

University of Wales Trinity Saint David

Wales Institute of Art and Science



Kinetic Energy Recovery Investigation

Alternate Propulsion Systems – ACHA5010

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1 Abstract

Kinetic Energy Recovery Systems (KERS) are becoming increasingly important in modern automotive design as manufacturers strive for reduced emissions and better fuel economy. Part of this development has seen manufacturers retrofit previously designed chassis for the addition of KERS. In the automotive industry, the need for standardised testing led to the creation of the Worldwide Harmonised Light Vehicle Test Procedure (WLTP), which compares all vehicles in a standardised series of actions in order to assess fuel consumption and emissions in Internal Combustion Engine (ICE) powered vehicles as well as the range and performance of electric vehicles.

2 Introduction

This report details an investigation carried out into the required specifications of a Kinetic Energy Recovery (KER) system that aims to improve fuel consumption and emissions performance during WLTP testing. A current production vehicle was selected for this report. WLTP data in addition to vehicle data is used in order to produce expected energy and power values in order to choose appropriate components for the KERS. The vehicle chosen for this test is a Honda Civic MK9 Type R (2015-2017). This vehicle was chosen as this style of sports car need to improve its fuel consumption and reduce its emissions in order to remain relevant to modern consumers. As described by Adnan, Ahmad and Khan (2022), consumers are becoming more eco-conscious when buying cars and therefore automobile manufacturers have to adapt to this new demand.

3 Kinetic Energy Recovery Systems

3.1 Hybrid Vehicles

ICE powered passenger vehicle are currently posing a significant threat to the environment as they produce harmful emissions and as described by Cozzi and Petropoulos (2019), passenger vehicles consume around one quarter of the world oil consumption. This reliance on fossil fuels such as oil is unsustainable. Knox-Hayes *et al.* (2013) describe in their paper how oil is a finite resource and the emission produced from its combustion to create energy risks destabilising the planets climate. The long-term solution for the automotive industry is moving to Battery Electric, Hydrogen, Biofuel and other alternate propulsion systems however the technology and infrastructure required for these to be viable is currently under development (Al-Hanahi *et al.*, 2021). Hybrid ICE powered vehicles are seen as a temporary solution to the problem, as they consume 31.2% fuel when compared to an equivalent ICE model (Ivanov *et al.*, 2019). Legislation has been announced to limit the sales of pure ICE powered

vehicles will be banned from sale in the UK by 2030 (UK Government, 2020). As such the automotive industry has placed an increasing focus on development and sale of hybrid ICE powered vehicles.

3.2 Energy Storage and Deployment

The various methods of energy storage usually split into two categories, chemical and physical storage. Chemical storage involves storing energy in a device such as a batteries and physical storage involves using a system such as a flywheel or supercapacitor to store energy. The table below (Table 1) describes benefits and weaknesses of each viable storage system for this project.

Table 1 - Energy Storage

Type	Storage	Benefits	Weaknesses	Power and Energy Densities
Chemical	Lead Acid	Comparably cheap (against NiMH and Li Ion). Widely available.	Comparably heavy (against NiMH and Li Ion). Comparably short life span. Loose effectiveness over time.	25–35 Wh/kg (Aktaş and Kirçiçek, 2021) 80–90 Wh/l, 250 W/kg (May, Davidson and Monahov, 2018)
	NiMH	Comparable cheap (Against Li Ion). Can operate at a broad range of temperatures.	Heavier than Li ion. Limited life span.	100 Wh/kg (Tsai and Chan, 2013) 170–420 Wh/L (Revankar, 2019) 200 W/kg (Aktaş and Kirçiçek, 2021)
	Li Ion	Lightest chemical storage option. Becoming widely available. Good Power Density.	Limited life span. Limited range of operating temperatures. Shortened lifespan in hot temperatures.	100-265 Wh/kg, 250-670 Wh/L (Clean energy institute, 2020) 800 W/kg (May, Davidson and Monahov, 2018)
Physical	Supercapacitor	High discharge rate. Long life span. High power density.	Expensive.	20Wh/kg, 4.8 kw/kg (Shinde and Singh, 2019)
	Flywheel	High power density. High discharge rate.	Loses energy over time. Limited energy storge by centrifugal force.	3.33 kw/kg (Collins, no date) 150 W h/kg (Ertz, Twiefel and Krack, 2014)

With a mechanical device such as a flywheel, the power can be transferred between the storage system and the wheels using a mechanical connection. However, with chemical and supercapacitor storage a motor is needed to transfer this energy to the wheels and recover energy during deceleration.

4 Methodology

4.1 Vehicle Data

The data for the vehicle in this test is shown in Table 2.

Table 2 - Vehicle Data

Vehicle	Test Mass (Kg)	Frontal Area (m ²)	Rolling Resistance Coefficient	Drag Coefficient	Air Density (Kg/m ³)	Gravity (m/s ²)
Honda Civic Type R (2015 - 2017)	1482	2.340	0.015	0.3	1.225	9.80665

The value shown in Table 2 are calculated in the following ways. The test mass (m) is the vehicles curb weight +100kg to account for a driver and luggage. Frontal area (A) is an assumption calculated as 85% of the vehicle width x height. Curb weight, drag coefficient (C_d), vehicle width and height are provided by Automotive Data (2023). Rolling Resistance Coefficient (C_{rr}) is the value given for car tyres on new asphalt (Engineering ToolBox, 2008). As stated by Ayodele and Ogunjuyigbe (2016), Air Density is assumed to be 1.225kg/m³. As stated by Dachi and Setiawan (2018) the value of gravity is 9.80665m/s² at sea level.

4.2 Test Data

The WLTP is an 1800 second test consisting of four phases, low, medium, high and extra high speed (Phases 1- 4). Total duration for each phase is shown below.

Table 3 - WLTP Phases

Phase Number	Phase	Duration (s)	Individual Duration (s)
1	Low	0 – 589	589
2	Medium	590 – 1022	433
3	High	1023 – 1477	455
4	Extra High	1478 – 1800	323

The tractive effort and breaking energy are calculated using equations 1-4. Equation 4, Rolling Resistance (RR), is an assumption of average Rolling Resistance. As described by (Srirangam *et al.*, 2015), RR changes with ambient temperature and tyre temperature, which is not accounted for in this equation.

The power and braking power required are calculated using simulated WLTP test data (Equation 5). This data is also used to calculate Kinetic Energy available (Equation 6). These values are used to be able to specify appropriate components for the vehicles hybrid system.

