ARCHITECTURAL PROPOSAL FOR LOW-COST LOW-EMISSION HIGH PRODUCTIVITY FREIGHT VEHICLES WITH ELECTRIC TRACTION SYSTEMS

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Abstract

This paper presents the findings of High Productivity Freight Vehicles (HPFVs) with different powertrains to understand the potential Electric Traction Systems (ETS) can bring to the industry, as well as the barriers holding different ETS back. A 30 m A-double is selected as the case study combination and 30 days of operational data from the combination was supplied by an industry partner to gain further insight into power demands, lead times and free payload capacity. Three drive cycles were selected and two different powertrains, pure electric and Through-The-Road Parallel (TTRP) hybrid, are numerically explored and compared back to the standard diesel powertrain. The weights and packaging of different battery capacities were found to have minimal impact on payload capacity. The extra weight of ETS was a larger impact, leading to increased energy demands. Fuel consumption and energy used from the battery have been reported over the three selected drive cycles. Cost values of fuel and energy have been applied to gain a perspective of payback time with expected battery costs in 2022.

Keywords: Commercial Vehicle Technology, High Productivity Freight Vehicles, Low Emission Transport, Safety, Electric Traction Systems, Through-The-Road Parallel Hybrid.

1. Introduction

In Australia, approximately 2,132 million tonnes (t) of freight is moved by road each year and there is growing freight demand between metropolitan ports and inland distribution centres. Many areas around Melbourne have recorded days exceeding particulate matter limits (EPA Victoria, 2013). Children living close to the main populated freight routes have increased risk for health conditions, such as asthma (Keith, 2013). One measures to control exposure to diesel is to adopt alternative technologies in transport industries.

Electric Traction Systems (ETS) are identified as one of the major disruptive technologies for the transport industry in the 21st century. Electrification of vehicles has the potential to reduce emissions and local pollutants (Björnsson and Karlsson, 2015). Yet ETS on heavy freight vehicles are not common, with major barriers being range, weight, packaging and cost. Nevertheless, the use of ETSs in prime movers is being explored by previous studies (Kenworth, 2016). Besides ETSs located on the prime mover, the Transformers-Project showed ETS on the semi-trailer can see real world fuel consumption reductions of around 3-5% (Zyl, Wilkins et al., 2017). However, with regard to the Australian industry, semi-trailer trucks are only one of the common freight vehicles used. A growing trend in High Productivity Freight Vehicles (HPFVs) is seen in the Australian context. HPFVs generally consist of heavy vehicles towing two or more trailers. The potential benefits of ETS located on the prime mover or trailer units in the HPFV context has yet to be explored and is a key gap in current studies so far.

In this paper, field data has been collected over 30 days from intermodal HPFVs carrying up to two 40 ft containers within Melbourne's port precinct, outer urban, and regional areas with Gross Combination Mass (GCM) up to 85 t. Field data has been used to build up an assessment of the possibilities of ETS on HPFVs. The powertrains compared are combustion, electric and TTRP Hybrid. ETS integrated on the semi-trailer has been explored to create a TTRP hybrid.

2. Field Data Summary

Drive Cycle (DC) data from trips around Melbourne's port precinct, outer urban and regional areas was record over 30 day period for two 30 m A-double combinations. From the two monitored combinations, over 648 trips have been recorded showing:

- 337 hours on the move
- 238 hours idling loading/unloading
- 863 hours of down time (between trips)
- 11,827 km travelled

3. Operational Weight Analysis

Monitored combinations had their GCMs and axle group weights record through on-board scales. This was used to understand the possible free capacity to package ETS. These vehicles have been granted PBS approval for PBS Level 2 operation. Axle group limits for PBS level 2 are shown in Table 1.

Table 1 - Operational limits at PBS Level 2

Axle Group Masses	Level 2B - Cubic	HML
Steer (t)	6.0	6.5
Drive (t)	Up to 16.5	17.0
A-Trailer (t)	Up to 20	22.5
Dolly (t)	Up to 16.5	17.0
B-Trailer (t)	Up to 20	22.5
Allowed Gross Total (t)	68.5	85.0

