MAX	1.36	1.58	3.59	2.71
Electric 50MAX, Medium Tare, Full Charge	0.70	1.31	2.99	1.75
Electric 50MAX, Medium Tare, 80% Charge	0.70	1.34	3.06	1.81
Electric 50MAX, High Tare, Full Charge	0.70	1.38	-	1.88
Electric 50MAX, High Tare, 80% Charge	0.71	1.41	-	1.94
Diesel 46T	1.29	1.54	-	-
Electric 46T, Medium Tare, Full Charge	0.68	1.23	-	-
Electric 46T, Medium Tare, 80% Charge	0.69	1.27	-	-

Note: Scenarios with a “-“ in Route C and D columns were not evaluated.

The 46T truck configuration required slightly lower energy consumption (3% to 5%) than the 50MAX configuration for each route evaluated. This was due to the lower payloads carried and slightly lower trailer tare weights.

Regenerative braking substantially reduced (15% to 50%) the energy consumption, compared with diesel configurations, for each route and BEHV truck configuration. The route which benefited most from regenerative braking was route A. It had the greatest ratio of loaded elevation descents to loaded ascents. Route C benefited least and had the lowest ratio.

Energy consumption was slightly less (1% to 2%) for the Full Charge battery management scenarios than the 80% Charge scenarios since the Full Charge scenarios tended to require a smaller battery than the 80% Charge scenarios.

Energy savings resulting from regenerative braking were a little less (1% to 5%) for the high tare weight BEHV's than the medium tare weight BEHV's.

Battery Size

Battery pack weights were determined by either the maximum power requirement or the amount of energy consumed (a function of the number of times per day that the route was repeated). A battery that could supply 400 kW was estimated to weigh 3215 kg[16]. The routes could be repeated twice per day for Routes A, B and D and once per day for Route C within the 11-hour operating time limit.

Table 2. Battery pack weights (kg) for selected routes and truck configurations.

Scenario	Battery Pack Weights (kg) for Energy and Power limiting condition. [E] = Energy limiting, [P] = Power limiting			
	Route			
	A	B	C	D
Electric 50MAX, Medium Tare, Full Charge	2490, 3215 [P]	2605, 3215 [P]	5360, 3215 [E]	2460, 3215 [P]
Electric 50MAX, Medium Tare, 80% Charge	3155, 3215 [P]	3375, 3215 [E]	7285, 3215 [E]	3180, 3215 [P]
Electric 50MAX, High Tare, Full Charge	2505, 3125 [P]	2700, 3125 [P]	-	2575, 3215 [P]
Electric 50MAX, High Tare, 80% Charge	3185, 3215 [P]	3515, 3215 [E]	-	3350, 3215 [E]
Electric 46T, Medium Tare, Full Charge	2490, 3215 [P]	2605, 3215 [P]	-	-
Electric 46T, Medium Tare, 80% Charge	3155, 3215 [P]	3375, 3215 [E]	-	-

Note: In each cell, the first battery pack weight is based on energy needs and the second is based on maximum power needs. The larger of the two determined the minimum battery weight required. Scenarios with a "-" in Route C and D columns were not evaluated.

For 12 of the 18 BEHV scenarios evaluated, power requirements determined the battery pack size (Table 2). For the other six BEHV scenarios, energy consumption requirements determined the battery pack size, ranging from 3350 kg to 7285 kg. Battery pack size, for all 18 BEHV scenarios, would have been determined by energy consumption requirements if one extra trip per day could have been squeezed in for Routes A, B and D. If meeting the power requirement was not a determinant of battery pack size, the range would have been larger; 2490 kg to 7285 kg.

[16] As noted in the methods section it was assumed that both diesel and electric trucks could supply up to 400kW of power. At a power density of 0.165 W/kg a battery size of 2425 kg would be required. When housing, cooling system, etc. is added to this a power-limited battery pack weight of 3215 kg is calculated.

There was a small difference (0 kg to 300 kg) in the required battery pack size, between the 80% Charge scenarios and the Full Charge scenarios, for three of the routes; A, B and D. There was a 1925 kg difference in required battery pack size for Route C. Larger battery pack sizes were required by the 80% Charge scenarios.