5 Analysis and Discussion

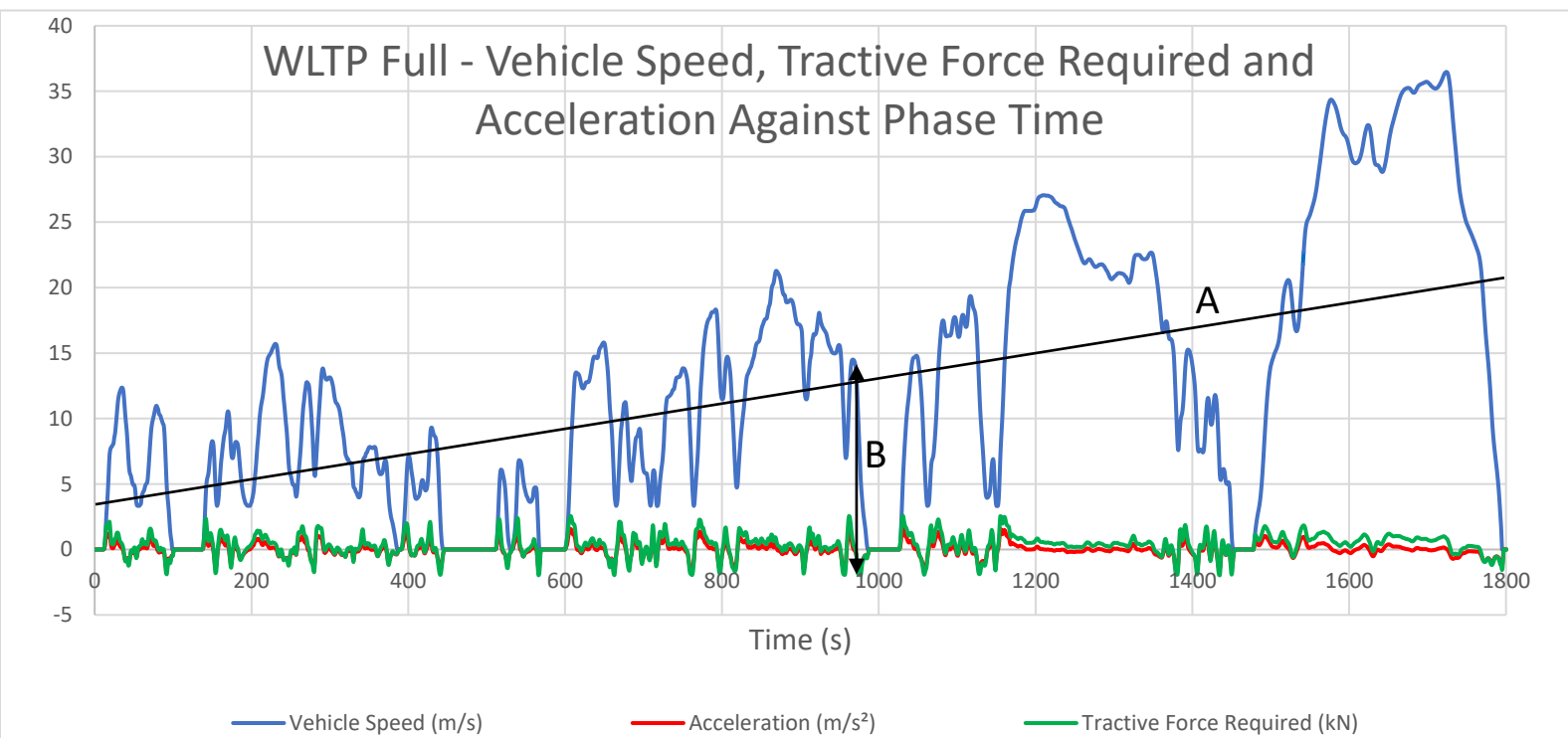


Figure 1 - Vehicle Speed, Acceleration and Tractive Effort for WLTP Test

From Figure 1 it can be observed that over the course of the test the average vehicle velocity increases (Line A). Line B shows an area of potential Kinetic Energy (KE) recovery, when the velocity is decreasing and tractive force is negative, the negative tractive force is braking energy needed. A version of this graph for each phase is shown in appendices (Figures 12-14).

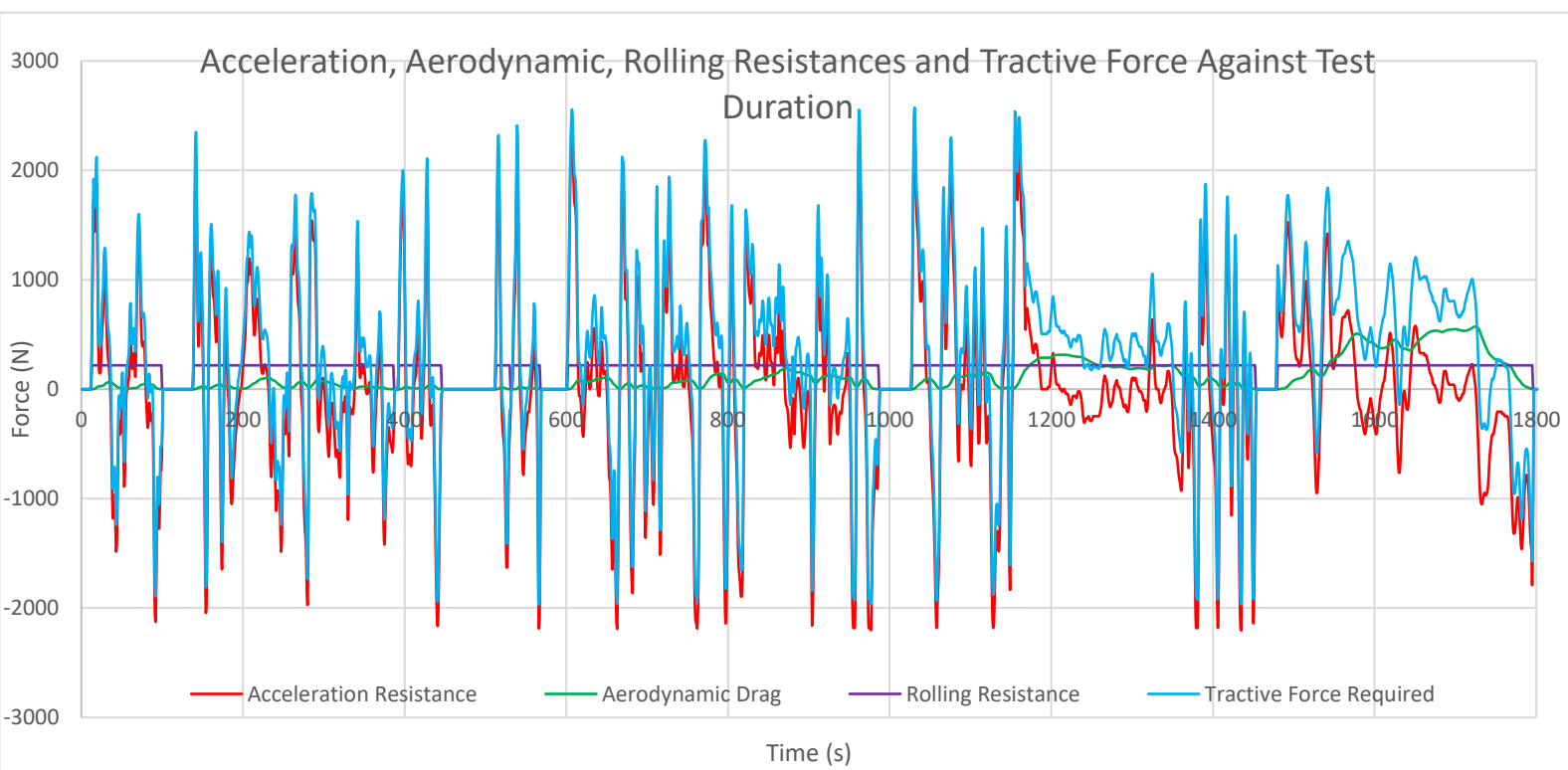


Figure 2 - Vehicle Resistances and Tractive Force over the WLTP Test

Table 4 - WLTP Test Data

Phase	Duration (s)	Stop Duration (s)	Distance (m)	Stop (%)	Max Velocity (km/h)	Max Velocity (m/s)	Average Velocity Without Stops	Average Velocity With Stops	Minimum Acceleration (m/s ²)	Maximum Acceleration (m/s ²)
Low	589	156	3095	26.5%	56.5	15.694	25.7	18.9	-1.47	1.47
Medium	433	48	4756	11.1%	76.6	21.278	44.5	39.5	-1.49	1.57
High	455	31	7158	6.8%	97.4	27.056	60.8	56.6	-1.49	1.58
Extra High	323	7	8254	2.2%	131.3	36.472	94.0	92.0	-1.21	1.03
All	1800	242	23262							

From Figure 2 it can be observed that acceleration resistance closely follows the trend of the Tractive Force required, this is due to the Acceleration Resistance being caused by inertia and the highest amount of tractive force is needed to accelerate the vehicle. This is true through the test until the High and Extra high phases where the Aerodynamic resistance has a greater impact. The areas of the graph that show read zero are areas where the vehicle has stopped, durations shown in Table 4. During these stops the engine is running at idle and still consuming fuel and producing emissions, therefore it would be beneficial for the hybrid system to have a stop-start feature. As described by Bent *et al.* (2013), stop-start implementation is predicted to improve fuel economy by 7.7% on similar drive cycles.

