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Kinetic Energy Recovery

Alternative Propulsion Systems – ACHA5010

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01/24

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Introduction

This report examines the integration of a Kinetic Energy Recovery System (KERS) in the 2018 BMW S1000RR, aiming to enhance performance and fuel efficiency. Initial scrutiny involves dynamic characteristics, aligning with the Worldwide harmonised Light vehicle Test Procedure. A comprehensive spreadsheet illustrates cumulative tractive and braking energy, identifying peak KERS potential. System specifications, component sizing, and efficiency determination follow. Graphs depict kinetic energy recovery, accompanied by operational explanations, assumptions, and driver experience variations. The chosen sport bike serves as a compelling case study, contributing insights to sustainable mobility discussions and the fusion of advanced technologies in high-performance vehicles.

Dynamic characteristics

Vehicle specifications



Figure 1: BMW s1000rr

(Beyl)

Power = 146KW at 13500rpm

Torque = 113Nm at 8000

Max engine speed = 14200 RPM

Kerb Weight = 208KG (ready for road, 90% fuel load)

Gross weight = 407kg

Bike power to weight ratio = 0.702 KW/KG or 0.941 hp/kg

(<https://www.manuals.co.uk/bmw/s-1000-rr-2018/manual?p=210>)

Test mass

As mentioned above the BMW has a kerb weight of 208kg, this weight is the bike with all fluids plus 90% load of fuel. The weight of the rider also needs to be added to give us the total test mass with the rider weighing 70kg and wearing 10kg of safety equipment brings the test weight to 288kg.

Rolling resistance

Rolling resistance is the resistance created by your tyres on the road that needs to be overcome to allow the vehicle to be able to accelerate. There are a lot of factors that effect the rolling resistance such as surface, pressures, contact patch, rubber and more. Rolling resistance has a considerable effect on the vehicles performance and uses about 3 to 5 % of a vehicles fuel consumption to overcome(<https://www.michelin.co.uk/auto/advice/tyre-basics/rolling-resistance>). The BMW s1000rr has a rolling resistance coefficient of 0.02, we can use this value to calculate the total rolling resistance force by using the equation below (Rolling resistance, n.d.)

$$\text{Rolling resistance force (N)} = \text{rolling resistance Co} * (\text{vehicle mass} * 9.81)$$

Aerodynamics

Frontal area

To calculate the frontal area of the bike I took an image of the BMW being ridden and used it in solid works to outline the perimeter of the bike and rider to be able to calculate the frontal area as shown in the figure below. It is worth noting that different riders will majorly affect the frontal area depending on their positioning and size.

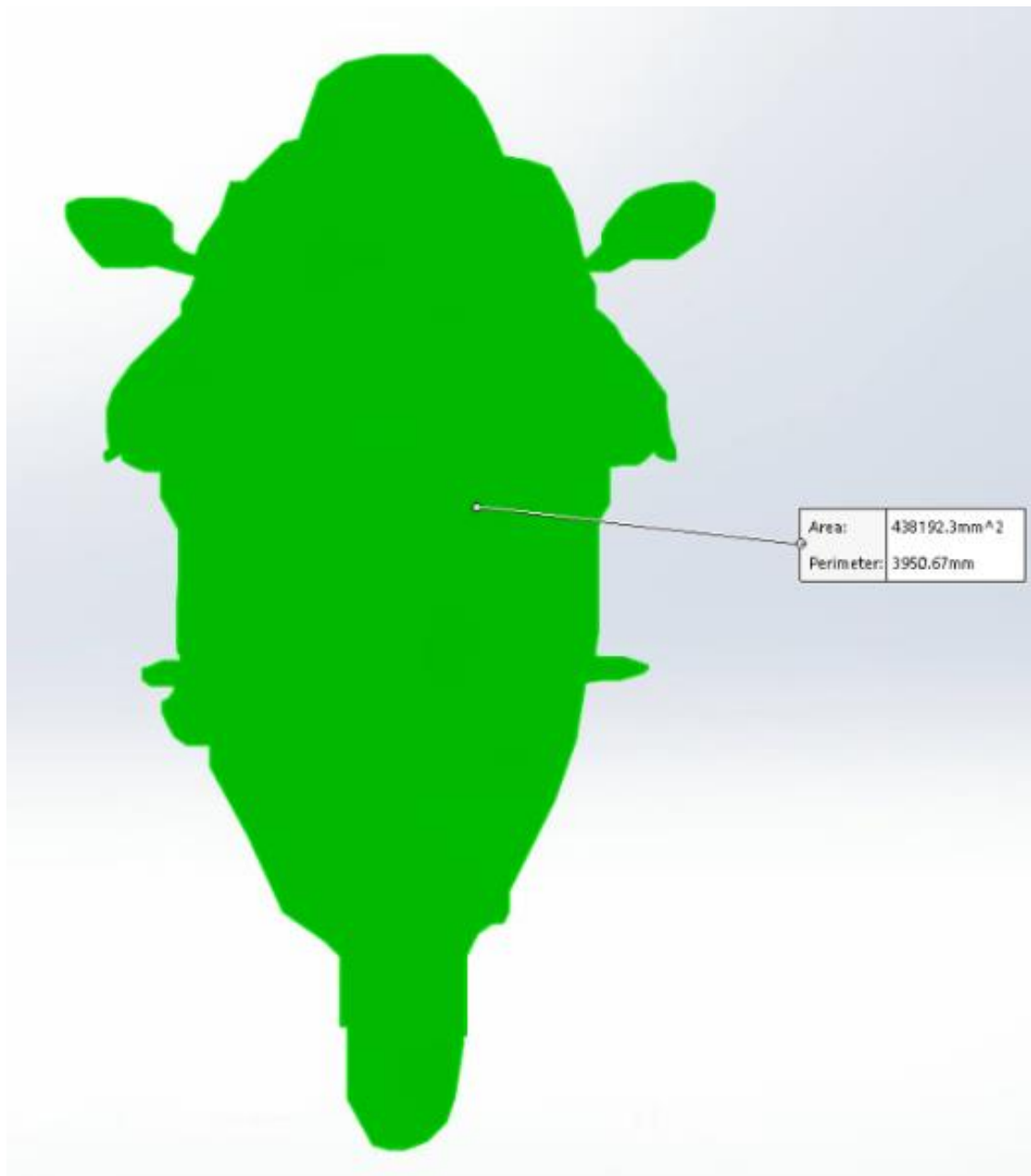


Figure 2: BMW s1000rr frontal area

As we see the bike has a total frontal area of 438192.3mm² or 0.438m²

Coefficient of aerodynamic drag

For the coefficient of drag I will be using the figure below with the rider in the upright position as this is the most common position of a road rider the low drag position is a position often seen in racing to be able to accelerate faster.

