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Motorcycle Geometry & Handling

Motorcycle Technology - ACHA4003

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1 Introduction

This report compares the geometry data of two modern motorcycles, focusing on how design choices like rake angle, trail, wheelbase, and centre of gravity locations impact a motorcycle's stability and manoeuvrability during dynamic situations. Manufacturer data is used in conjunction with real world data gathered to determine motorcycle handling characteristics and theoretical speeds.

2 Motorcycle Geometry Data

Geometry data was gathered using a variety of methods. Microsoft Excel is used to store data and calculate geometry, figures 1-10 show data collected from an Aprilia RS250 and Kawasaki ZXR750 and are visualised using a 1:10 scale drawing.

Using the below formulae we are able to calculate X and Y co-ordinates for the CoG of the motorcycle, the combined motorcycle and rider CoG and the percentage of weight distribution to the front and rear.

The frontal area is calculated using a head-on image of the motorcycle with the rider in full tuck imported into SolidWorks. The perimeter of motorcycle and rider is selected and a body is extruded, SolidWorks provides the area for this extension.

$$\text{Lift Angle} = \sin^{-1} \left(\frac{\text{Block Height}}{\text{Wheel Base}} \right)$$

$$\text{CoG}_x = \frac{(\text{Back Weight} * \text{Wheel Base})}{(\text{Front Weight} + \text{Rear Weight})}$$

$$\text{CoG}_y = \frac{\text{Wheel Base} * (\text{Rear Weight} - \text{Lifted Weight})}{(\text{Front Weight} + \text{Rear Weight}) * \tan(\text{Lifted Angle})} + \text{Average Wheel Radius}$$

$$\%_f = \left(\frac{\text{Front Weight}}{\text{Front Weight} + \text{Rear Weight}} \right) * 100$$

$$\%_r = \left(\frac{\text{Rear Weight}}{\text{Rear Weight} + \text{Front Weight}} \right) * 100$$