Payload

Payloads were 31.70 and 28.60 tonnes for the Diesel 50MAX and Diesel 46T truck configurations, respectively (Table 3).

Payloads for the BEHV 50MAX Medium Tare Weight truck configurations were calculated to be 1.51 to 1.68 tonnes lower for Routes A, B, and D and 3.66 to 5.58 tonnes lower for Route C. Payloads for the BEHV 50MAX High Tare Weight truck configurations were calculated to be 3.03 to 3.34 tonnes lower for Routes A, B, and D.

Payloads for the BEHV 46T Medium Tare Weight truck configurations were calculated to be 0.72 to 1.13 tonnes lower for Routes A and B.

Table 3. Payloads (tonnes) for selected routes and truck configurations.

Scenario	Payloads (tonnes)			
	Route			
	A	B	C	D
Diesel 50MAX	31.70	31.70	31.70	31.70
Electric 50MAX, Medium Tare, Full Charge	30.19	30.19	28.04	30.19
Electric 50MAX, Medium Tare, 80% Charge	30.19	30.02	26.12	30.19
Electric 50MAX, High Tare, Full Charge	28.67	28.67	-	28.67
Electric 50MAX, High Tare, 80% Charge	28.67	28.36	-	28.53
Diesel 46T	28.60	28.60	-	-
Electric 46T, Medium Tare, Full Charge	27.88	27.88	-	-
Electric 46T, Medium Tare, 80% Charge	27.48	27.47	-	-

Note: Scenarios with a “-“ in Route C and D columns were not evaluated.

Costs

Costs ranged between $16.75 per tonne and $49.70 per tonne for diesel truck configurations (Table 4). Costs were closely linked to the length of the route; the lengths, from shortest to longest, being those associated with Routes D, B, A, and C. For the same route diesel 46T truck configurations had higher costs than 50MAX configurations. Costs were sensitive to the assumed diesel prices. A 35 cent (15%) reduction in diesel price resulted in a 3% reduction in costs per tonne for the two routes evaluated.

Table 4. Costs ($ per tonne) for selected routes and truck configurations. Percent of base 50MAX or base 46T diesel scenarios are shown in brackets.

Scenario	Costs ($/t)			
	Route			
	A	B	C	D
Diesel 50MAX – Base Scenario	$29.53 [100]	$19.41 [100]	$49.70 [100]	$16.75 [100]
Diesel 50MAX with 35 cents/litre lower diesel cost	$28.76 [97]	$18.91 [97]	-	-
Electric 50MAX, Medium Tare, Full Charge	$28.80 [98]	$21.43 [110]	$55.35 [111]	$19.52 [117]
Electric 50MAX, Medium Tare, 80% Charge	$26.77 [91]	$19.73 [102]	$61.67 [124]	$17.73 [106]
Electric 50MAX, High Tare, Full Charge	$30.33 [103]	$22.48 [116]	-	$20.63 [123]
Electric 50MAX, High Tare, 80% Charge	$28.20 [95]	$21.15 [109]	-	$18.99 [113]
Electric 50MAX, Medium Tare, 80% Charge with 3 cents/kWh higher electricity costs	$26.89 [91]	$19.64 [101]	-	-
Electric 50MAX, Medium Tare, 80% Charge without exempt RUC's	$30.91 [105]	$21.97 [107]	-	-
Electric 50MAX, Medium Tare, 80% Charge with double insurance costs	$28.20 [95]	$21.20 [109]	-	-
Electric 50MAX, Medium Tare, 80% Charge with 390 kg battery housing and attachments	$26.42 [89]	$19.47 [100]	-	-
Diesel 46T – Base Scenario	$31.35 [100]	$20.75 [100]	-	-
Electric 46T, Medium Tare, Full Charge	$30.56 [97]	$22.92 [110]	-	-
Electric 46T, Medium Tare, 80% Charge	$28.58 [91]	$20.97 [101]	-	-

Note: Scenarios with a "-" in Route C and D columns were not evaluated.