Table 3. Drag/lift forces and coefficients for different positions taken by the rider.

	C_D	C_L	C_L/C_D	$C_D A \text{ [m}^2\text{]}$	$C_L A \text{ [m}^2\text{]}$	$F_D \text{ [N]}$	$F_L \text{ [N]}$	$F_{D_{rider}} \text{ [N]}$
Rider in low-drag position	0.3867	-0.0062	-0.0161	0.1899	-0.0031	72.69	-1.17	9.35
Rider in upright position	0.5330	0.0194	0.0365	0.3595	0.0131	137.62	2.51	73.55

Figure 3: Drag Co

Table 2. Percentage contribution of each component to the drag and lift force values.

No.	Elements	Drag Contribution (%)	Lift Contribution (%)
1	Front fairing	32.94	33.28 (↘)
2	Front fender	5.75	9.32
3	Front forks	14.22	2.63 (↘)
4	Front wheel	7.89	6.33 (↘)
5	Frame, Battery and Engine	23.41	7.81 (↘)
6	Pro Link Suspension	0.02	0.09 (↘)
7	Swingarm	0.40	0.38
8	Rear wheel	0.22	0.14 (↘)
9	Rear fender	0.94 (↘)	0.58
10	Rear fairing	0.36	4.68
11	Rider	12.42	34.48
12	Handlebar	1.42	0.27

Figure 4: Drag Co contributions.

(Piechna & Winski, 2022)

Aerodynamic resistance

Using the 2 sections above we can calculate the aerodynamic resistance being forced onto the vehicle. Using the equation below we can see as the vehicle increases speed it encounters exponentially more force as shown by the graph below. To decrease the aerodynamic resistance of a vehicle you need to decrease the drag coefficient or frontal area of the motorcycle; this can also be done by the rider tucking in behind the screen of the bike to increase aerodynamic efficiency.

$$\text{Aerodynamic resistance} = 0.5 * \text{drag co} * 1.225 * \text{Frontal area} * \text{velocity}^2$$

WLTP

Worldwide harmonised light vehicle test procedure (WLTP)

The WLTP is a standardized testing protocol introduced in 2017 by the European Union to measure and evaluate the fuel consumption, emissions, and performance of vehicles in a realistic and representative way by creating the test using real-life data. The WLTP makes use of a wide range of vehicle loads such as high speeds, increased accelerations and more, giving the test a much broader range. The WLTP aims to aid consumers and regulatory bodies with information on fuel efficiency and emissions reflecting real-world situations. The WLTP tests are split into 3 different classes based on the vehicle's power-to-mass ratio or PMR; because of this, the BMW is going to be in the 3rd class. Below in figure 5 we can see the 3 classes of test involved in the WLTP as well as a graph displaying the velocity over the course of the test in figure 6.

WLTP test cycles			
Category	PMR	Speed phases	Comments
Class 3	PMR > 34	Low, Middle, High, Extra-High	If v_max < 135 km/h, phase 'extra-high' is replaced by a repetition of phase 'low.'
Class 2	34 ≥ PMR > 22	Low, Middle, High	If v_max < 90 km/h, phase 'high' is replaced by a repetition of phase 'low.'
Class 1	PMR ≤ 22	Low, Middle	If v_max ≥ 70 km/h, phase 'low' is repeated after phase 'middle.' If v_max < 70 km/h, phase 'middle' is replaced by a repetition of phase 'low.'

Figure 5: WLTP test cycles

(INTERNATIONAL: LIGHT-DUTY: WORLDWIDE HARMONIZED LIGHT VEHICLES TEST
PROCEDURE (WLTP), n.d.)