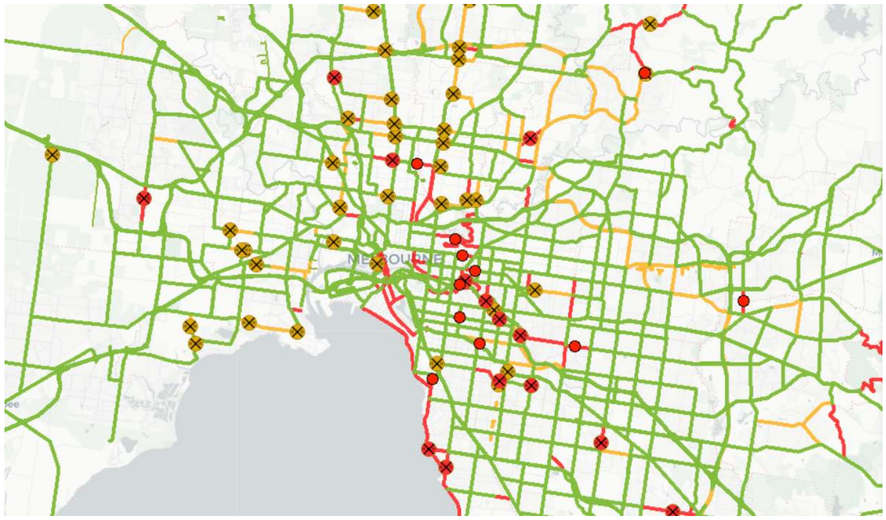

Figure 1 – PBS level 2B (Cubic) network access for 68.5 t in Melbourne (Vic Roads, 2018)

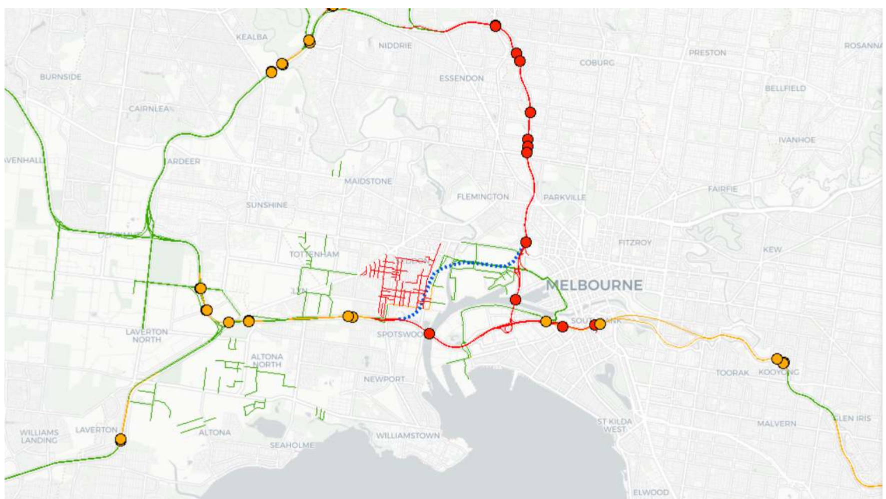

Figure 2 – PBS level 2 network access for 85 t in Melbourne (Vic Roads, 2018)

Figure 1 shows network access for GCMs up to 68.5 t and Figure 2 shows network access for GCMs up to 85 t. Comparing Figure 1 and Figure 2, road access between 68.5 t and 85 t in Melbourne is currently significantly different. It was therefore determined when packaging ETS, GCMs should be kept to 68.5 t to aim for uninterrupted fleet operations. However, road access for 85 t is under development and is expected to grow. Therefore, the potential benefits of operating at 85 t is also explored. In Figure 3, the recorded GCMs have been added together in a cumulative distribution to identify the possible spare weight capacity for ETS. As shown in Figure 3, the 95 percentile of record data operated at 43.7 t or less. This leaves a potential 24.8 t free for operation at 68.5 t and 41.3 t free for operation at 85 t.

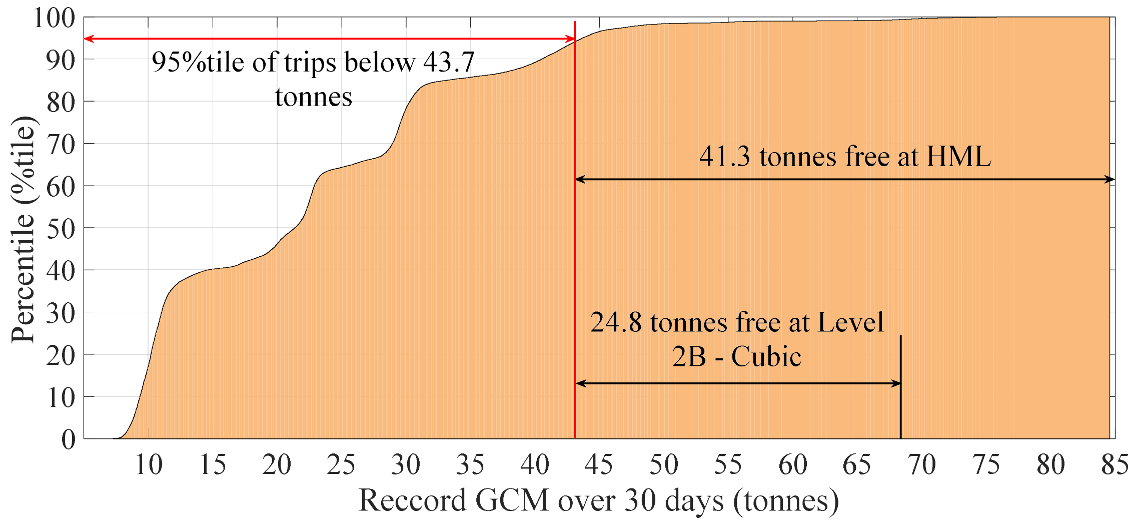

Figure 3 - Overall GCM over 30 day operational period

However, axle group weights need to be considered when adding the extra weight of ETSs to ensure current operations are not affected, and payload capacity is not reduced. Results from on-board scales were analysed to understand how each axle group is being used, see Figure 4.