There was no consistent cost reduction or cost increase for utilising a BEHV log truck on the routes evaluated. BEHV trucks had higher costs (+2% to +24%) for Routes B, C and D, and mixed cost changes (-9% to +3%) for Route A. As noted above, however, a 35c drop in the assumed diesel price would result in a 3% reduction in the costs for the diesel 50MAX truck configuration. This could be expected to widen the gap between BEHV and diesel truck configuration costs for Routes B, C and D, and reduce the BEHV cost benefit gap for Route A.

There were some consistent trends for the costs in Table 4. Not unexpectedly, BEHVs with high tare weights had higher costs (4 to 7%) than BEHVs with low tare weights, partly as a result of having lower payloads. Additionally, 80% Charge battery management scenarios had lower costs (-6% to -10%) than all Full Charge battery management scenarios for Routes A, B and D, despite the payloads for the 80% Charge scenarios sometimes being smaller. The additional infrastructure costs associated with the time needed for a Full Charge versus an 80% Charge outweighed any gains associated with higher payloads.

A 3 cent (15%) increase in electricity price resulted in a 0.5% to 0.7% increase in costs per tonne for the two routes evaluated and would not have moved the BEHV truck configuration from having a cost advantage to a cost disadvantage over the diesel truck configuration.

Electric BEHV trucks are exempt of road user charges up until 2025. This exemption does not apply to the trailers. When the exemption expires in 2025 the cost for the two routes (Route A and Route B) evaluated would increase; resulting in BEHVs having a cost disadvantage over the equivalent diesel truck configuration for both routes.

Some forest owners have expressed a concern that lithium-ion batteries used in BEHV log trucks, if not handled correctly, can self-ignite, and may pose a fire risk. Insurance costs may rise as a result of this increased risk. Doubling truck insurance costs would result in a 4 to 5% increase in overall log transport costs. For Route A the BEHV would still have an overall cost advantage over the diesel equivalent truck configuration. For Route B, the higher insurance costs would widen the cost disadvantage gap between BEHVs and diesel log trucks. At this stage we point out that it is unknown whether there will be a cost increase associated with BEHV's and, if so, how large the increase is likely to be.

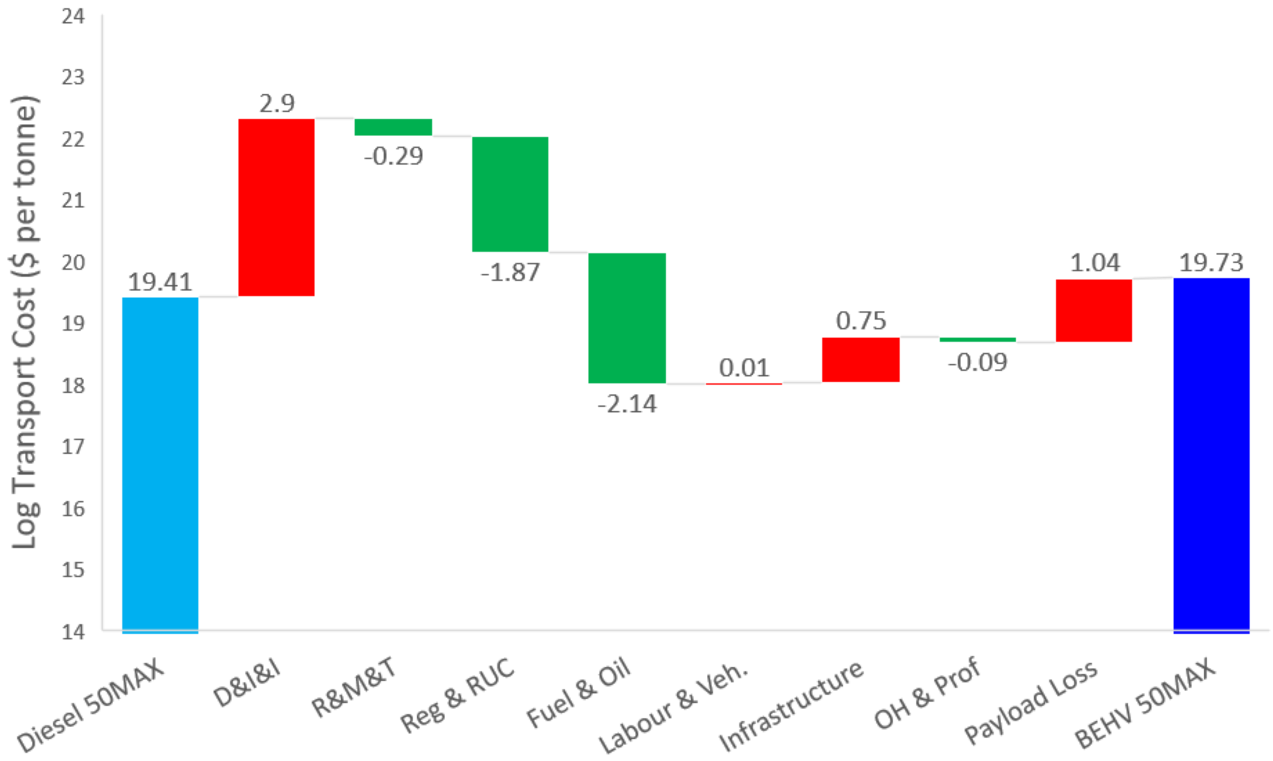
Sensitivity of costs to the calculated weight for battery housing and attachments was carried out by halving the value of these to 390 kg. This would result in a 400 kg increase in payload, and a 2% reduction in log transport costs.