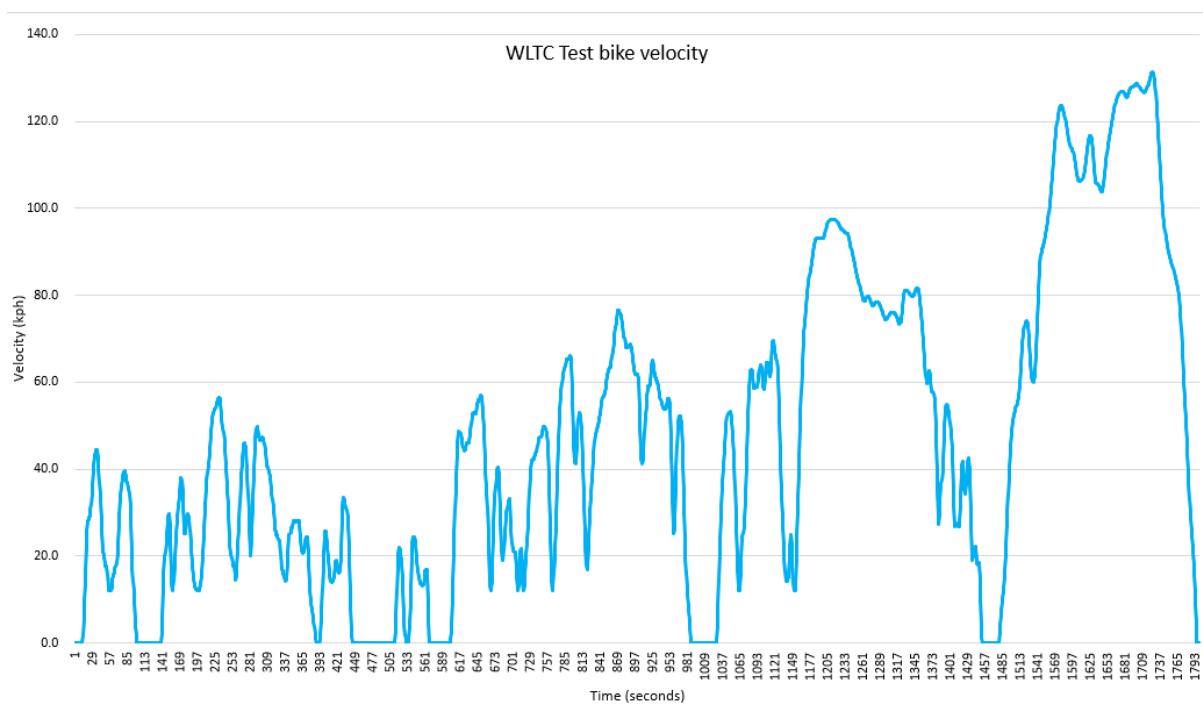


Figure 6: WLTP test vs velocity

Tractive force

The Tractive force is the force exerted from the bikes rear tyre to allow the bike to meet the speed requirements displayed on the WLTP. The tractive force is calculated by using the acceleration force what is the force required to move the bikes test weight * by the rate of acceleration + the total resistance from aerodynamics and rolling resistance. We can see the equation below.

$$\text{Tractive forces} = \text{acceleration} + (\text{rolling resistance} + \text{aerodynamic resistance})$$

Using figure 7 we can see the required tractive force to complete the WLTP test.

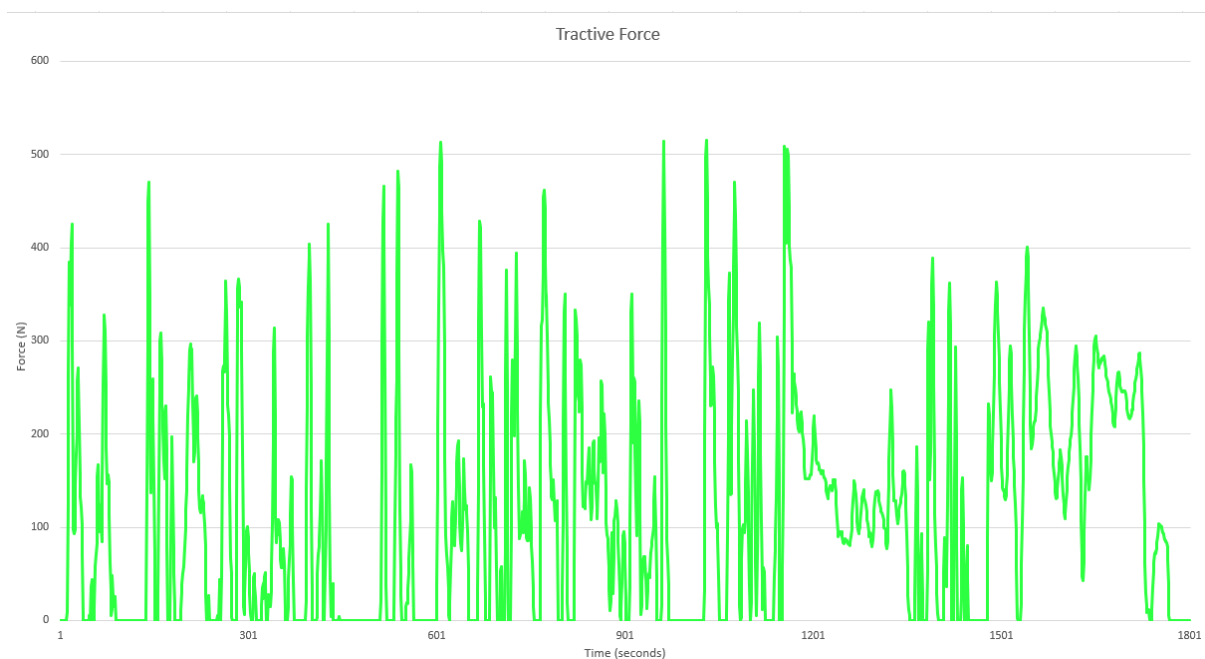


Figure 7: WLTP test vs tractive force

Tractive force isn't also based on forward acceleration it can also be used when the vehicle is decelerating as shown in figure 8, we can have a deceleration force of 72N but are total resistive force is too much at 78N meaning we need a 6N of tractive force to meet this deceleration force requirement.