2.1 Aprilia RS250

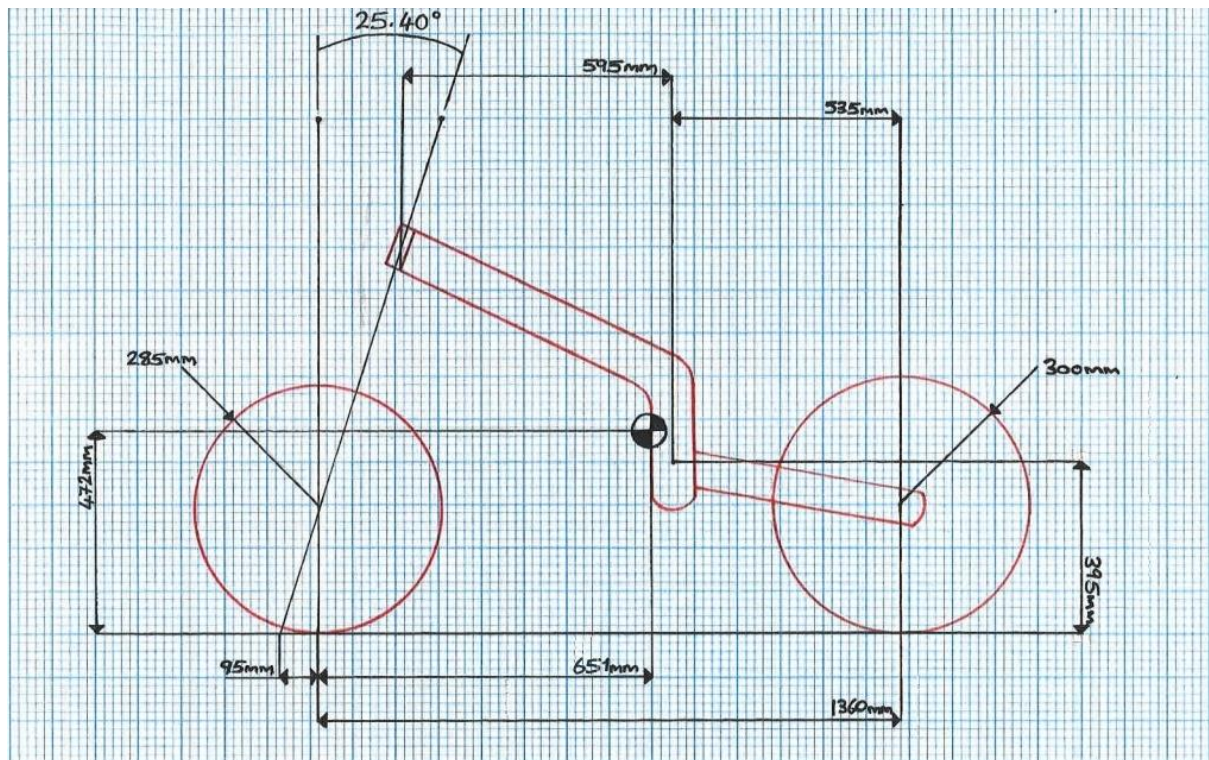


Figure 1: RS250 drawing with geometry data.

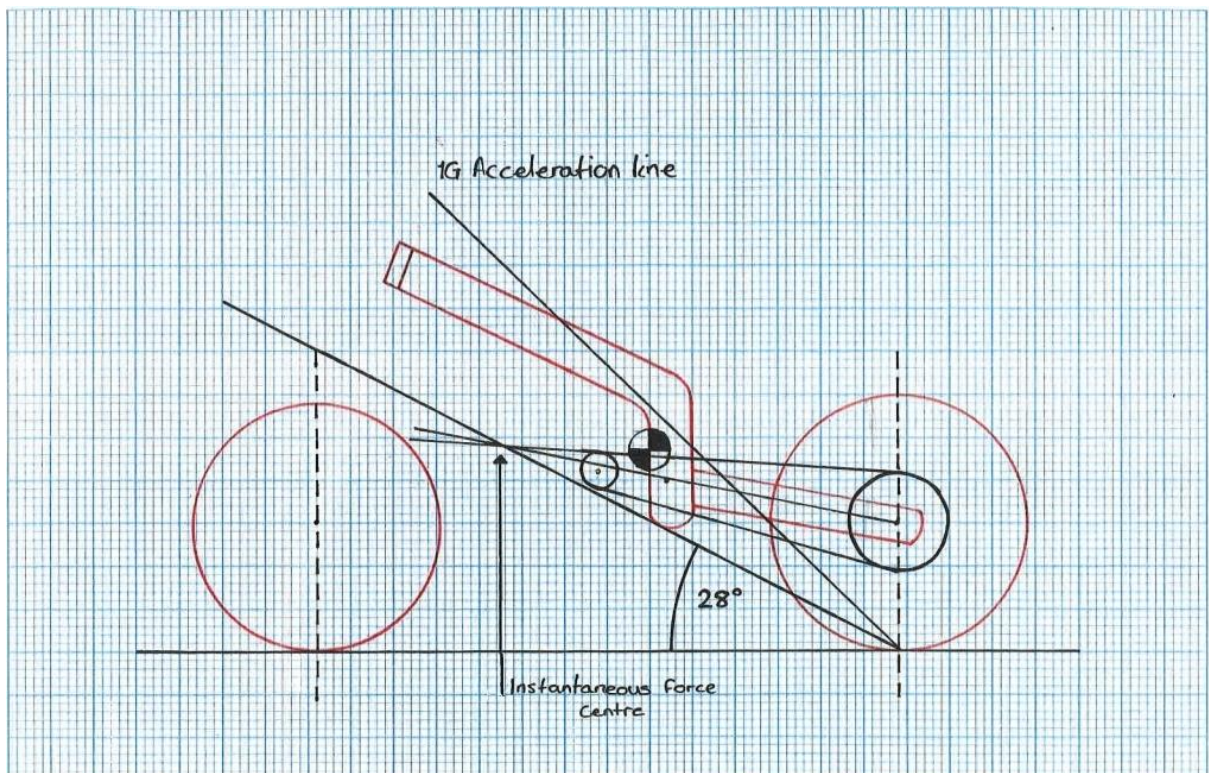


Figure 2: RS250 drawing with 1G line and anti-squat angle.