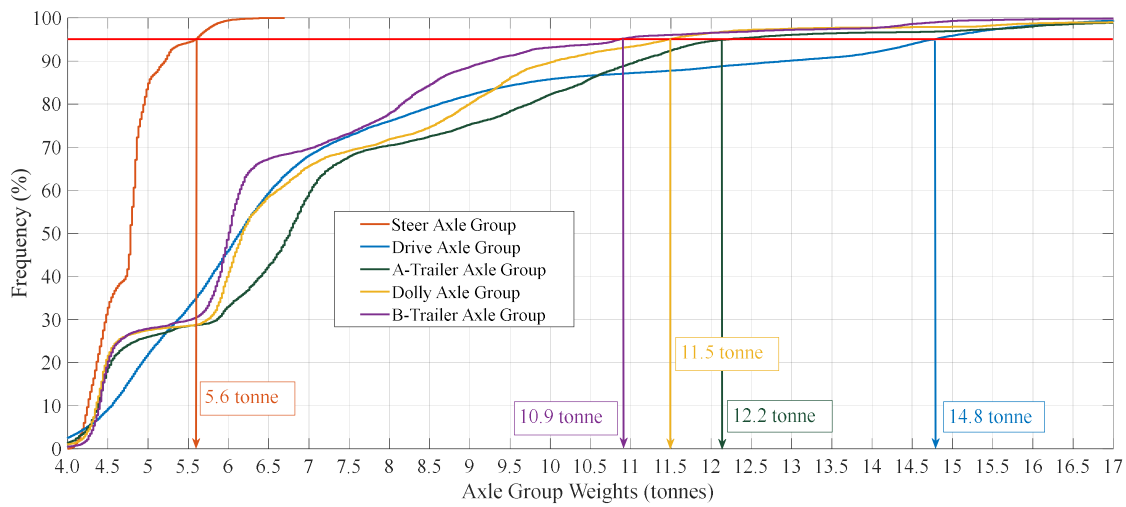

Figure 4 – Axle group loading over 30 days operational period

From axle group measurements, a new understanding of the free capacity was found. Adding up the peak axle group weight up to the 95 percentiles of operations, the new 95 percentile GCM became 55 t, leaving 13.5 t extra for max GCM at 68.5 t and 30 t extra for max GCM at 85 t. The distribution of new axle free capacity was compared against values in Table 1 and updates presented in Table 2. Two constraints are now in place for the additional mass of ETSs.

Table 2 – Axle Group limits based of 95 % of operational scope

Axle group	A1	A2	A3	A4	A5
Used axle mass capacity (t)	5.6	14.8	12.2	11.5	10.9
2B Cubic available mass (t)	0.4	1.7	7.8	5	9.1
HML available mass (t)	0.9	2.2	10.3	5.5	11.6

4. Operational Volume Analysis

The allowed packing space was examined, (see Figure 5). The analysis considered the volume free for battery packaging. For simplicity, it was assumed the motor, controller and other required components were packaged within axles. Due to the fifth wheel location on the prime mover, packaging space on A-trailer was smaller than B-Trailer. Therefore, volumes on the trailers were kept to 8.7m³ or less to assure flexibility in trailer placement.

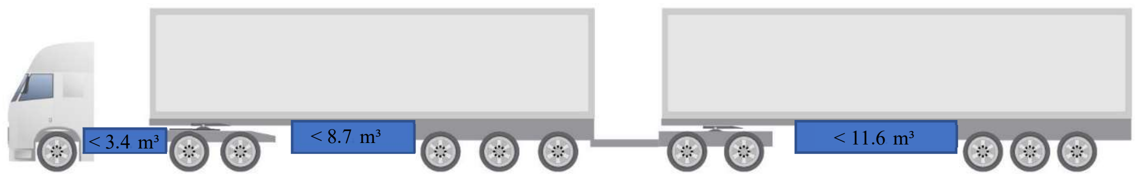

Figure 5 – Volume analysis of 30m A-double for battery packaging zones

5. Battery Capacity Analysis

Over the 30 days, total energy required (kWh) was calculated as a running sum for each combination and only charging time will reduce the running sum. Energy required at each time step was calculated using vehicle power equations (Naunheimer, Bertsche et al., 2011) and input parameter assumptions as described in Table 3.