Total elapsed time	Phase elapsed time	WLTC class 3, version 5, vehicle speed	WLTC class 3, version 5, acceleration	acceleration	rolling resistance	aerodynamic resistance	Forward acceleration Force	Total resistance	Tractive force	Deceleration	Braking force	Tractive Power	Braking power	Cumulative tractive power	Cumulative braking power	Potential kinetic energy	Recoverable kinetic energy
s	s	km/h	m/s	m/s²	N	N	N	N	N	N	N	W	W	W	W	J	J
21	21	28.1	7.81	0.11	56.5056	8.711943513	32	65.21754351	97.2175435	0	0	758.836937	0.0	11440.2	0.00	8773.44	0.00
22	22	28.3	7.86	0.10	56.5056	8.836398273	28	65.34199827	93.3419983	0	0	733.77182	0.0	12174.0	0.00	8898.78	0.00
23	23	28.8	8.00	0.11	56.5056	9.1513968	32	65.6569968	97.6569968	0	0	781.255974	0.0	12955.2	0.00	9216.00	0.00
24	24	29.1	8.08	0.28	56.5056	9.34304389	80	65.84864389	145.848644	0	0	1178.9432	0.0	14134.2	0.00	9409.00	0.00
25	25	30.8	8.56	0.39	56.5056	10.46655703	112	66.97215703	178.972157	0	0	1531.20623	0.0	15665.4	0.00	10540.44	0.00
26	26	31.9	8.86	0.46	56.5056	11.22751844	132	67.73311844	199.733118	0	0	1769.85736	0.0	17435.2	0.00	11306.78	0.00
27	27	34.1	9.47	0.65	56.5056	12.82954248	188	69.33514248	257.335142	0	0	2437.53566	0.0	19872.8	0.00	12920.11	0.00
28	28	36.6	10.17	0.69	56.5056	14.77966471	200	71.28526471	271.285265	0	0	2758.06686	0.0	22630.9	0.00	14884.00	0.00
29	29	39.1	10.86	0.65	56.5056	16.86770224	188	73.37330224	261.373302	0	0	2838.80448	0.0	25469.7	0.00	16986.78	0.00
30	30	41.3	11.47	0.47	56.5056	18.81925879	136	75.32485879	211.324859	0	0	2424.36574	0.0	27894.0	0.00	18952.11	0.00
31	31	42.5	11.81	0.28	56.5056	19.92875973	80	76.43435973	156.43436	0	0	1846.79452	0.0	29740.8	0.00	20069.44	0.00
32	32	43.3	12.03	0.19	56.5056	20.68608018	56	77.19168018	133.19168	0	0	1601.99993	0.0	31342.8	0.00	20832.11	0.00
33	33	43.9	12.19	0.15	56.5056	21.26333843	44	77.76893843	121.768938	0	0	1484.90455	0.0	32827.7	0.00	21413.44	0.00
34	34	44.4	12.33	0.08	56.5056	21.75045524	24	78.25605524	102.256055	0	0	1261.15801	0.0	34088.9	0.00	21904.00	0.00
35	35	44.5	12.36	0.00	56.5056	21.8485406	0	78.3541406	80.3541406	0	0	869.655349	0.0	34958.5	0.00	22002.78	0.00
36	36	44.2	12.28	0.00	56.5056	21.55494652	0	78.06054652	80.06054652	0	0	74.4100434	0.0	35032.9	0.00	21707.11	0.00
37	37	42.7	11.86	-0.60	56.5056	20.11676586	0	76.62236586	0	172	95.3776341	0	1131.3	35032.9	1131.28	20258.78	20182.16
38	38	39.9	11.08	-0.79	56.5056	17.56500195	0	74.07060195	0	228	153.929398	0	1706.1	35032.9	2837.34	17689.00	17614.93
39	39	37.0	10.28	-0.74	56.5056	15.10448281	0	71.61008281	0	212	140.389917	0	1442.9	35032.9	4280.23	15211.11	15139.50
40	40	34.6	9.61	-0.65	56.5056	13.2085337	0	69.7141337	0	188	118.285866	0	1136.9	35032.9	5417.09	13301.78	13232.06
41	41	32.3	8.97	-0.78	56.5056	11.51085162	0	68.01645162	0	224	155.983548	0	1399.5	35032.9	6816.61	11592.11	11524.09
42	42	29.0	8.06	-1.00	56.5056	9.278940862	0	65.78454086	0	288	222.215459	0	1790.1	35032.9	8606.68	9344.44	9278.66
43	43	25.1	6.97	-0.94	56.5056	6.951041061	0	63.45664106	0	272	208.543359	0	1454.0	35032.9	10060.69	7000.11	6936.65
44	44	22.2	6.17	-0.58	56.5056	5.43761381	0	61.94321381	0	168	106.056786	0	654.0	35032.9	10714.71	5476.00	5414.06
45	45	20.9	5.81	-0.25	56.5056	4.819422304	0	61.3250223	0	72	10.6749777	0	62.0	35032.9	10776.68	4853.44	4792.12
46	46	20.4	5.67	-0.19	56.5056	4.591586747	0	61.09718624	5.09718624	56	0	78.8840554	0.0	35061.8	10776.68	4624.00	0.00

Figure 8: WLTP test excel.

Braking force

The braking force is the opposite to the tractive force as it's the force need to help reduce the speed of the motorcycle, this is done with the use of friction brakes and engine braking by standard. We can calculate the forces once again by using the decelerate of the motorcycle and the total resistance being applied to the bike as shown by the equation below.

$$\text{Braking force} = \text{deceleration} - \text{total resistance}$$

Unlike the traction force we don't need to use any braking force until the force required is greater than the total resistance as anything below that will be made up by the bike aerodynamic and rolling resistances

By using figure 9 we can see the brake force over the course of the WLTP test

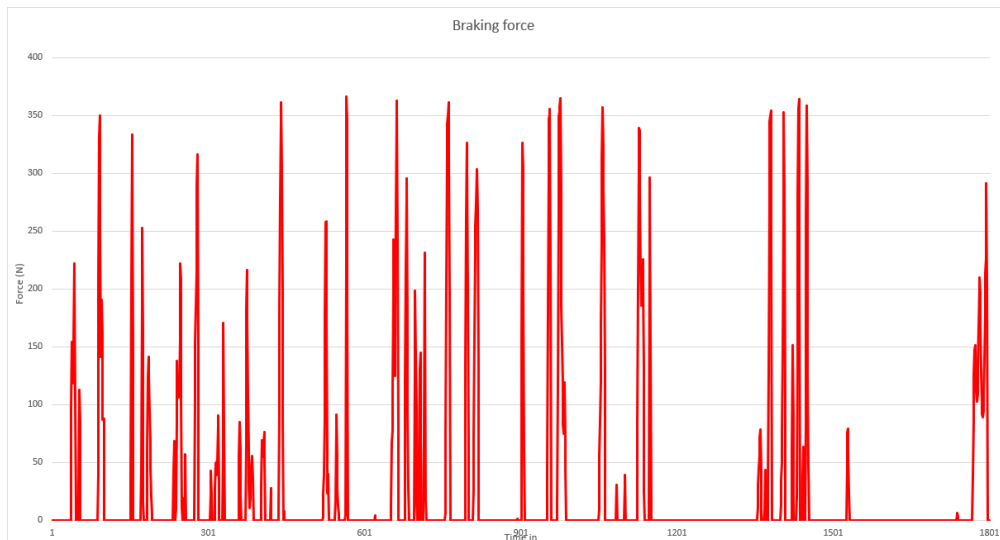


Figure 9: WLTP braking force.

We can then compare the two forces against each other in figure 10.