Battery swapping provides a potential opportunity for increasing the number of loads per day by eliminating the need to wait for a battery to be recharged if it does need to be recharged. For the four routes evaluated there would have been insufficient time for an extra load even with using a battery swap system. To evaluate the impact of using a battery swap system Route B was shortened by 8.8 km on forest gravel roads; i.e., by assuming the stand was 4.4 km closer to the port. This would allow an extra trip per day for both diesel and BEHV log trucks. The cost for log transport by the diesel trucks would be $17.03 per tonne. If the battery had needed to be recharged prior to the third trip the cost of log transport for a medium tare weight 50MAX BEHV log truck which used batteries that were charged to 80% capacity was estimated to be $18.59 per tonne. The cost for a BEHV log truck which swapped batteries that were charged to full capacity was $21.45 per tonne. A battery swap system requires at least one additional battery per truck[17] (Sessions and Lyons 2018) (with an additional capital cost requirement of $321,500), infrastructure for swapping the battery, and

[17] For large fleets of electric trucks all passing a single battery swapping point it is conceivable that less than one additional battery per truck would be required.

time for swapping the battery. For this route there would have been no benefit from using a battery swap system.

Figures 7 demonstrates gains and losses in log transport cost for one of the routes (Route B), compared with a diesel 50 MAX log truck, for a medium tare weight truck scenario. Significant cost increases, shown in red, are incurred for depreciation, insurance, and interest, for charging infrastructure, and for payload losses associated with battery pack size. Significant cost decreases, shown in green, are incurred for registration and Road User Charges, and for fuel and oil. Figure 7 shows an overall cost disadvantage for the medium tare weight BEHV.



D&I&I = depreciation, insurance and interest, R&M&T = repairs and maintenance and tyres, Reg &RUC = registration and road user charges, Labour & Veh. = labour and drivers company supplied vehicle, Infrastructure = infrastructure costs for charging station and (battery swap station if needed), OH & Prof = overheads and profit, Payload Loss = change in log transport cost as a result of reduced payloads.

Figure 7 Gains and losses in transport cost for medium tare weight BEHV log truck compared with a diesel log truck.