Table 3 – Combination specifications

Vehicle	30m A-double	Tire size (m)	0.51
GCM range (t)	Up to 85	Rolling resistance coefficient	0.011
Road gradient (%)	-7 to 7	Air density (kg/m³)	1.2
Drivetrain Efficiency	0.93	Combination CdA (m^2)	9.67

To assure daily fleet operations are not affected with battery charging times, only down time was used as charging time. Idle time during loading and unload payload was not used for charging in this analysis. When a total of 30 minutes or more down time was recorded, an assumption was made that a 450 kW charger was available. Total kWh charged in the down time was deducted from running energy sum, and a new battery size starts to calculate again. In total, 145 different battery sizes were calculated and are depicted in Figure 6. Each battery size recorded had the capacity multiplied by 1.2 to allow 20% margin for unusable capacity. From Figure 6, it was found that the majority of extremely larger battery sizes (872 kWh and greater) contributed to SoC not returning to 100% SoC in the downtime, leading the next trip with a disadvantage of adding an average of 300 kWh.

For battery pack modelling, lithium ion battery cells in the form 18650 were used for packaging requirements. Battery package weight was set at 14kg/kWh and package volume at 0.005 m³/kWh (Saw, Ye et al. 2016). Battery package weights and volume are then assigned to 145 battery sizes to understand the packaging requirements. The worst-case operation required a battery of around 2400 kWh, which was beyond the 85 t limit, and therefore pure electric operation was not considered. Another observation, shown in Figure 6, was that axle weight limits were the limiting constraint not volume limits. Keeping within 68.5 t limit, only 4m³ or less was required for the battery package. This fits within a trailer and potentially inside a prime mover, (see Figure 5).

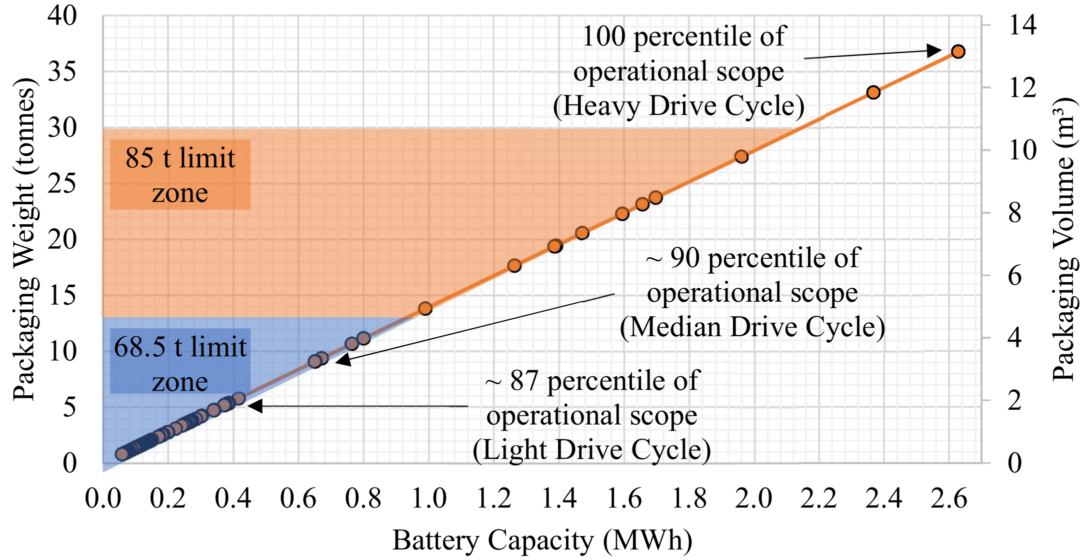

Figure 6 – Battery capacity required vs. battery weight and volume packaging

6. Drive Cycle

Based on the battery analysis, further numerical simulations are completed for actual required battery capacities based on dynamic powertrain loses. From Figure 6, three DCs are selected to cover the spread of operational demands in DCs; Light – 85 percentile of operations, Median – 90 percentile of operations and Heavy – 100 percentile of operations. DC summary data is shown in Table 3, and an example of drive cycle segment in Figure 7.

Table 3 – Combination specifications

DC	Avg. Speed (km/h)	Min. GCM (t)	Avg. GCM	Max. GCM	Trip Distance (km)	No. Idles	Time (hours)
Light	37	10.1	33.7	44.6	152	13	6.6
Median	33	15.0	32.2	60.0	256	53	15.3
Heavy	73	8.0	36.6	43.7	797	15	13.1