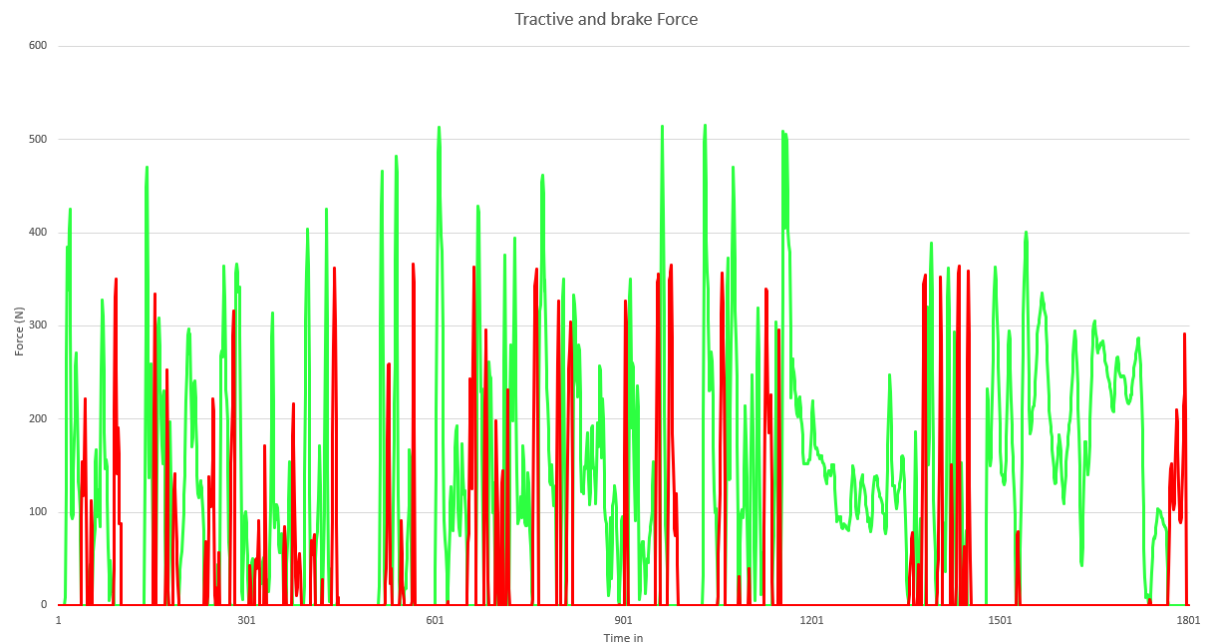


Figure 10: WLTP braking force vs tractive force.

As we can see there is a lot more required Tractive force due to it having to overcome the total resistance as well as the braking force being assisted by the resistances being placed on the motorcycle.

Tractive and braking power

We can then use the Tractive force to calculate the amount of power needs to be applied to the wheels by the engine or kers system to complete the test, we can also calculate the braking power so we can see at what points in the test regeneration for a kers system would be the most efficient. Using the equations below we can calculate the tractive and braking power.

$$\text{Tractive power} = \text{Tractive force} \times \text{velocity}$$

$$\text{Brake power} = \text{Brake force} \times \text{velocity}$$

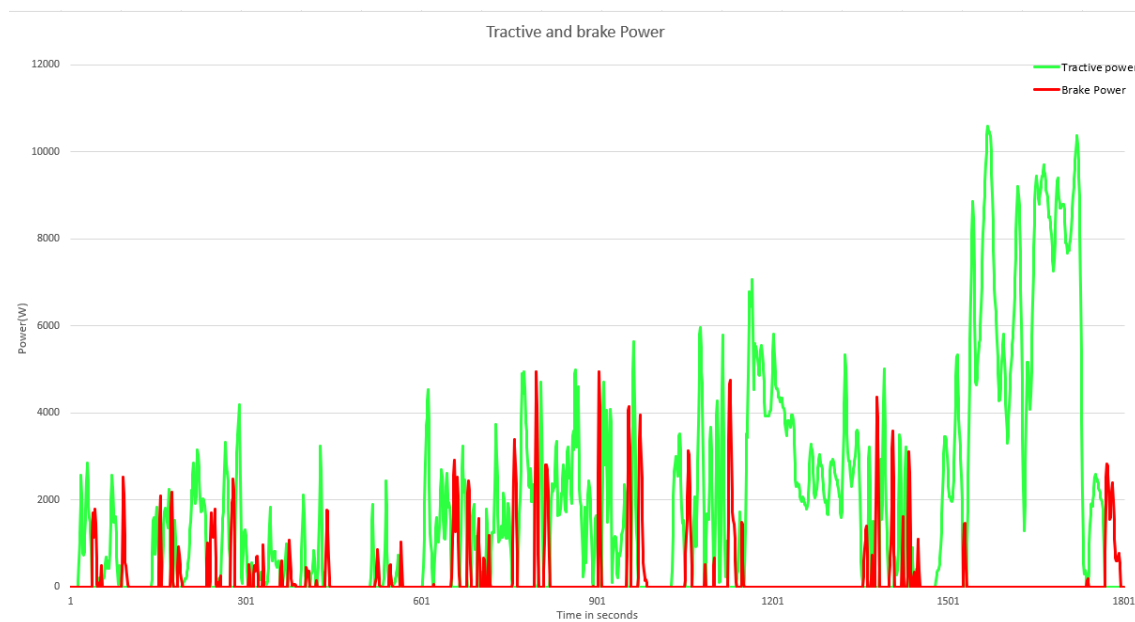


Figure 11: WLTP braking power vs tractive power.

As shown above in figure 11 we can see the tractive and brake power overlayed over the course of the test. By using this data, we can input them into tables to see what average and max power is for each section of the test.

Tractive power					
	low	middle	high	extra high	Total
max	4178.36125	5639.31913	7070.37875	10584.8286	10584.8286
average	1037.55342	1938.24208	2755.41682	5254.55591	2804.35923

Figure 12: WLTP tractive power max and average

Braking power					
	low	middle	high	extra high	Total
max	2512.1	4953.5	4760.4	3577.0	4953.5
average	685.9	1711.5	1514.9	1310.6	1206.4

Figure 13: WLTP braking power max and average

As show above in figure 12 and 13 we can see that as we increase the test speeds, we see an increase in the average and peak tractive power for the tests this is due to the exponential increase in aerodynamic resistance that is needed to be overcome as well as higher. We get a peak power 1567 seconds in the test at an acceleration of 0.47m/s^2 and 34.33m/s velocity this is the near the max acceleration seen in the extra high test. Unlike the tractive power the brake power doesn't increase on average for the test speed this is because as the test speeds increase the total resistance increases reducing the need for braking power and causing a loss in potential energy recovery. We can see the highest peak and average occurs in the middle phase with a deceleration at 903 seconds into the test with a velocity of 15.17m/s and a deceleration of -1.44m/s^2 what is nearly the peak in this phase.