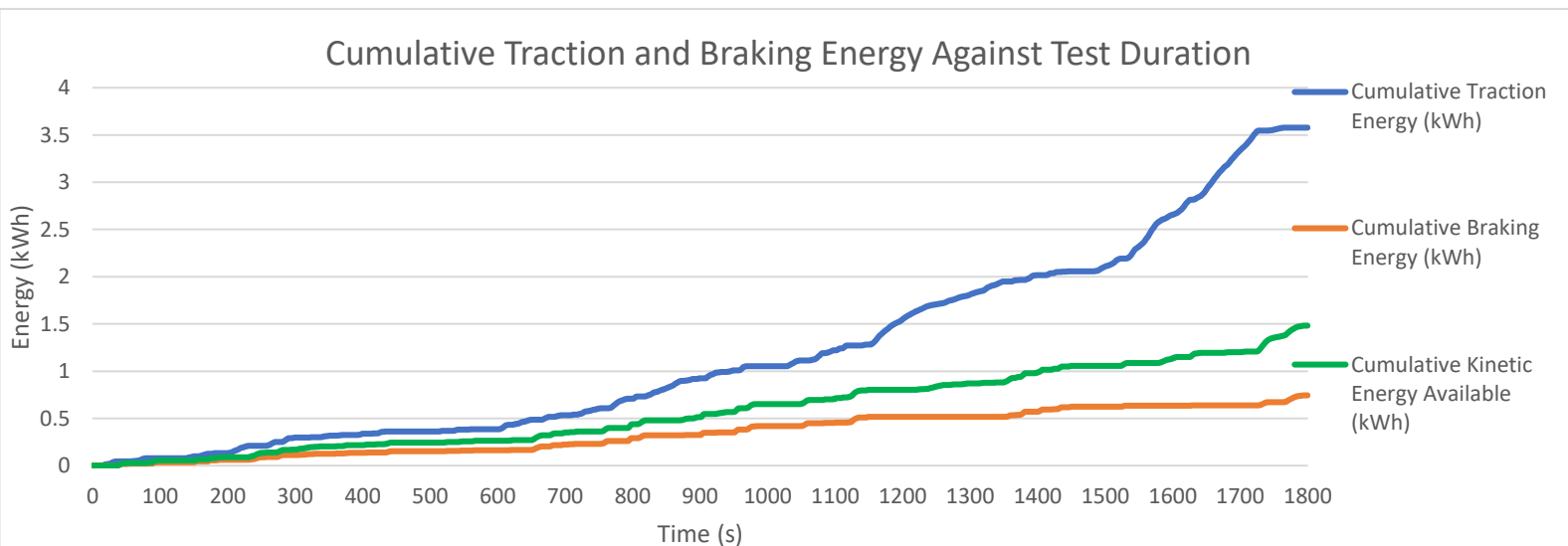


Figure 3 - Cumulative Traction and Braking Energy Against Test Duration

Table 5 - Cumulative Traction and Braking Energy for Test Phases

Phase Number	Phase	Cumulative Traction Energy (kWh)	Traction Energy for Phase (kWh)	Cumulative Braking Energy (kWh)	Braking Energy for Phase (kWh)	Energy Available (%)
1	Low	0.39	0.39	0.16	0.16	42.63
2	Medium	1.05	0.67	0.42	0.25	38.05
3	High	2.06	1.00	0.62	0.21	20.43
4	Extra High	3.58	1.52	0.74	0.12	7.95

Figure 3 shows the Cumulative Traction and Braking Energies for the test as well as an ideal KE available through the test, this is the sum of all KE losses over the test. Graphs for individual phases are shown in appendices (Figures 16-19). It can be observed that the rate at which Cumulative Traction Energy increases is greater than that of Braking Energy, especially during the High and Extra High phases. Suggesting that a greater proportion of energy is available for recovery in the Low and Medium phases. This is supported by the percentage of energy available shown in Table 5, calculated as a percentage of braking energy to traction energy, and shown in Figure 4.

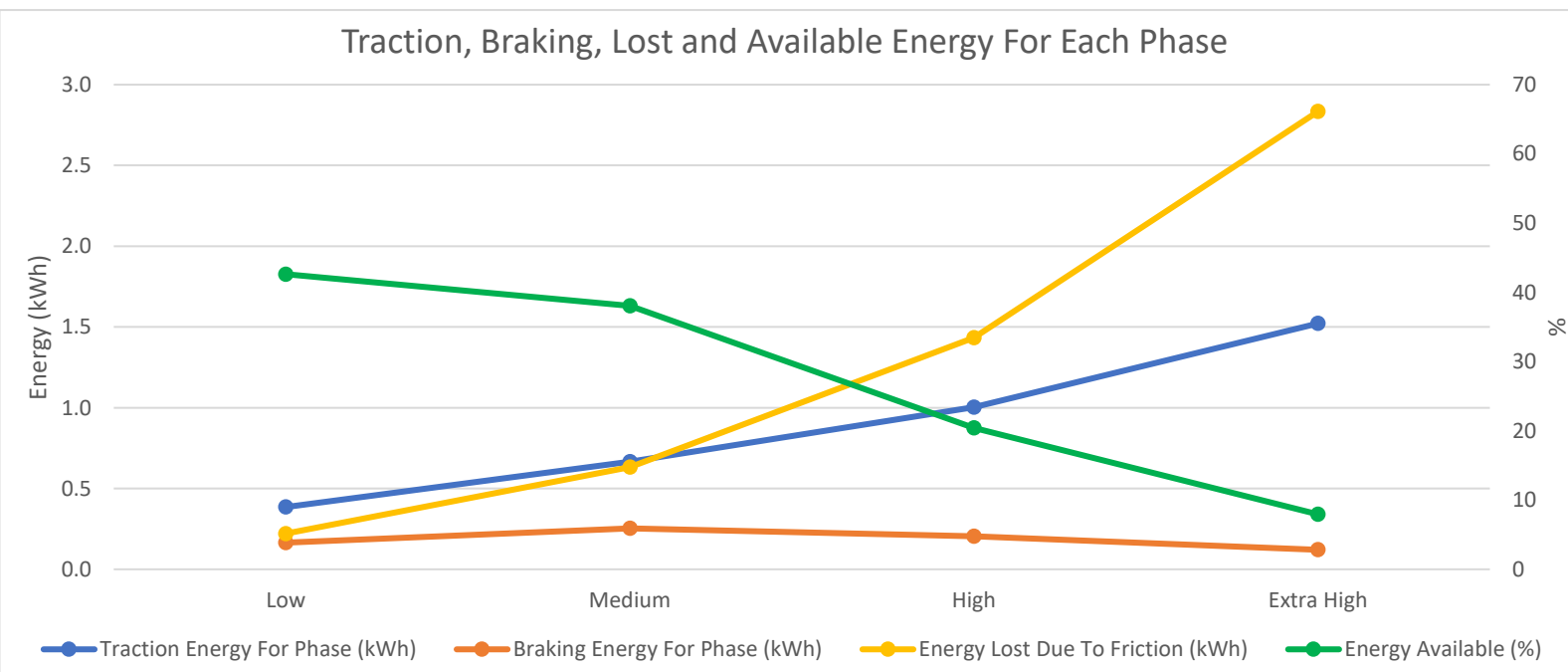


Figure 4 - Traction, Braking, Lost and Available Energy for Each Phase of the WLTP Test

Table 6 - WLTP Test Data 2

Phase Number	Phase	Max Power Required (kW)	Average Power Required (kW)	Total Power Required (kW)	Max Braking Power Required (kW)	Average Braking Power (kW)	Braking Power (kW)	Max KE (kJ)	Max KE (kWh)	Energy Lost Due to Friction (kWh)	Max Aerodynamic Drag (N)	Cumulative Kinetic Energy Available (Wh)	Cumulative Kinetic Energy Available for Phase (kWh)
1	Low	20.05	5.14	1387.47	13.61	3.48	591.43	182.52	0.05	0.22	105.92	263.27	0.26
2	Medium	27.77	8.65	2397.11	27.66	8.45	912.19	335.48	0.09	0.63	194.68	652.25	0.39
3	High	33.12	10.89	3615.75	26.36	7.94	738.83	542.41	0.15	1.43	314.77	1055.74	0.40
4	Extra High	42.54	20.91	5477.73	18.06	8.07	435.52	985.70	0.27	2.83	572.01	1481.57	0.43
	All	42.54	11.29	12878.07	27.66	6.30	2677.98	985.70	0.27	5.12	572.01		