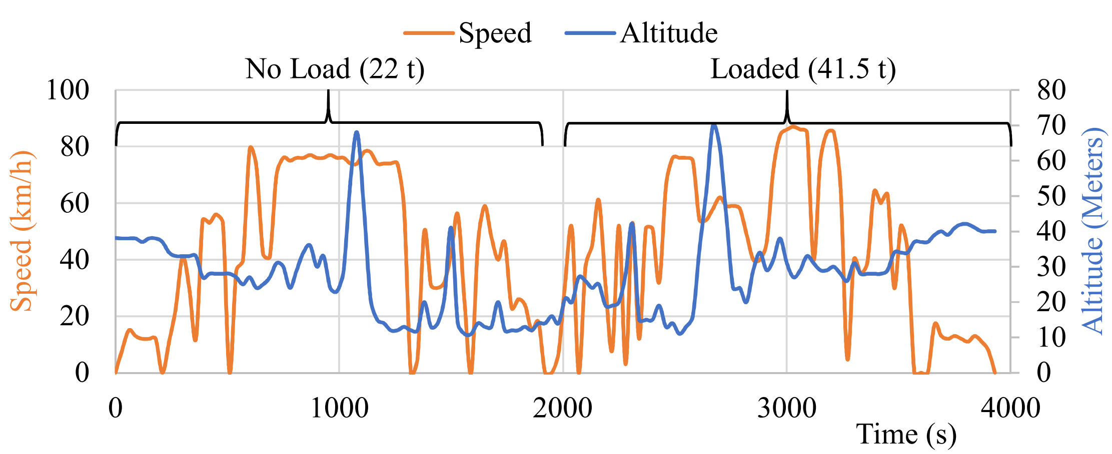

Figure 7 – Example of drive cycle

7. Powertrain Modelling Architecture

Three different architectures were examined; combustion, electric, and Through-The-Road (TTR) parallel hybrid. These architectures were built into a modified backward-facing powertrain model, (Figure 8). For the simulation of vehicle performance, Powertrain Architectures (PAs) were built in Matlab/Simulink™ with empirical components. During the development of the PAs, a modified backwards-facing model approach was selected as the ideal approach for comparing powertrains. In other modelling approaches, such as the forward-facing model, torque and rpm demands can be modified depending on the vehicle tracked performance and is better suited to vehicle controller developments (Mohan, Assadian et al. 2013). Common disadvantages with backwards-facing models is the limited dynamic flexibility. This has been addressed with a feedback loop between transmission and engine/motor blocks which contained statues information such as operational limitations, SOC of battery and ideal gear selections.

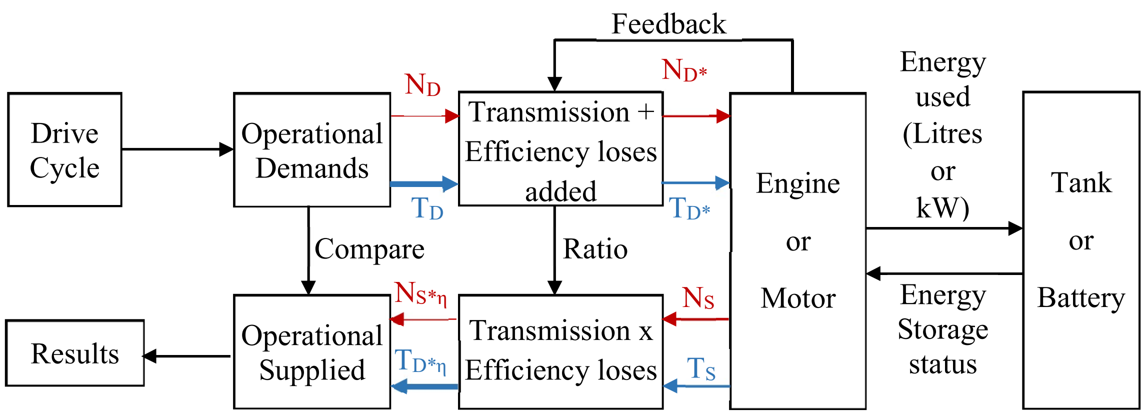

Figure 8 – Modified backwards-facing model for combustion and electric powertrains

7.1 Combination Architecture

The combustion model is built to the specifications of the combination which recorded the DC data, as shown in Table 4. A 600 hp 15 litre engine efficiency map was sourced from greenhouse Gas Emissions Model (GEM) for medium and heavy-duty vehicle compliance (EPA United States, 2017). The operational zone was limited to the Mack MP8 500. A layout of the combination is shown in Figure 9. Validation of model was achieved through comparing simulated fuel burn (1.51-1.87km/L) to fleets average recorded fuel burnt (1.81 km/L).