Energy loss

The energy losses can be seen in figure 14 below what shows the cumulative power for both tractive and brake power, this shows the how much energy is lost during the WLTP test as everything highlighted in green is energy used from tractive power that can't be recovered and the brake power in red is where energy can be recovered.

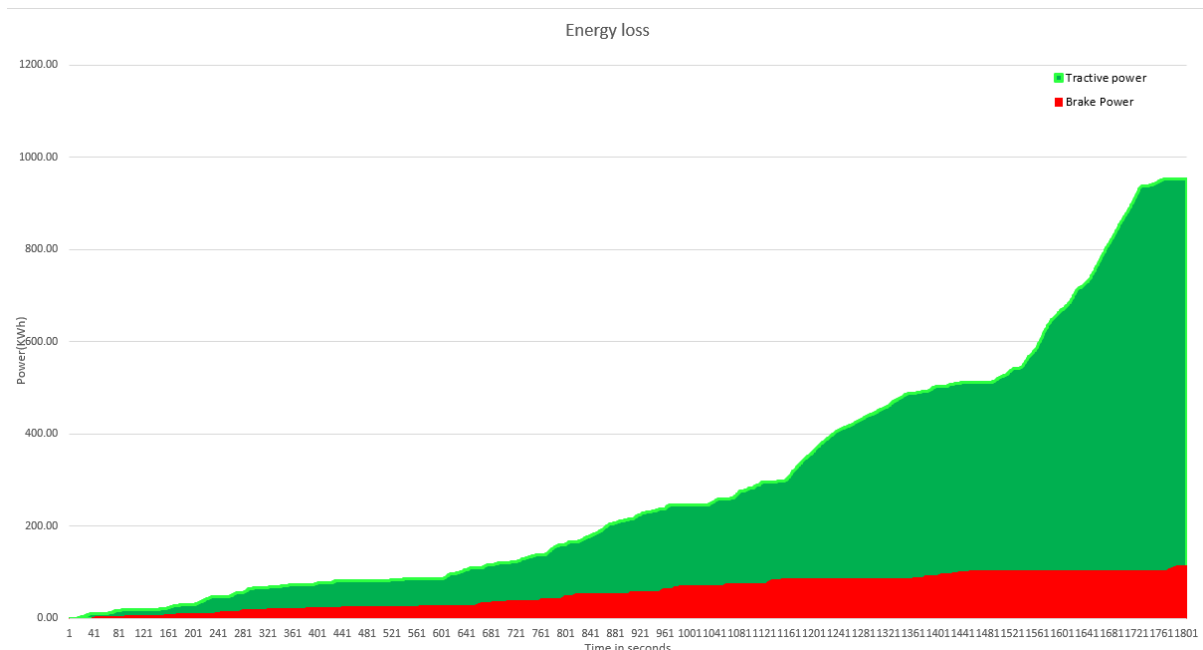


Figure 14: WLTP Energy loss

This means over the course of the WLTP we lose 1068 KWh with most of this being lost in the later phases of the test where the velocities are a lot higher than the previous phases.

kinetic energy and recoverable energy

As the vehicle performs the WLTP we can calculate the vehicles stored kinetic energy. We can use the vehicles kinetic energy to be able to calculate how much recoverable energy we are able to get from the vehicle.