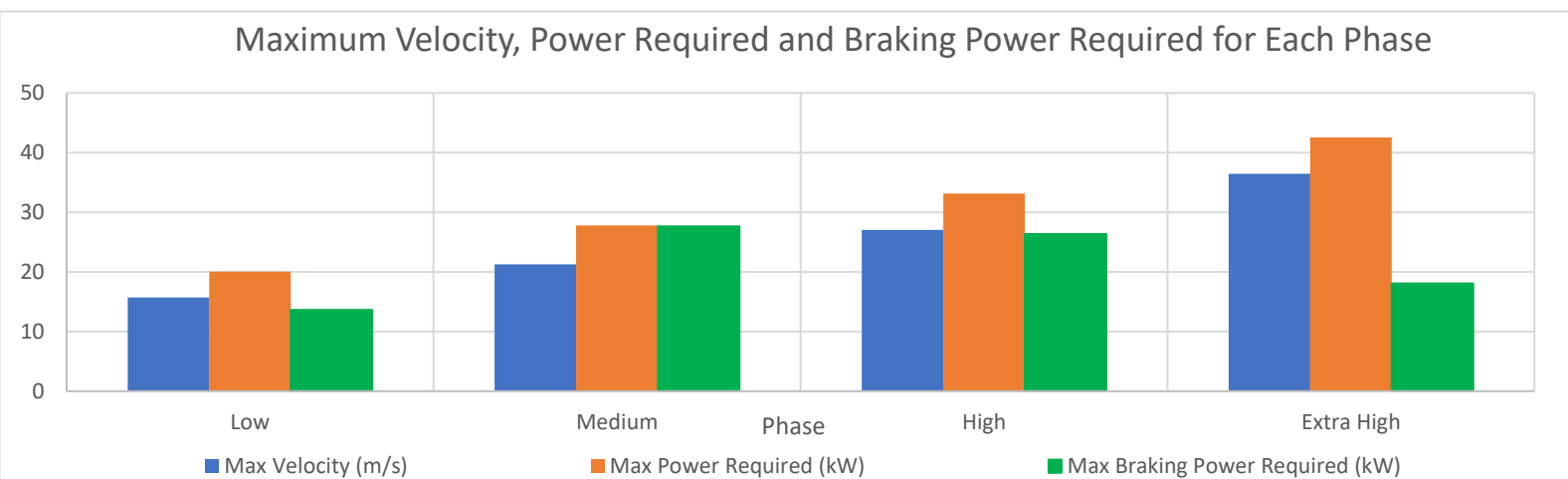


Figure 5 - Max Velocity, Power and Braking Power Required for Each Phase

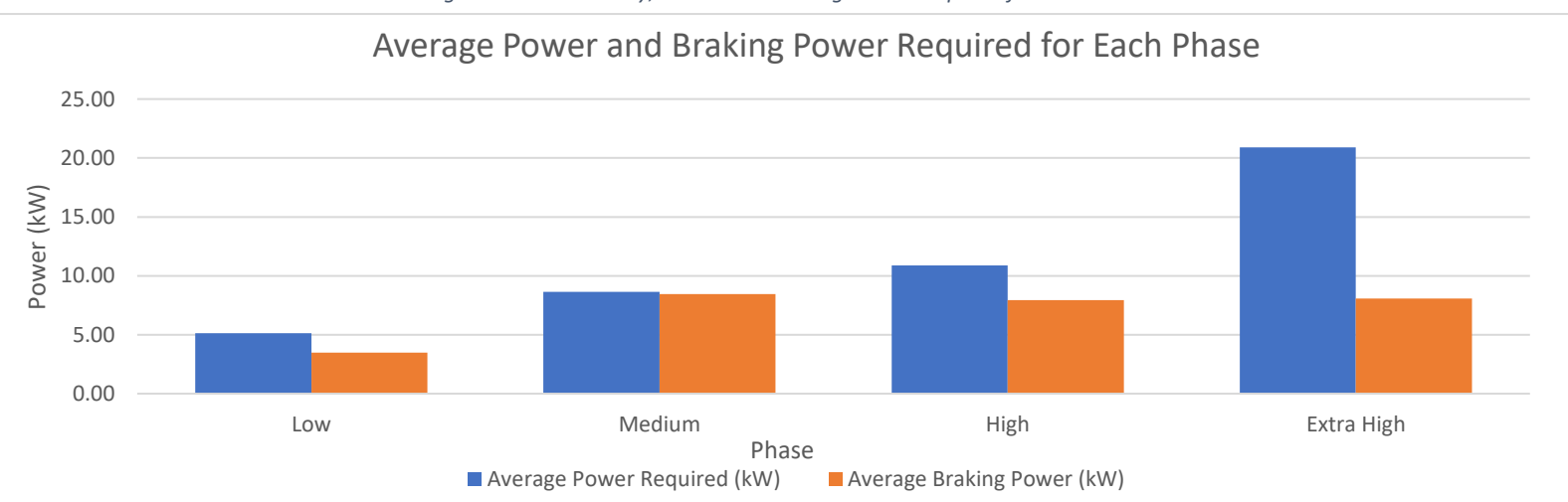


Figure 6 - Average Power and Braking Power Required for Each Phase

Figures 5 and 6 show Maximum (Max) and Average Power (Avg) and Braking Power for each phase from data in Table 6. From Figure 5 it can be observed that Max and Avg Power Required increases over the course of the test with Max Velocity however, Max and Avg Braking Power does not increase in the same way. This is due to the increase in energy lost to friction that can be calculated as the difference between Cumulative Traction and Brake Energy shown in Figures 4 and 7. More energy is lost during the High and Extra High due to the increase in velocity leading to an increase in Aerodynamic Drag, this can be observed in Figure 8. These factors suggest that focusing on the Low – High Phases would be most beneficial as a greater proportion of the energy is unrecoverable in the Extra High Phase. This is also supported by Figure 9 where it can be observed that the Extra High phase has the highest energy requirement and the least energy available for recovery.

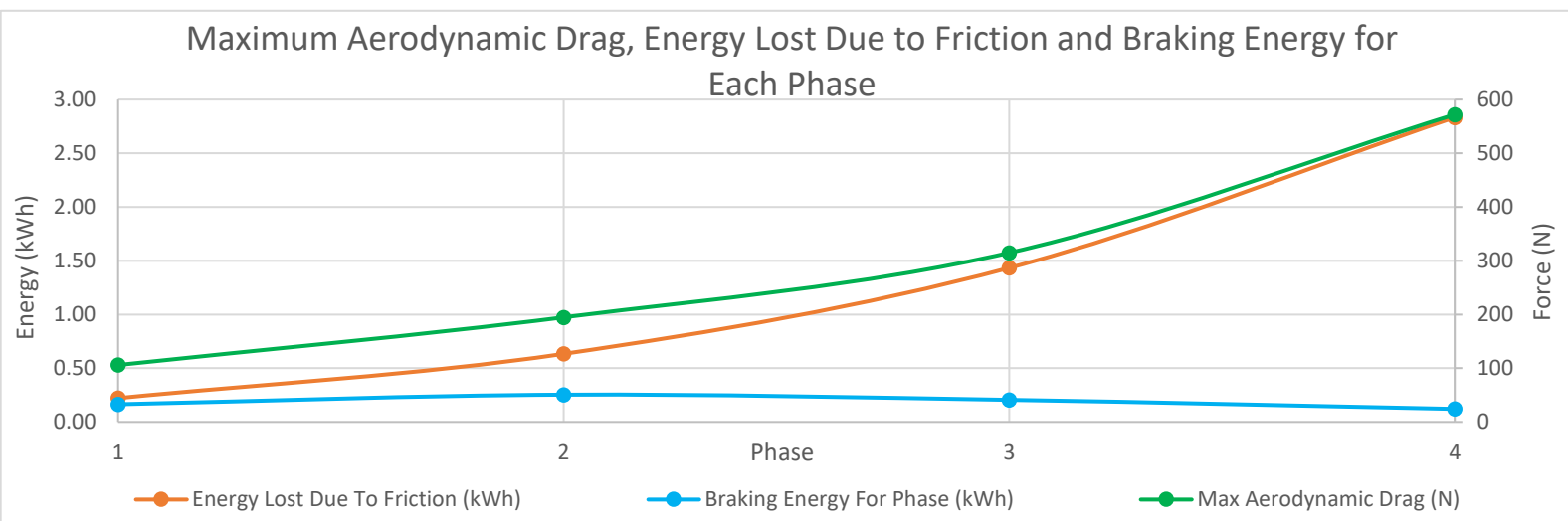


Figure 7 - Max Aerodynamic Drag, Energy Lost due to Friction and Braking Energy for Each Phase