DISCUSSION

The “tank-to-wheel” energy consumption for BEHV trucks varied between 0.68 and 3.06 kWh/km for the four routes evaluated. This compares with predicted BEHV consumption rates of 1.4 to 1.5 kWh/km for long haul and regional delivery routes with maximum grades of 7% in Europe (Basma *et al.* 2021) and 1.83 to 2.04 kWh/km for “heavy” highway routes with large elevation differences in Germany (Mareev *et al.* 2018). Sessions and Lyons (2018) predicted BEHV consumption rates of 1.52 kWh/km for the sort yard to forest route they modelled. They also noted that consumption rates would rise to 1.68 kWh/km if an additional 120 km of highway travel was added to the route.

Regenerative braking substantially reduced (20% to 50%) the energy consumption, compared with diesel configurations, for each route and BEHV truck configuration. Sessions and Lyons (2018) reported a 16% reduction in energy requirements for the “same” route if the grade for the entire route was assumed to be 0%. Their model would provide no opportunity for regenerative braking on 0% grades.

Given that the number of trips per day was limited by the available work time, it was found that battery size, and therefore payload, was determined by power demands rather than energy demands for most of the scenarios evaluated in this study. Sessions and Lyons (2018) also found that battery size was determined by power demands for the forest route they evaluated. They noted that energy demands were sensitive to the energy conversion efficiency that was assumed between the engine and the wheels; a higher conversion efficiency would result in lower energy demands. In our model a conversion efficiency of 68% was used whereas Sessions and Lyons (2018) used a conversion efficiency of 75% in their base case model.

Mareev *et al.* (2021) reported that BEHVs were 1.7 to 2.5 times more energy efficient than diesel heavy vehicles depending on the route. Predictions from our model predicted that BEHV log trucks would be 1.2 to 1.9 times more energy efficient for the routes we evaluated.

Mareev *et al.* (2021) found that BEHVs could be cost competitive with diesel trucks for some of the scenarios they evaluated. Similarly, we found that BEHV log trucks could be cost competitive for some, but not all, routes that we evaluated. Reduced energy costs and reduced road user charges were the main sources of cost reduction, but increased capital costs and reduced payloads negated these reductions. Removal of the RUC exemption in 2025 will significantly increase the BEHV log transport cost. Insurance cost increases due to potential fire risk, if any, will reduce BEHV cost benefits as will any increases in electricity prices or reduction in diesel prices.

Route C required very large batteries for the two scenarios evaluated (5360 and 7285 kg) (Table 2). At the assumed price of NZ$100 per kg, which was based on the price for a 2500 kg battery, this equates to battery capital costs of $536,000 and $728,500. While the literature consistently expresses average battery costs in terms of $ per kg, we have been unable to determine whether there would be a $ per kg cost penalty for large batteries or a cost discount. The breakeven battery prices, where there would have been no difference in total costs for the BEHV and diesel trucks, for the two scenarios evaluated were $349,000 and $361,100.

The large battery size and high battery cost have a significant impact on the competitiveness of BEHVs. Improvements in the near future are expected in these features, however. The US Department of Energy reported five-fold increases in energy density for batteries between 2010 and

2020 (Figure 8). Energy densities of 0.260 kWh per kg and power densities of 0.340 kW per kg are forecast by the mid-2020s. Similarly, Bloomberg reports an eight-fold decrease in battery cost per kWh for the same period (Figure 9). Changes of this magnitude could improve the competitiveness of BEHVs for many forest routes in New Zealand.