$$\text{Kinetic energy} = 0.5 * \text{Test Mass} * \text{Velocity}^2$$

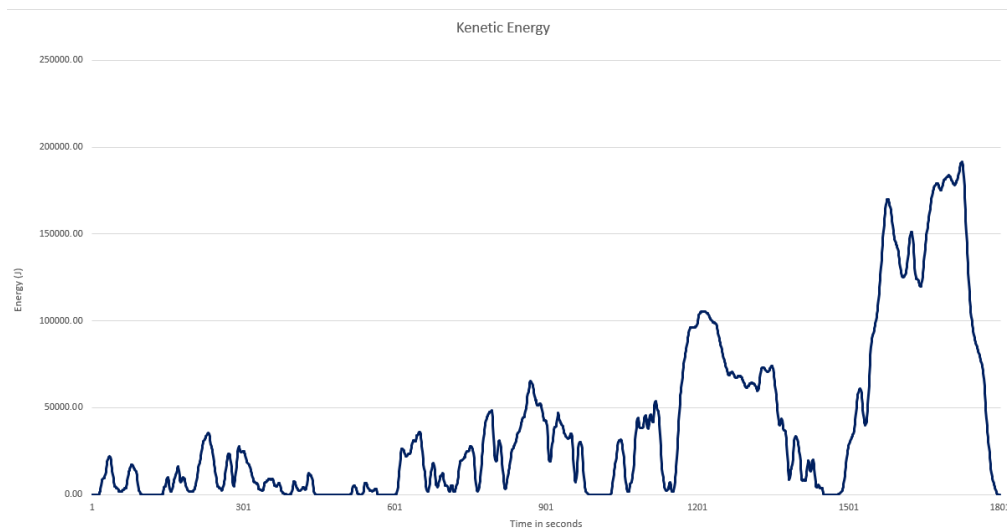


Figure 15: WLTP Kinetic energy

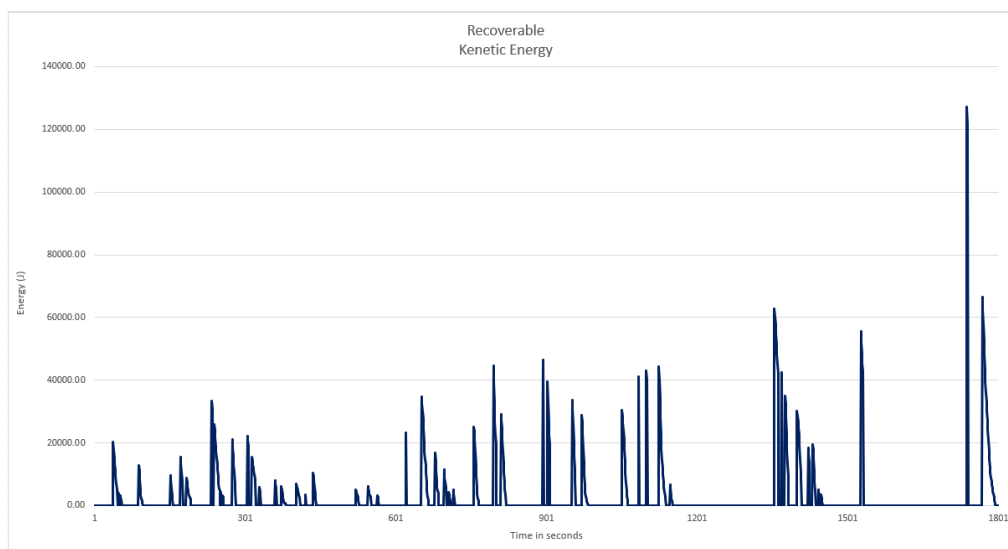


Figure 16: WLTP Recoverable kinetic energy

As shown by figure 15 and 16 we can see that we are only able to recover a small amount of the kinetic energy in the bike mainly coming from braking zones this is especially true at high speeds where there is a lot more drag on the vehicle. Figure 16 give us a base line on the amount of kinetic energy available to be recovered and will be essential for choosing a kers system.

Recoverable energy					
	low	middle	high	extra high	total
max	33399.2	4953.5	4760.4	3577.0	4953.5
average	685.9	1711.5	1514.9	1310.6	1206.4

Figure 17: WLTP recoverable energy max and average

Keres

Kers options

Flywheel

On the surface Flywheel seems like a good option for a kers system on the motorcycle, with the gross weight of the vehicle being 407kg and are current test mass being 288kg this only leaves us with 119kg to fit are kers system without breaching this weight. The fly wheel would likely weight 6kg with the kers module itself weighing 60kg what is under are weight limit. The Fly wheel would also only take up 200mmx120mm from the bike what is important as the bike doesn't have a lot of spare room like a car (Volvos flywheel kers puts a new spin on hybrid cars, n.d.). The flywheel is also very energy efficient as it doesn't need to transfer the energy to different store it reduces loses during energy recovery.

Unfortunately, with the flywheel having such a high rotational inertia it will affect the bike much more than its 4 wheeled counter part as it will stop the bike from turning requiring much more force from the rider to counter the gyroscopic effects of the bike.

(Mathews, 2013)

(Collins, n.d.)

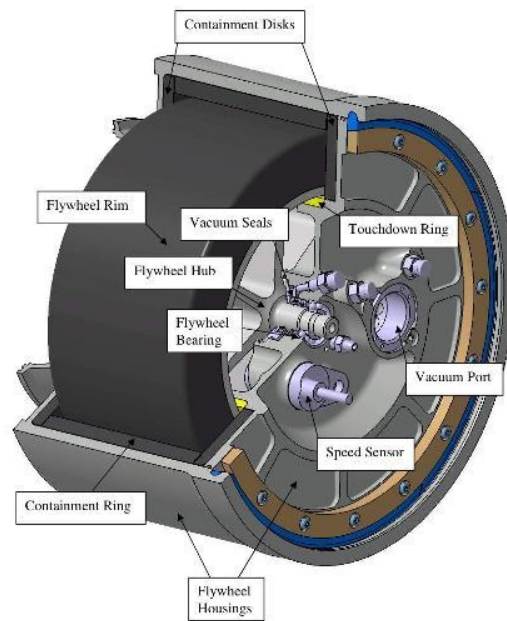


Figure 18: Volvo flywheel

(Collins, n.d.)

Generator

With the electric motors used to drive the wheel we can also use a generator to fill batteries or capacitors. One advantage of this option is its lower rotational inertia compared to the flywheel allowing the bike to have drastically better handling in comparison. But on the downside, these do require batteries or capacitors to store the energy meaning the systems ends up weighing a lot more than the flywheel what's not ideal when you have around 100kg to work with.

(Ukessays, 2018)

Battery's vs super capacitors

When using a generator as a source of kers we need somewhere to store the energy. The most viable storage for this energy is in batteries or super capacitors with batteries excelling in storing large amounts of energy over an extended period making them suited for providing sustained power and maximizing overall energy capacity. They also face challenges delivering energy in quick bursts which would be essential for the WLTP test. Supercapacitors on the other hand are designed to discharge energy rapidly, offering a high specific power that is advantageous in acceleration as well as being able to recover a much high amount of energy during recovery compared to batteries.

(sleepy, 2015)

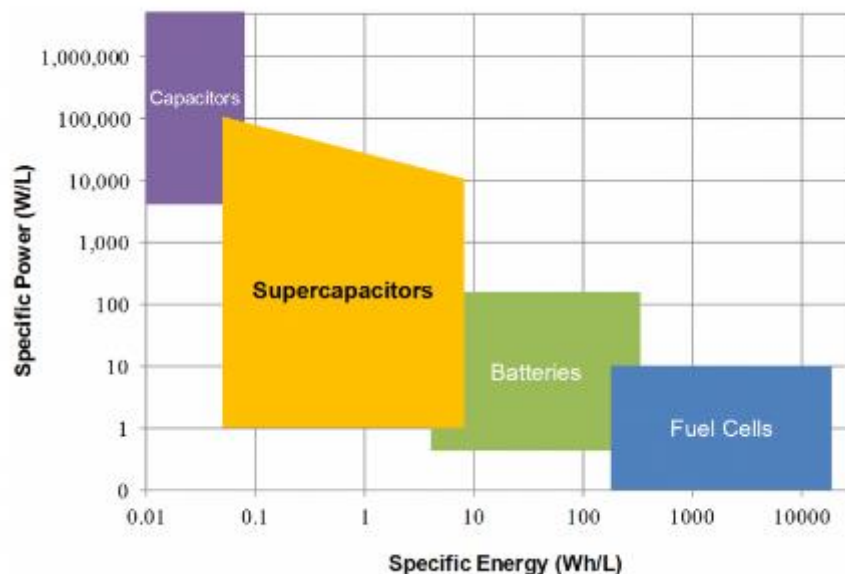


Figure 19: supercapacitors vs batteries

(Batteries & Energy storage, n.d.)