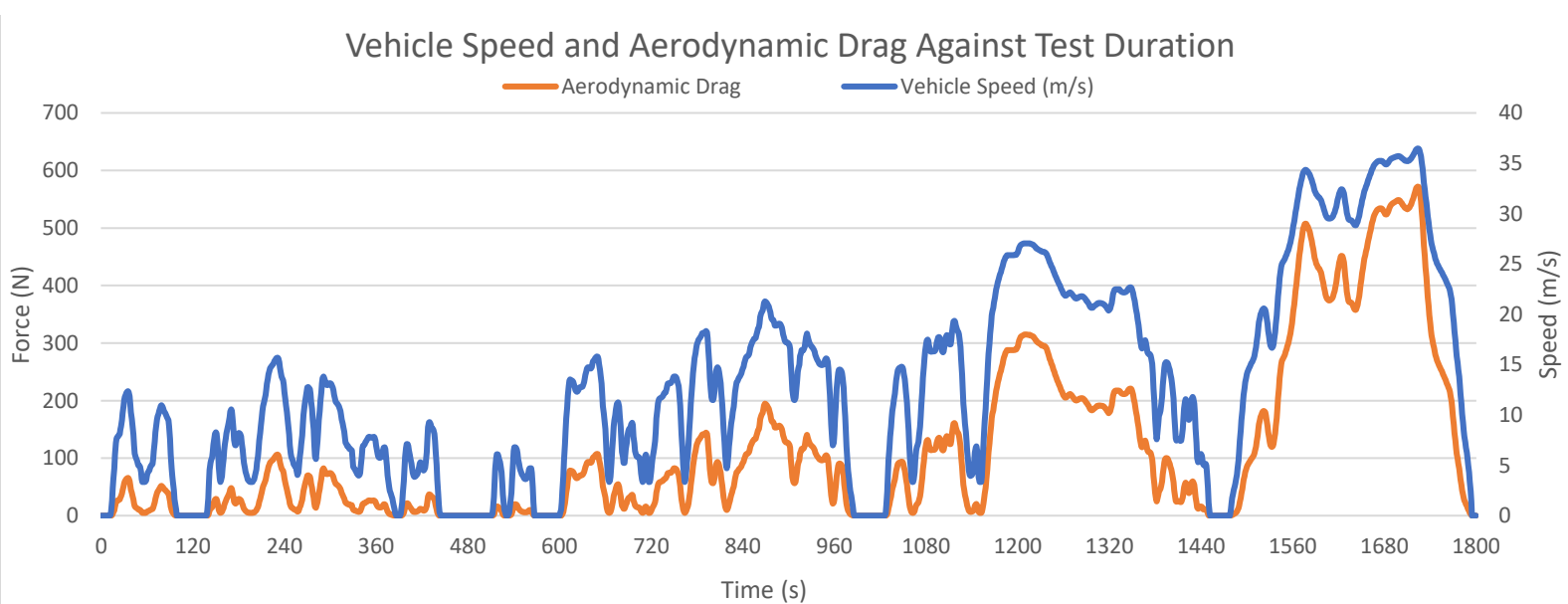


Figure 8 - Vehicle Speed and Aerodynamic Drag Against Test Duration

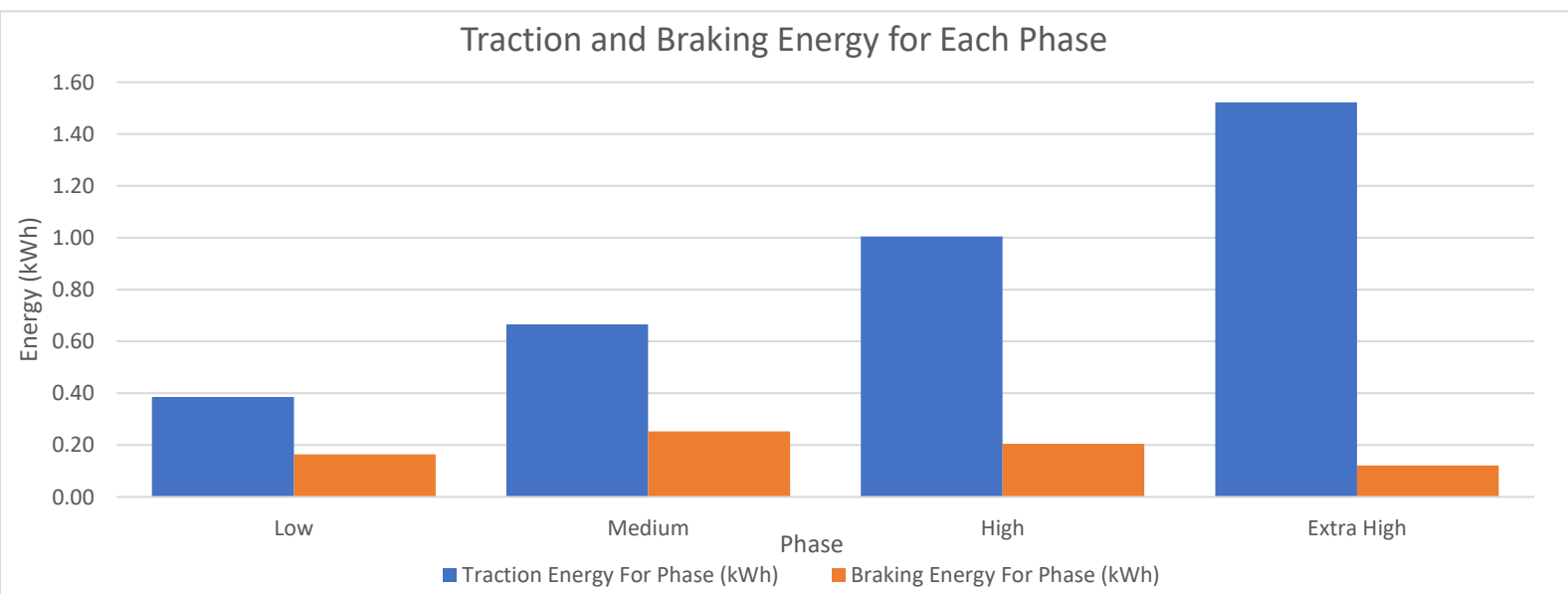
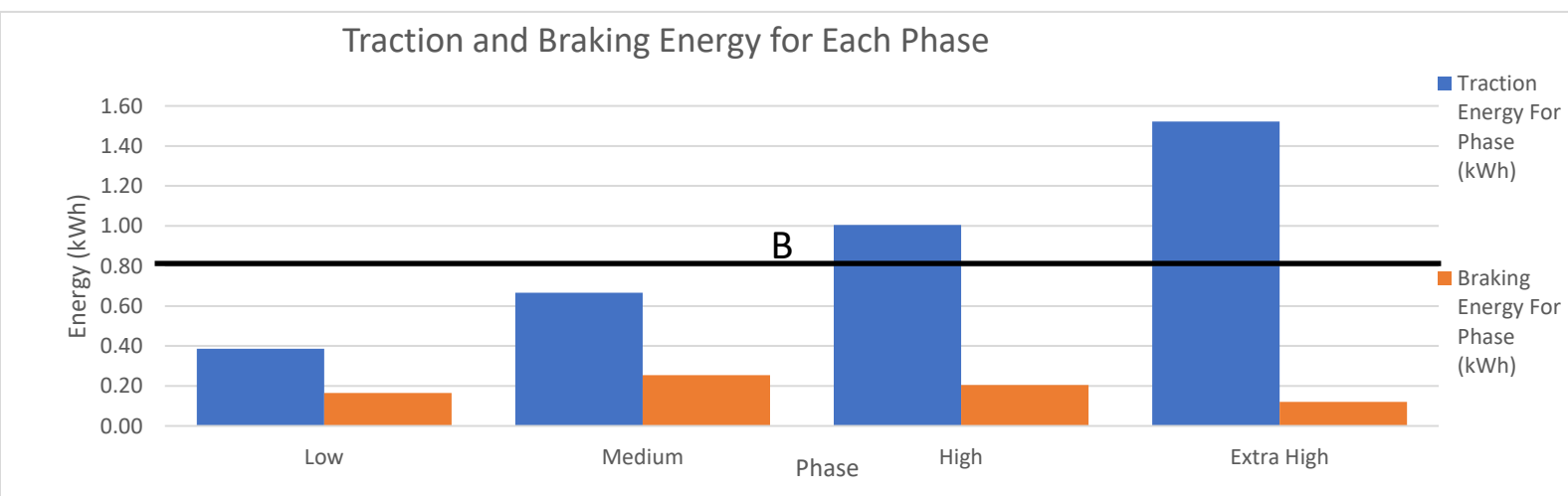
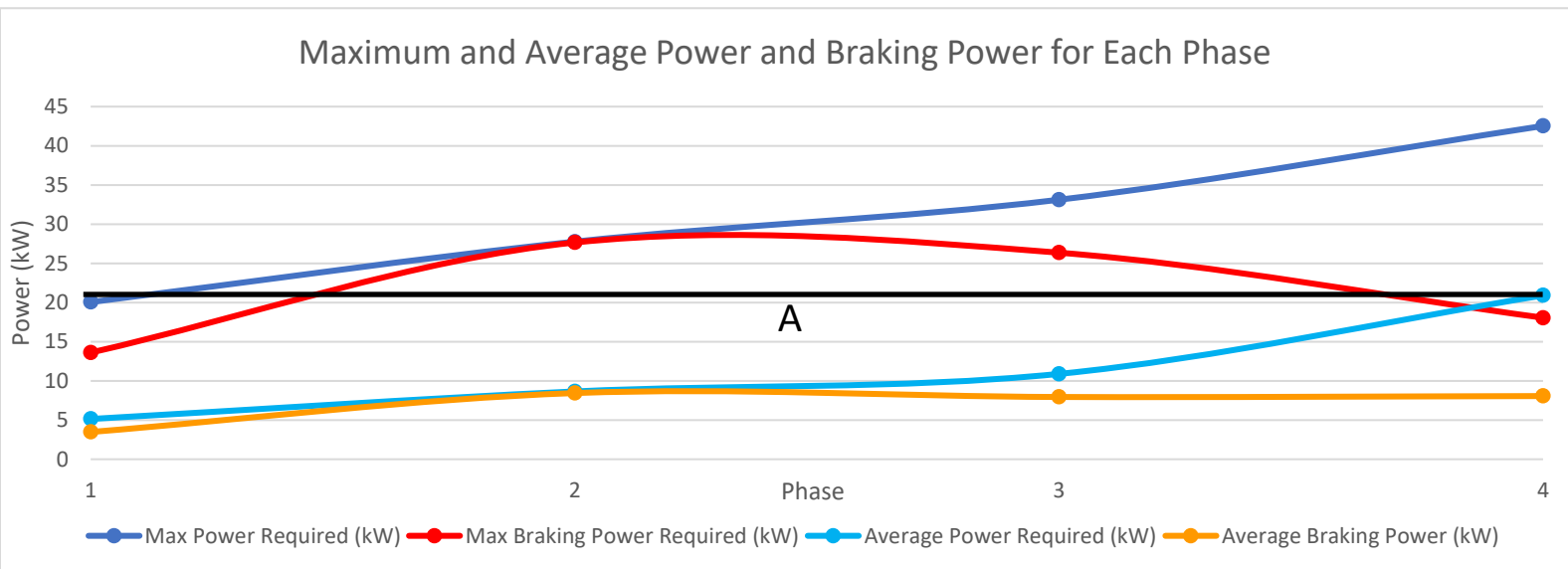