Table 4 – Combustion model combination specifications

Engine	Mack MP8 500	Transmission	Mack AT2612D
Peak Power/ Torque	373kW/2495Nm	Transmission weight	333kg
Engine weight, wet	1229kg	Differential	3.42:1

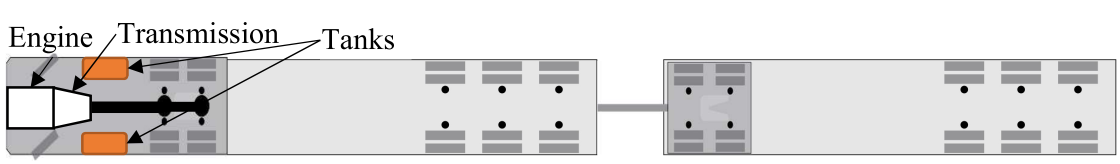

Figure 9 – Combustion 30m A-double architecture

7.2 Electric Architecture

The electric model was built dimensionally like the combustion model. However, combustion powertrain was swapped with ETS on the prime mover and an extra battery to the A-trailer, as shown in Figure 10. The Mack Transmission and differential axle ratio was used with the electric motors, giving the motors access to 12 gears to seek optimal operational efficiency. New vehicle details are shown in Table 5. Each different battery capacity simulated is multiplied by 14kg/kWh to determine the battery weight. The battery, motor and controller weights were added to the GCM for the new GCM simulation.

Table 5 – Electric model combination specifications

Motor	TM4 SUMO HD HV3500 -9P-L-01	System voltage	600V
Motor weight	340kg	Cell peak/nominal/min voltage	4.2V/3.6V/3V
Peak power/Peak Torque	372kW/3444Nm	SoC range	100% to 20%
Controller	CO300-HV	Regeneration available	SoC ≥ 90%
Controller weight	36kg	Discharge/Charge C Rating	2/2*

*Charge C-rating allowed for 10 seconds, continues is set at 0.5

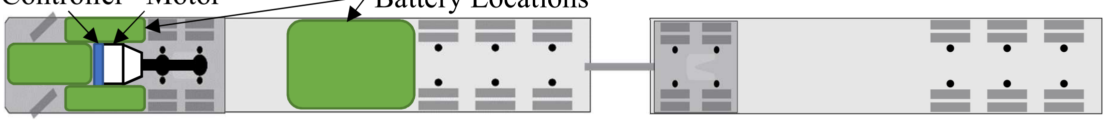

Figure 10 – Electric 30m A-double architecture 2

7.3Through-The-Road Parallel Hybrid

The combustion prime mover was used with an electric trailer to form the TTR parallel hybrid, sharing the power demands as shown in Figure 11. To split the power between powertrains, the ICE was treated like a generator. The most efficient point of the ICE was to set as the 'power mid-point', then a 'power radius' was applied allowing the ICE to operate fixed range, as shown in Figure 12. This approach was selected to not only reduce fuel burnt, but also reduce emissions. Keeping the ICE away from high power range and high exhaust temperatures helps with to reduce emissions (Thiruvengadam, Besch et al., 2012). The remaining power was supplied from the ETS, which included lower and high range power demands. The power radius was decreased and expanded as needed to change the demand on the ETS. Highest full savings resulted from battery capacity lasting the whole drive cycle, SoC = 20% at end of trip. Therefore, power radius was adjusted at each battery capacity tested to match this condition. Table 6 contains new and changed values for TTR parallel hybrid simulations.

Table 6 – TTR parallel hybrid combination specifications

Power mid-point	251kW	Motor Differential	3.8:1

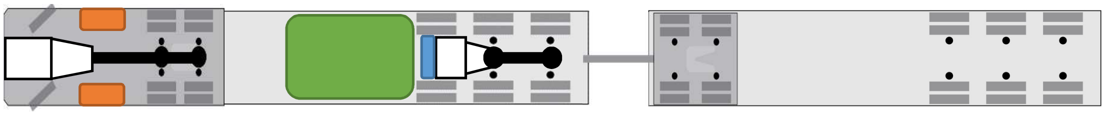

Figure 11 – TTR Parallel Hybrid 30m A-double architecture

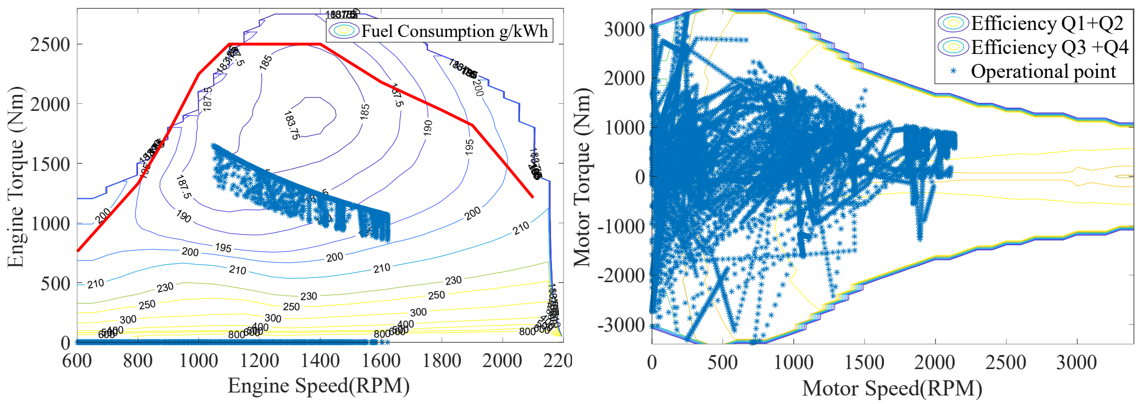

Figure 12 – Example of operational points mapped over DC. Left: 600 hp 15 litre GEM Fuel map restricted to MP8 operating range. Right: TM4 Motor Efficiency map