RS250	
Rake Angle (Degrees)	25.40
Trail (mm)	130
Triple Clamp Offset (mm)	35
Trail - Triple Clamp Offset (mm)	95
Fork Length (mm)	688
Swing Arm Length (mm)	535
Swing Arm Pivot Height (mm)	395
Swing Arm to Steering Stem (mm)	595
Rear Sprocket Radius (mm)	110
Rear Sprocket Teeth	42
Front Sprocket Radius (mm)	39.5
Front Sprocket Teeth	14
Sprocket Distance (mm)	667
Front Sprocket Height (mm)	400

Figure 3: RS250 geometry data

Aprilia RS250			
	Weight (kg)		Geometry (m)
Front	69.45	Wheel Base	1.36
Rear	63.70	Front wheel radius	0.285
Front (rider)	98.3	Back wheel radius	0.300
Rear (rider)	115	Average radius	0.293
Lifted	54.50	Lift height	0.629
Lifted (rider)	87.8	Lifted Angle (Degrees)	27.60
	Centre of Gravity (m)		Weight Split (%)
X	0.651	Front	52.16
Y	0.472	Rear	47.84
Xrider	0.733	Rider Front	46.09
Yrider	0.624	Rider Rear	53.91
Rider Weight (Kg)	81.05	Block Height (m)	0.630

Figure 4: RS250 data used to calculate CoG.