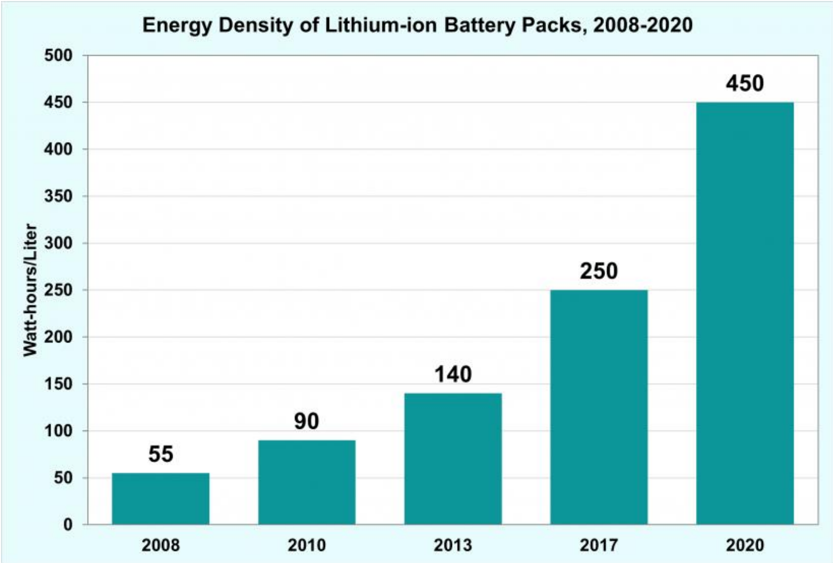


Figure 8 Energy density trends of battery packs between 2008 and 2010 (Source: US Department of Energy)

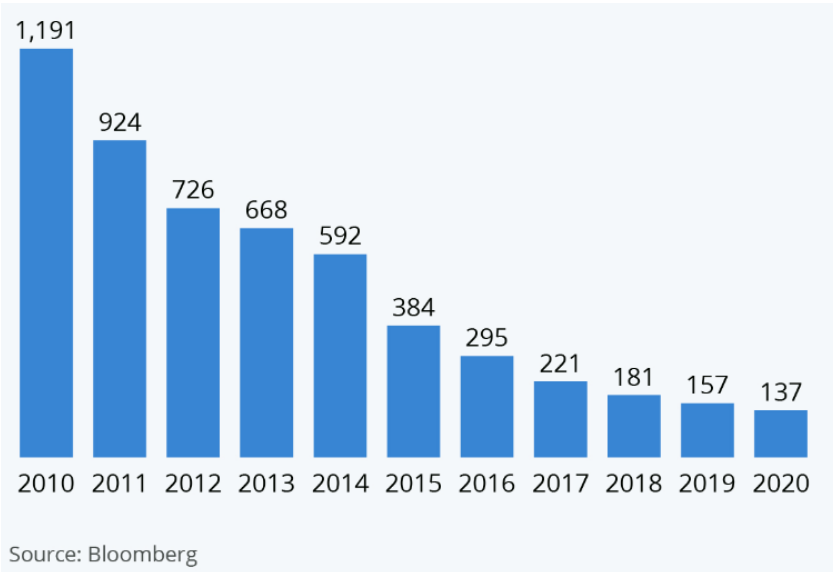


Figure 9 Battery price trends (US$/kWh) between 2010 and 2020 (Source: Bloomberg)

SUMMARY

This study analyses the energy consumption, required battery size and log transport costs of BEHV trucks with a gross weight of up to 50 t. To calculate the energy consumption of the BEHV truck a techno-economic model was created and parameterized for different truck and trailer configurations. The model was applied to four log transport routes in New Zealand that had large changes in elevation. The resulting tank-to-wheel energy consumption for battery electric trucks varied between 0.68 and 3.06 kWh/km. Compared to the simulated diesel trucks the BEHV shows a 1.2 to 1.9 times higher efficiency.

For most of the scenarios evaluated battery pack size was determined by power demands rather than energy demands due to limitations on the number of hours per day log trucks are operated and the number of times a route can be repeated in the available work time. Compared with diesel trucks payload was reduced by 4% to 18%.

The transport costs of heavy-duty trucks, including the charging infrastructure, were calculated. There was no consistent trend in cost reduction or cost increase from utilising a BEHV log truck on the routes and scenarios evaluated. BEHV trucks had higher costs for three routes and mixed cost changes for one route. Cost advantages and disadvantages of BEHV trucks were dependent on truck tare weights and battery management systems. Costs were also sensitive to the assumed road user charges, diesel prices, insurance costs, and battery cell-to-pack ratios.

Finally, cost gains for BEHV log trucks from lower fuel, repairs and maintenance, and road user charges were sometimes negated by higher depreciation, insurance, interest and infrastructure costs and lower payloads compared with diesel log trucks.

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