Figure 9 - Traction and Braking Energy for Each Phase

6 Kinetic Energy Recovery System Specifications

6.1 System Specifications



As previously discussed, the focus for this system will be on phases 1-3. From Figure 10 it can be observed that a 20kW (Line A) motor would be able provide and recover all power in Phase 1, most of the power needed in Phases 2 and 3 and recover all power available in Phase 4. Additionally, this specification of motor is above the average Power and Braking Power needed for all Phases apart from Phase 4. Figure 11 shows how a 0.8kWh (Line B) energy storage system would be capable of storing all possible recovered energy from all phases, in addition to this if the storage system is at full capacity at the start of the test then the KERS would be able to deploy all power energy needed for Phase 1, and if not for the limitation of the motor it would be able to provide enough energy for Phase 2 as well. A storage system of this capacity would also be beneficial during the vehicle road use where the larger capacity could take advantage of the power available during long sections of downhill driving. The

storage method chosen is a Li Ion battery (0.8kWh), chosen for its low mass and availability. Using values in Table 1, a 0.8kWh Li Ion battery would have a mass of 30kg and a size of 11.94l (0.01194m³). A battery of this size could fit under the rear seats of the vehicle to maintain the practicality of the vehicle, a slight amount of rear headroom may be lost. The addition of 30kg to the vehicles mass should not affect handling characteristics to a large degree, however the placement of the battery may lower and better centralise the vehicles centre of gravity improving handling characteristics. The motor chosen for this is a 20kW brushless DC motor attached to the engine's flywheel. As described by Majid Hussain *et al.* (2020), DC motors are efficient, easy to maintain and are easier to control than AC motors. Additionally, brushless motors are more suitable than brushed as they have a longer life span.

6.2 Driver Considerations

The most efficient way to recover energy while decelerating would be to have the KERS and friction brakes in series, where energy is recovered by the KERS until at full capacity in which time the friction brakes take over however the transition point between these can be quite unpleasant for pedal feel. One potential solution to this is to have the system runs in parallel, where friction brakes and KERS work together, however in this case some potentially recoverable energy is lost. Therefore, the best option is to have the systems run in series but have the KERS recover in 0-5% throttle range with the friction brakes functioning as normal when the brake pedal is pressed to allow energy to be recovered without the use of the friction brakes. When providing power, it would be beneficial for the motor to deploy all of its power between 5-30% throttle and to push the opening of the throttle body further into the throttle pedal travel to allow the vehicle to deploy as much energy as possible while utilising the ICE as little as possible to increase efficiency. The vehicle's stop-start feature will start the engine from the electric motor by spinning the flywheel as such eliminating the need for cranking and removing the delay caused when starting from a stop in most stop-start systems.

7 Conclusion

The vehicle chosen will be fitted with a 20kW DC Brushless Motor and a 0.8kWh Li Ion Battery including a stop-stat feature. This will improve fuel consumption during the WLTP through recovering KE during braking and deploying this energy during periods of acceleration. This will make the car more relevant to modern consumers and less damaging to the environment.

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9 Appendices

WLTP Low Phase - Vehicle Speed, Tractive Force Required and Acceleration Against Phase Time

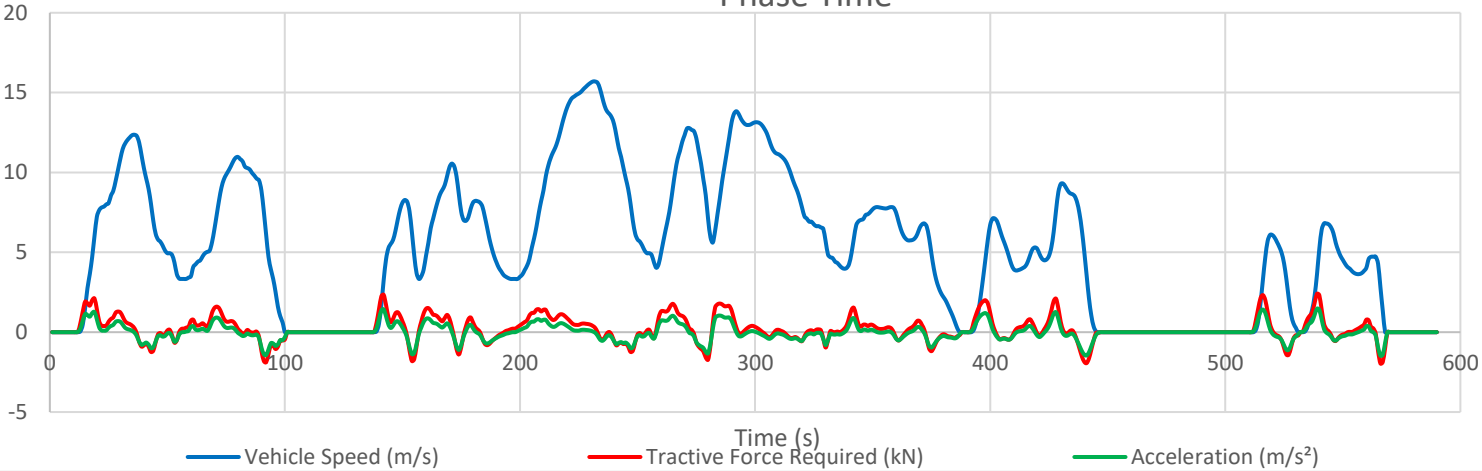


Figure 12 - Vehicle Speed, Acceleration and Tractive Effort for WLTP Test Low Phase

WLTP Medium Phase - Vehicle Speed, Tractive Force Required and Acceleration Against Phase Time

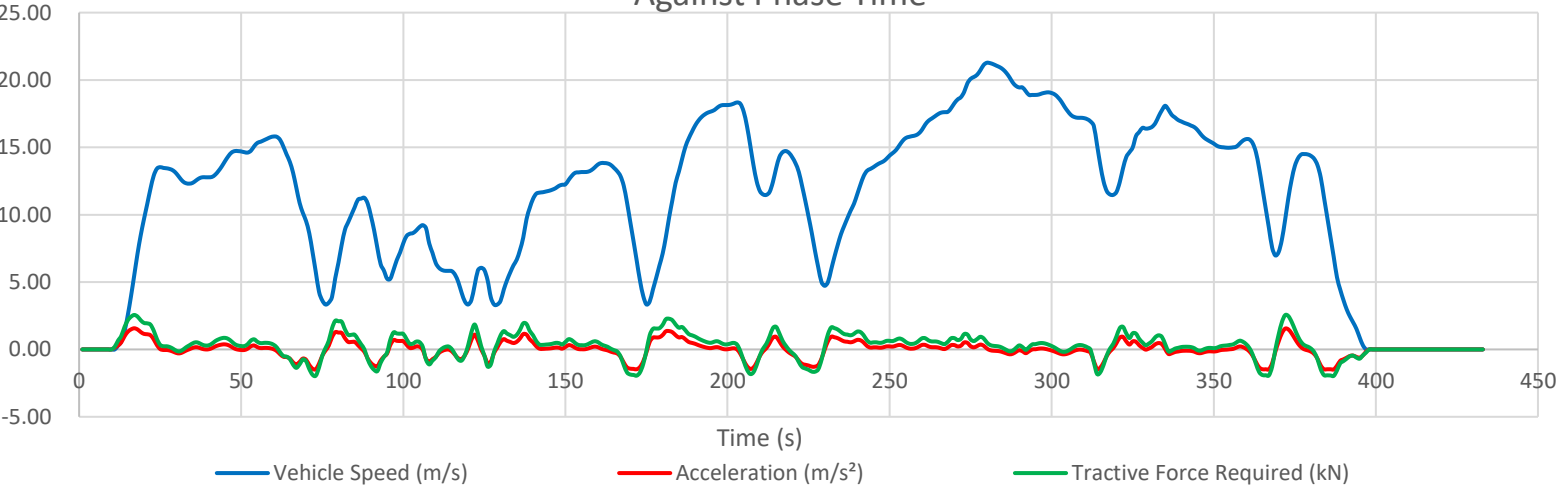


Figure 13 - Vehicle Speed, Acceleration and Tractive Effort for WLTP Test Medium Phase