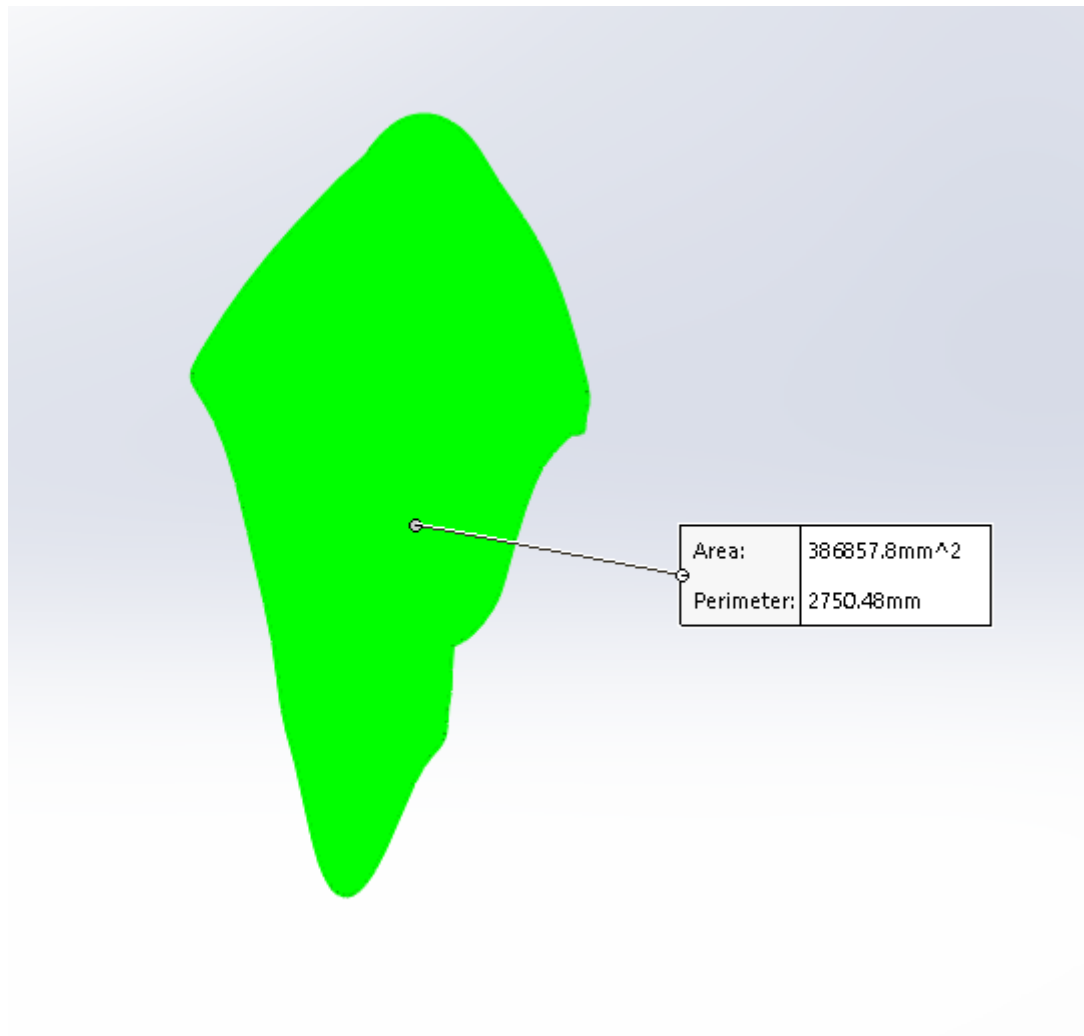


Figure 5: RS250 frontal area.

2.2 Kawasaki ZXR750

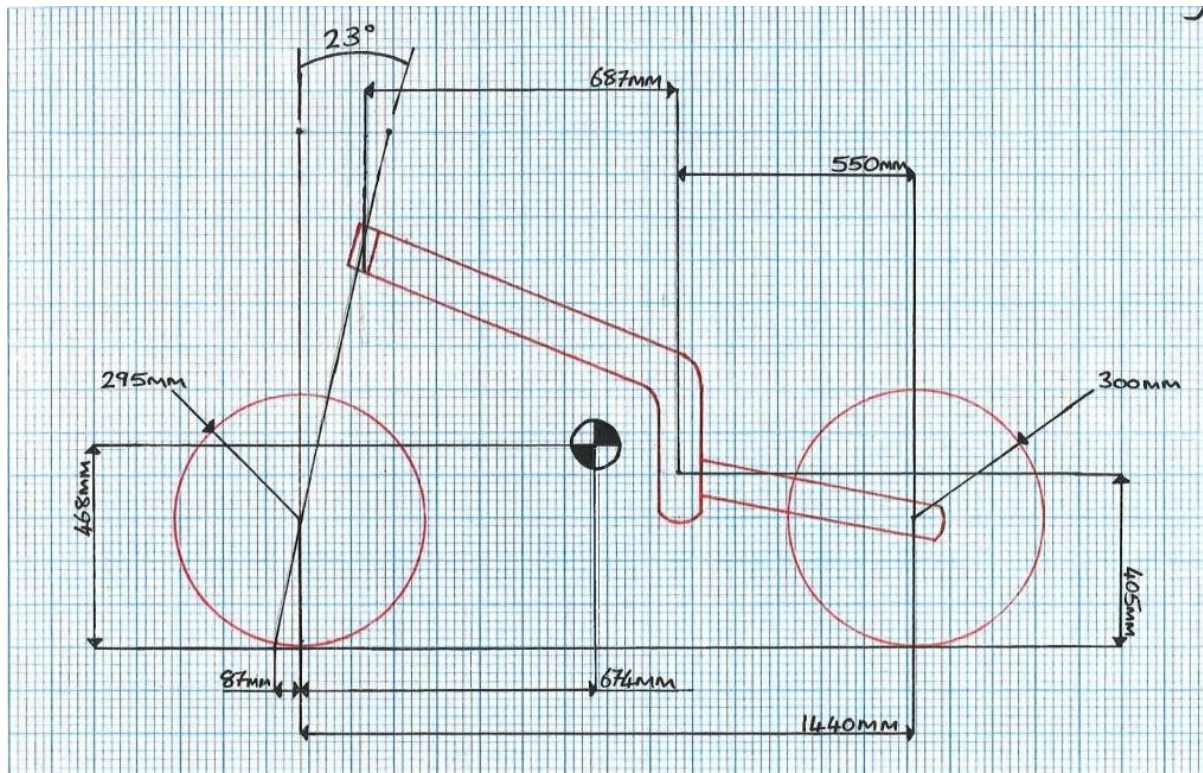


Figure 6: ZXR750 drawing with geometry data.