8. Simulation Results

Three different DC were simulated with Combustion, Electric and TTR parallel hybrid powertrains. For light and median DCs, all three powertrains were simulated with battery capacity increasing at 100kWh increments till pure electric was achieved. For heavy DC, pure electric was not possible due to GCM limits as described in section 5. For all simulations, fuel burn was reduced, even with the increased GCM brought on by battery weight as shown in Figure 13.

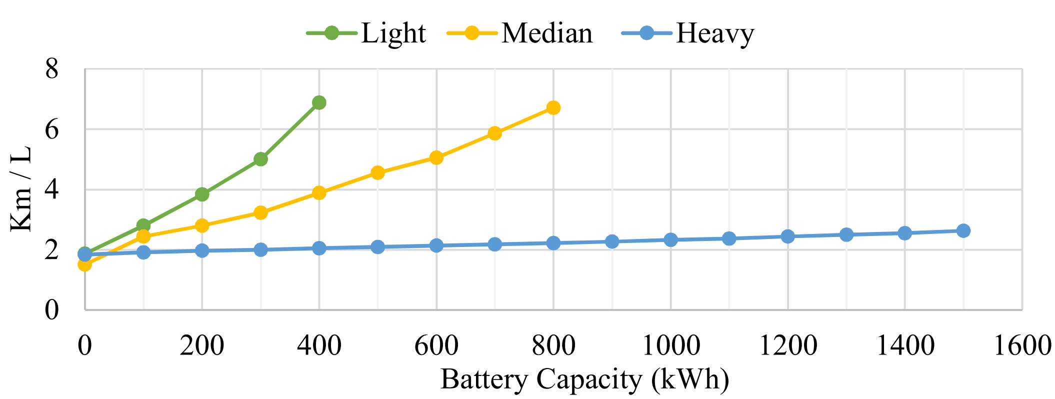

Figure 13 – Km travel against fuel burnt with different battery capacities

However, as fuel was reduced, a resulting increase in energy demands was placed on the ETS. The amount of battery kWh used on each DC shown in Table 7 as battery capacity increases. To understand the adjusted trip cost, a cost value was assigned to the total fuel and energy used over the DC. Diesel was set at $1.40 AUD and electricity prices at $0.23 AUD per kWh. The total cost of fuel and energy used was summed for each battery capacity simulated and compared back to the pure cost of running on diesel fuel only, (see Figure 14).

Table 7 – Fuel and kWh used over DCs

DC	Battery Capacity (kWh)	0	100	200	300	400	500
Light	Fuel Burnt (L)	81	54	40	30	22	0
	Energy used (kWh)	0	82	161	239	321	403
Median	Fuel Burnt (L)	170	105	92	79	66	56
	Energy used (kWh)	0	80	160	237	317	399
Heavy	Fuel Burnt (L)	434	417	403	399	390	382
	Energy used (kWh)	0	79	159	240	320	400

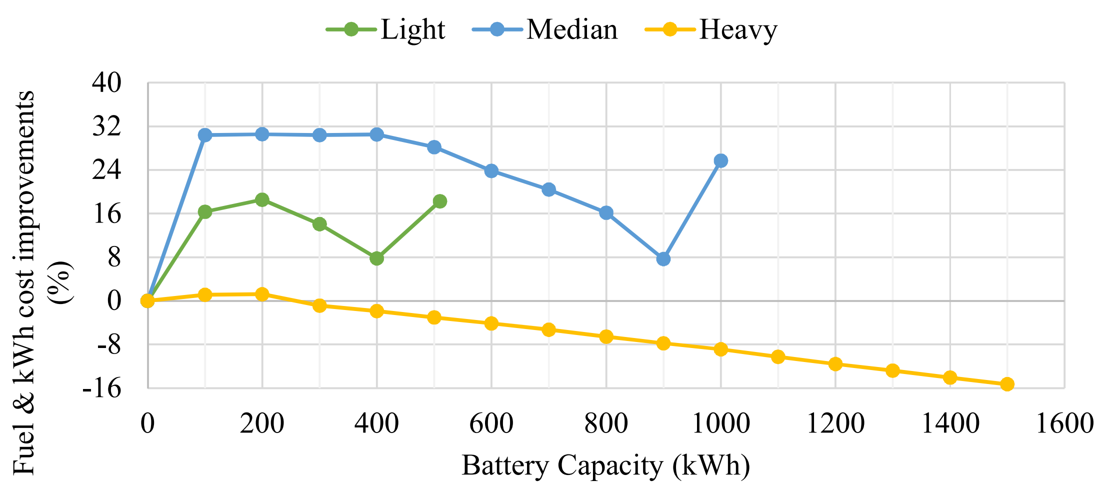

Figure 14 – Cost sum of fuel and battery kWh used over DC against different battery capacities