Chosen kers.

For the BMW's kers system I've decided to go with an electric motor and super capacitors, the main reason for this is the high inertia from the flywheel would seriously impact the handling of the motorcycle and for a highspeed sports bike this wouldn't be feasible.

Because we are using electric Kers's system, we will need to store the power because of this I've decided to go with supercapacitors because of there faster charge time allowing use to recover more kinetic energy as well as to discharge more energy allowing the bike to meet the acceleration demands of the WLTP. Another reason for selecting the is its KW/KG as it can hold around 3x more energy per kilo of weight what is extremely important with the limitations of the motorcycle. Supercapacitors also have a better operating temperature range meaning they can be used in more extreme climates.

Characteristic	Supercapacitors	Lithium Ion Batteries
kW/kg (Specific Power)	10	1-3
Wh/kg (Specific Energy)	up to 10,000	up to 3,000
Charge time (of a cell)	Seconds	minutes
Cell voltage	c. 2.5	3.6
Cycle Life	1 million+	up to 3,000
Operating temperature range	Discharge: -40 to 65°C (-40 to 149°F) Recharge: -40 to 65°C (-40 to 149°F)	Discharge: -20 to 60°C (-4 to 140°F) Recharge: 0 to 45°C (32°to 113°F)
Self Discharge	50% within a month	up to 3% per month

Figure 20 : supercapacitors vs batteries 2

(Batteryguy, n.d.)

I've decided to use the rear wheel for the motor/generator as it gives the rider a more conventional ICE feel as we can use the regen as a source of engine braking meaning the rider can adjust this depending on the amount of regen, 'engine brake' and road conditions he is riding on. Another reason for placing the rear of the motorcycle is when re applying the power a motorcycle often fully

unloads the front wheel meaning a kers system on the front wheel wouldn't be able to apply any power during hard acceleration. A downside to this is that more of the braking force is typically done by the front of the motorcycle meaning the limiting factor will be grip but this shouldn't be an issue in normal driving conditions as the decelerating rate isn't typically that high meaning the rear of the motorcycle will have enough load to recover energy. The front wheel is also the turning point for the motorcycle so it will also massively affect the rider when he wants to turn the bike, the front also doesn't have the same amount of space as the rear meaning supporting a motor would be a much harder task.

With this system we will be able to get 85% of the potential energy recovered back to the road, meaning we can calculate are total energy recovered also the total energy saved by using this kers system compared to the standard combustion engine.

In figure 21 we can see the charge over the WLTP, and we can then work out are total weight of batteries needed.

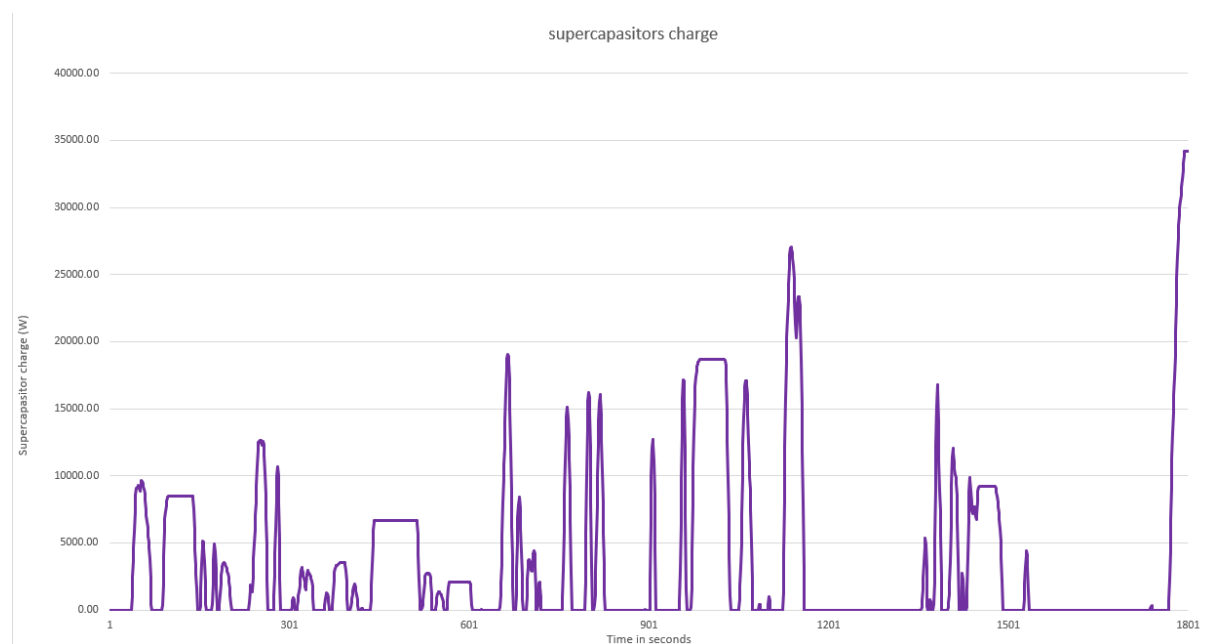


Figure 21 : Supercapacitors charge

As we can see the highest charge, we reach is 35000 watts means that we would only need 4 kg of supercapacitors to complete this test. This means we will be below the gross weight of the vehicles with both the motor and supercapacitors.

Conclusion

In conclusion, integrating a Kinetic Energy Recovery System (KERS) into the 2018 BMW S1000RR emerges as a viable solution to enhance performance and fuel efficiency. The chosen electric motor and supercapacitor configuration, situated on the rear wheel, offers a balanced approach, recovering kinetic energy while simulating engine braking for an intuitive rider experience. Thorough analysis of dynamic characteristics, WLTP, and energy profiles reveals the potential benefits and challenges associated with KERS implementation. Despite considerations such as added weight and handling effects, a well-designed KERS system, tailored to the motorcycle's specifications, promises increased efficiency and sustainability. Careful component selection, power rating specifications, and operational efficiency considerations are crucial for successful integration. Ultimately, this report supports the feasibility of a KERS system, contributing positively to the performance and environmental impact of the 2018 BMW S1000RR in real-world scenarios.

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