WLTP High Phase - Vehicle Speed, Tractive Force Required and Acceleration Against Phase Time

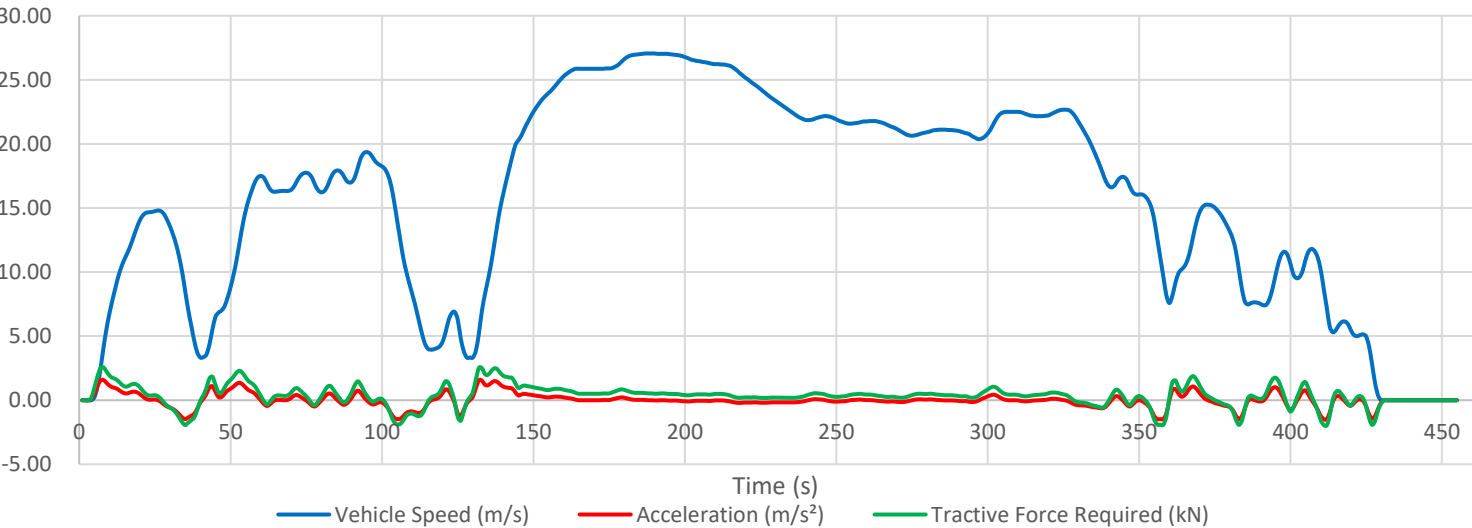


Figure 14 - Vehicle Speed, Acceleration and Tractive Effort for WLTP Test High Phase

WLTP Extra High Phase - Vehicle Speed, Tractive Force Required and Acceleration Against Phase Time

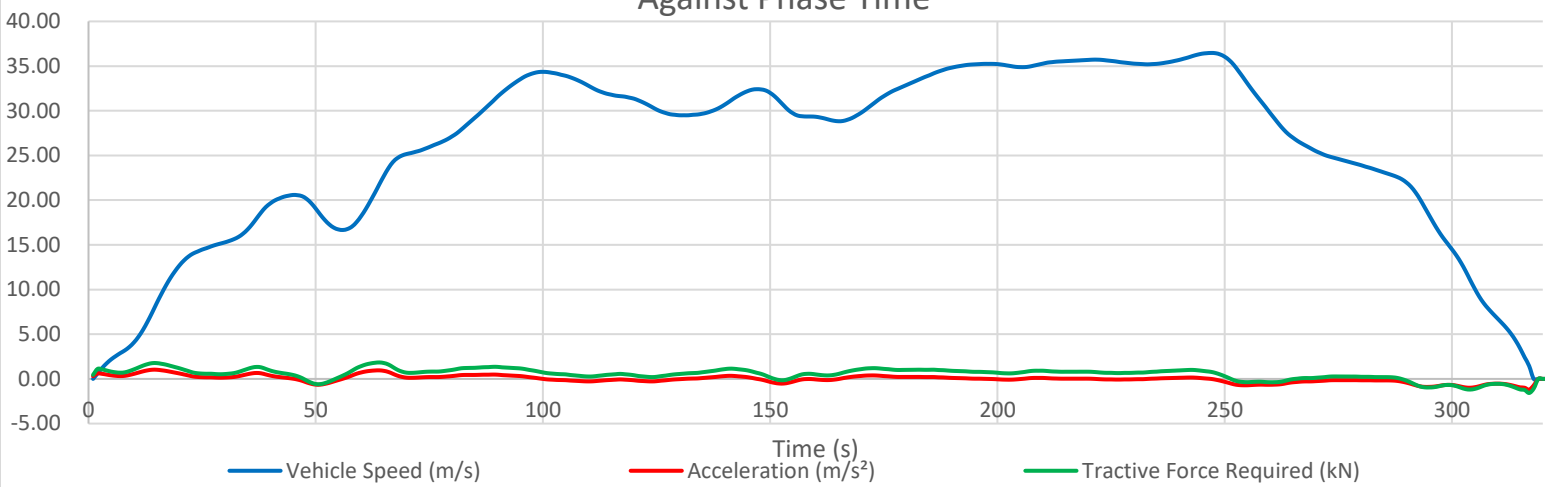


Figure 15 - Vehicle Speed, Acceleration and Tractive Effort for WLTP Test Extra High Phase