All DCs were ahead till around 200kWh, (refer Figure 14). After that point, the battery weight becomes a cost that is greater than ETS efficiency gains and % improvements decline. Spikes in light and median DC were due to pure electric driving - zero fuel costs. To put the % improvements into perspective, the upfront costs of the ETS needs to be compared. With the battery being the largest cost factor, two values of battery cost were selected based on expectations in 2022. The value of optimistic battery costs was set at $159 AUD (€100)/kWh and pessimistic battery costs were set at $477 AUD (€300)/kWh (Weldon, Morrissey et al., 2018). A percentile average of $169 is set at the combustions fuel cost at each operational day. A percentile average of values of the savings for each battery capacity was taken, (see Figure 14). Results of payback period up to 300kWh are shown in Table 8.

Table 8 – Payback period based of operational savings and battery costs

Battery Capacity (kWh)	savings based of percentile average	Saving ($) each operational day	Saving ($) in 312 working days	Payback at $159/kWh (years)	Payback at $477/kWh (years)
100	16	26.2	8189	1.9	5.8
200	17	29.5	9198	3.5	10.4
300	13	22.6	7066	6.8	20.3

In conclusion, the viable option in selecting battery capacity was strongly reliant on battery costs hitting $159/kWh, as payback periods within 5 years are deemed acceptable. However, this study is purely looking at fuel and energy costs. Payback period potentially can be improved by maintenance costs; such as reduced wear on the engine, transmission and brakes. Throughout DCs, regenerative braking reduced engine/frictional braking by 90.4%.

Furthermore, energy prices might drop if energy is sourced from renewable energy sources such as solar panels, lower electricity costs will have a strong effect on payback period. Additionally, further analysis is required to examination the impact of taxation credits currently applied to diesel fuels and electricity to determine what impact taxation may have on the payback period. Lastly, the cost of batteries was not the only factor to focus on, smart packaging and weight reduction could see the kg/kWh drop leading to less impact on combination GCM and less power demand.

9. PBS Assessment

Vehicle dynamics have been analysed through Tiger Spider™ for a PBS Assessment with ETS. The comparison was set to look at driveline performance at 68.5 t and 85 t. Four different powertrains were examined as shown in Table 9. Powertrain values were kept similar as described in section 7. Electric results show faster acceleration, but different gear ratios will result in better performance. TTRP Hybrid -fixed ratio results show a design flaw. For pure take off at a fixed ratio, it was not possible due to the large torque demands. However, a clutch was a potential solution, allowing maximum motor torque being accessible. Larger gear ratios are needed to improve startability and gradeability, however this can limit maximum speed. Finally, if combustion and electric powertrains are combined (combustion on prime mover and electric on trailer), more than double the traction is available which leads to increased performance across all metrics.

Table 9 – PBS driveline results

GCM (t)	PBS Metric	Combustion	Electric	TTRP Hybrid - fixed ratio	Combustion + Electric
68.5	Startability (%)	16.7	16.9	6.4	38.8
	Gradeability (A) max grade (%)	16.7	16.9	7.2	38.8
	Gradeability (B) km/h on 1% grade	90.2	82.9	83.0	118.3
	Acceleration capability 0-100m (s)	15.7	14.7	17.4	13.1
85.0	Startability (%)	13.6	15.2	5.1	39.5
	Gradeability (A) max grade (%)	15.2	15.2	5.8	39.5
	Gradeability (B) km/h on 1% grade	78.9	73.5	73.7	112.7
	Acceleration capability 0-100m (s)	17	15.8	19.3	13.6

10. Conclusions

Electrification of vehicles can potentially reduce emissions and operating costs, given the appropriate battery capacity. ETSs directed at HPFVs will allow an entry into lower emission road freight transport class. Additionally, HPFVs operate at relatively low cost compared to single semi-trailer configurations and therefore they offer a more realistic operating cost benchmark; ETS research should be more focused on HPFVs. The results in this paper show the possibilities of ETS strongly reducing fuel consumption and emissions. Yet the biggest obstacle to overcome was battery prices (optimistic prices set at $159 AUD(€100)/kWh). With the addition of battery packaging weight decreases, a strong business case can be built to support the uptake of HPFVs powered by ETS.

In addition, government bodies potentially can incentivise zero-emission HPFVs through better access to road networks. Operational areas around the selected DCs are affected by night curfews. Pure electric driving provides the possibility of HPFVs gaining 24/7 access between metropolitan ports and inland distribution centres. Driving in electric mode through curfew zones can reduce emissions, noise pollution and road congestion during the day time.

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