Cumulative Traction and Braking Energy Low Phase

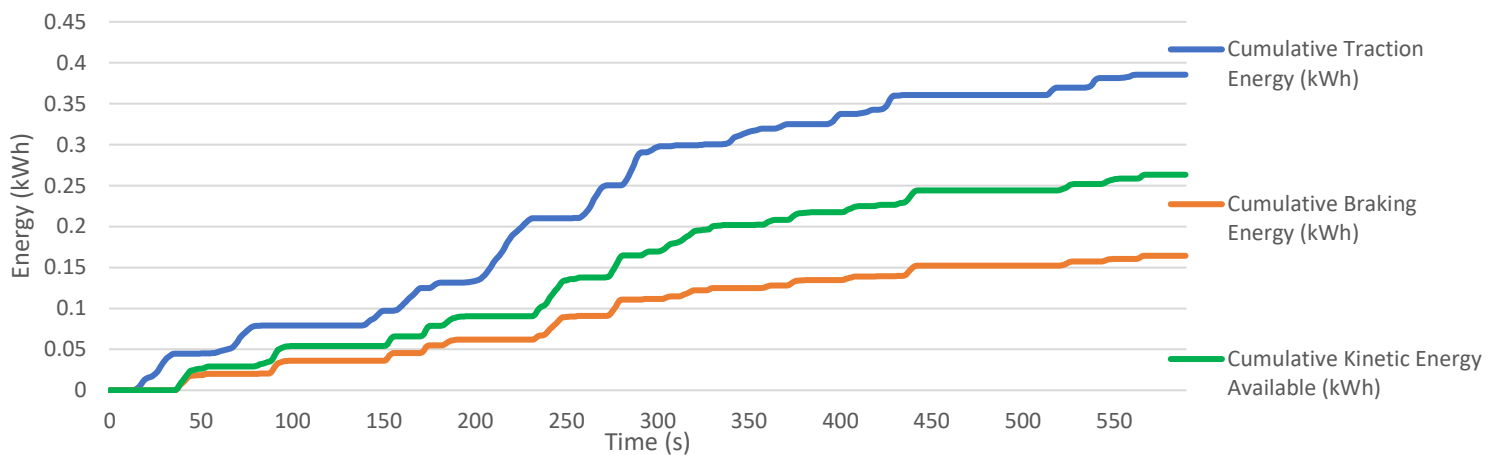


Figure 16 - Cumulative Traction and Braking Energy Low Phase

Cumulative Traction and Braking Energy Medium Phase

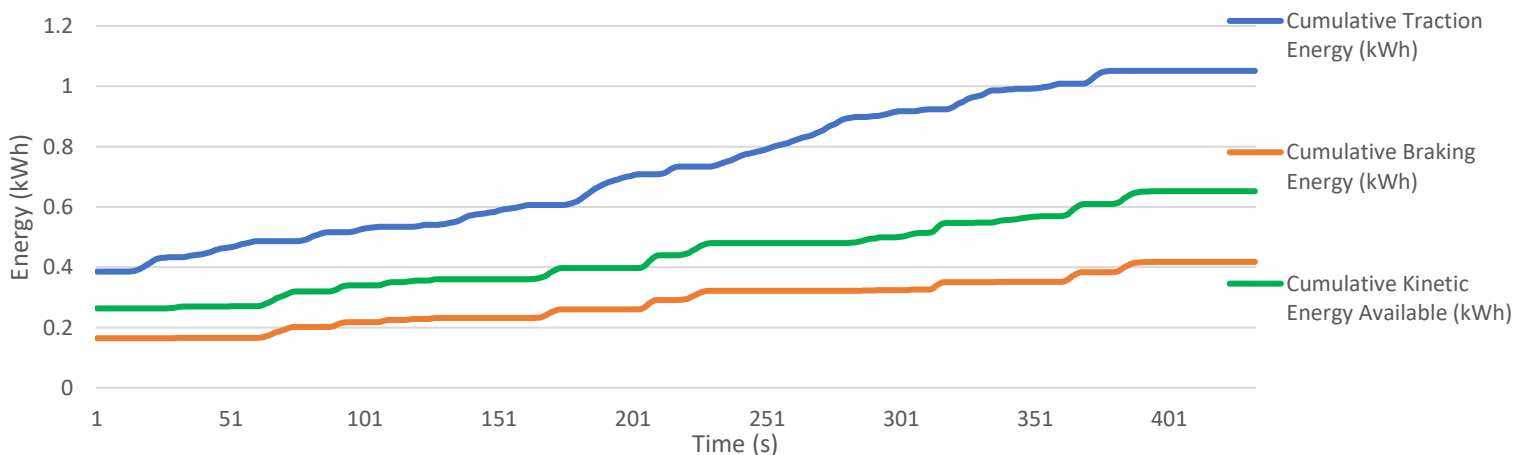


Figure 17 - Cumulative Traction and Braking Energy Medium Phase

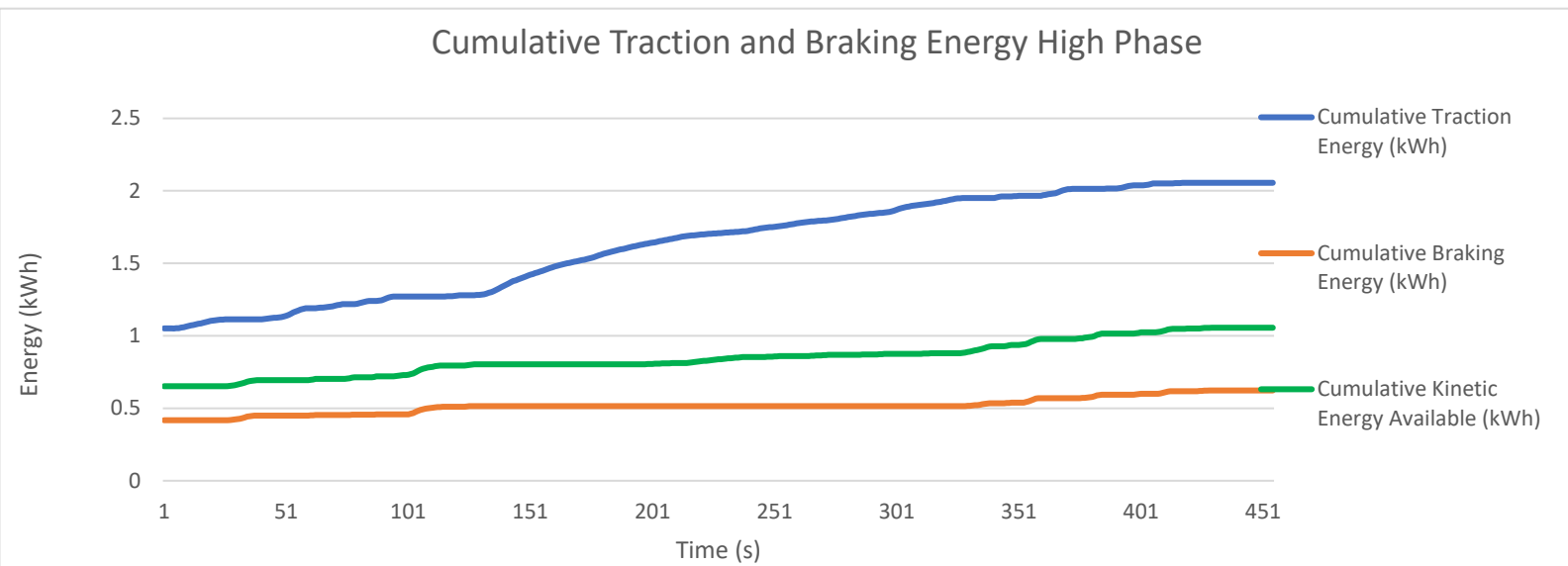


Figure 18 - Cumulative Traction and Braking Energy High Phase

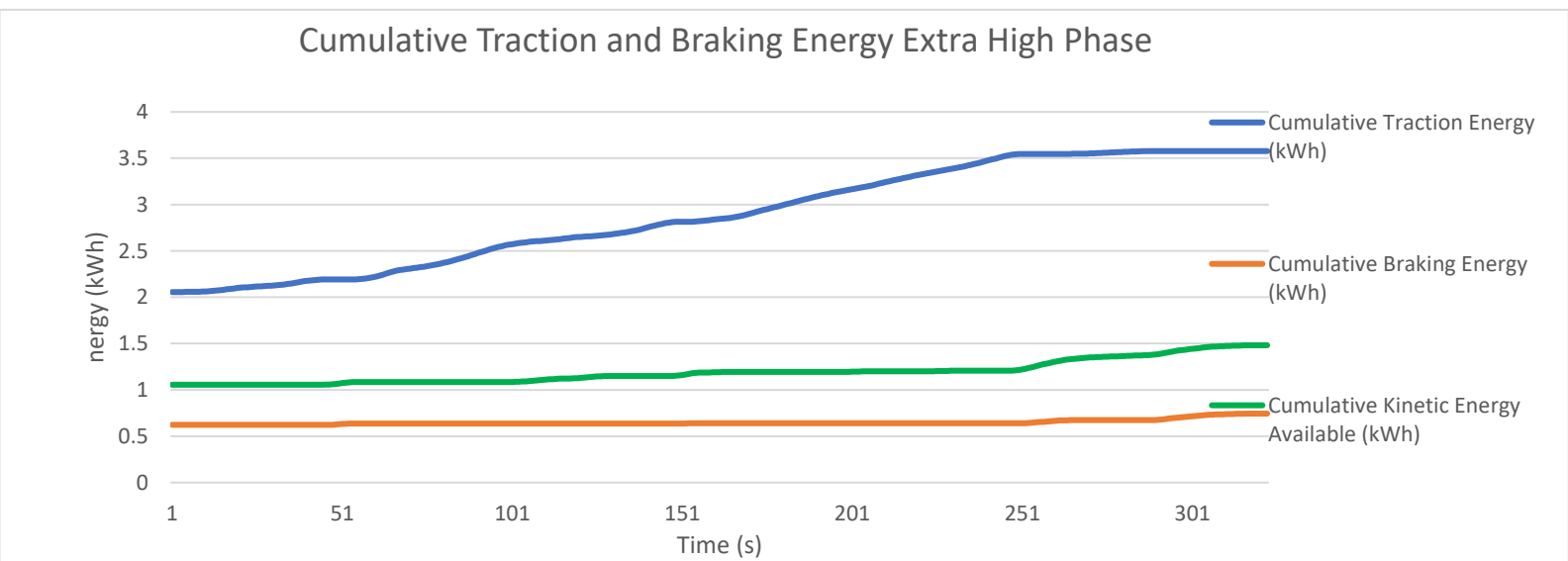


Figure 19 - Cumulative Traction and Braking Energy Extra High Phase

Table 7 - Equations

Number	Name	Equation
1	Tractive Effort	$E_T = R_A + D + F_r$
2	Acceleration Resistance	$R_A = m \times a$
3	Aerodynamic Drag	$D = C_d \times \frac{1}{2} \times \rho \times v^2 \times A$
4	Rolling Resistance	$F_r = C_{rr} \times m \times g$
5	Power	$P = E_T \times v$
6	Kinetic Energy	$KE = \frac{1}{2} \times m \times v^2$

Table 8 - Terms and Abbreviations

Term	Definition
KE	Kinetic Energy
KRES	Kinetic Energy Recovery System
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
ICE	Internal Combustion Engine
KER	Kinetic Energy Recovery
NiMH	Nickel Metal Hydride
Li Ion	Lithium Ion
m	Test Mass
A	Frontal Area
W	Vehicle Width
H	Vehicle Height
E_T	Tractive effort
R_A	Acceleration Resistance
D	Aerodynamic Drag
F_r	Rolling Resistance
a	Vehicle Acceleration
C_d	Vehicle Drag Coefficient
C_{rr}	Coefficient of Rolling Resistance
ρ	Air Density
v	Vehicle Velocity
g	Gravity
P	Power
Max	Maximum
Avg	Average