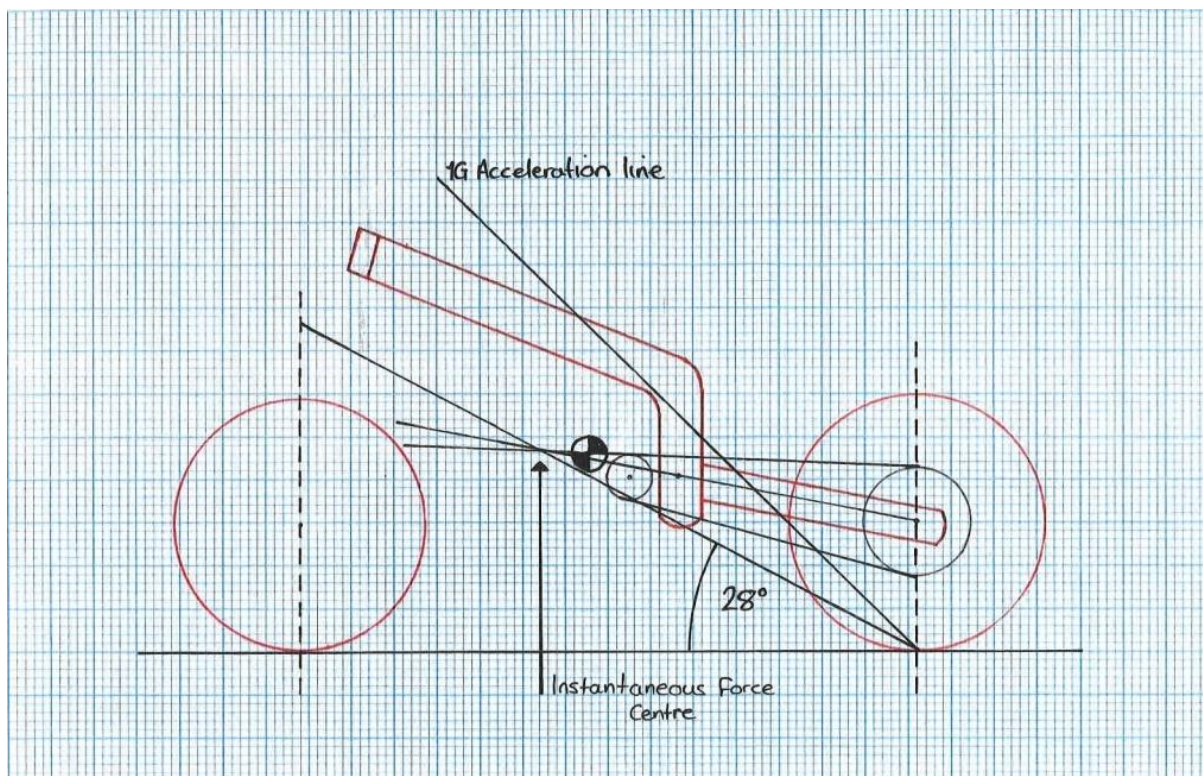


Figure 7: ZXR750 drawing with 1G line and anti-squat angle.

ZXR750	
Rake Angle (Degrees)	23.00
Trail (mm)	120
Triple Clamp Offset (mm)	33
Trail - TCO (mm)	87
Fork Length (mm)	695
Swing Arm Length (mm)	550
Swing Arm Pivot Height (mm)	405
Swing Arm to Steering Stem (mm)	687
Rear Sprocket Radius (mm)	122
Rear Sprocket Teeth	47
Front Sprocket Radius (mm)	42
Front Sprocket Teeth	15
Sprocket Distance (mm)	644
Front Sprocket Height (mm)	405

Figure 8: ZXR750 geometry data.

ZXR750			
	Weight (Kg)		Gemoterty (m)
Front	102.10	Wheel Base	1.44
Back	89.80	Front wheel radius	0.29
Front (rider)	133.50	Back wheel radius	0.302
Back (rider)	138.80	Average radius	0.296
Lifted	78.65	Lift height	0.629
Lifted (rider)	111.20	Lifted Angle (Degrees)	25.94
	Centre of Gravity (m)		Weight Split (%)
X	0.674	Front	53.20
Y	0.468	Back	46.80
Xrider	0.734	Rider Front	49.03
Yrider	0.596	Rider Back	50.97
Rider Weight (Kg)	81.05	Block Height (m)	0.630

Figure 9: ZXR750 data used to calculate CoG.

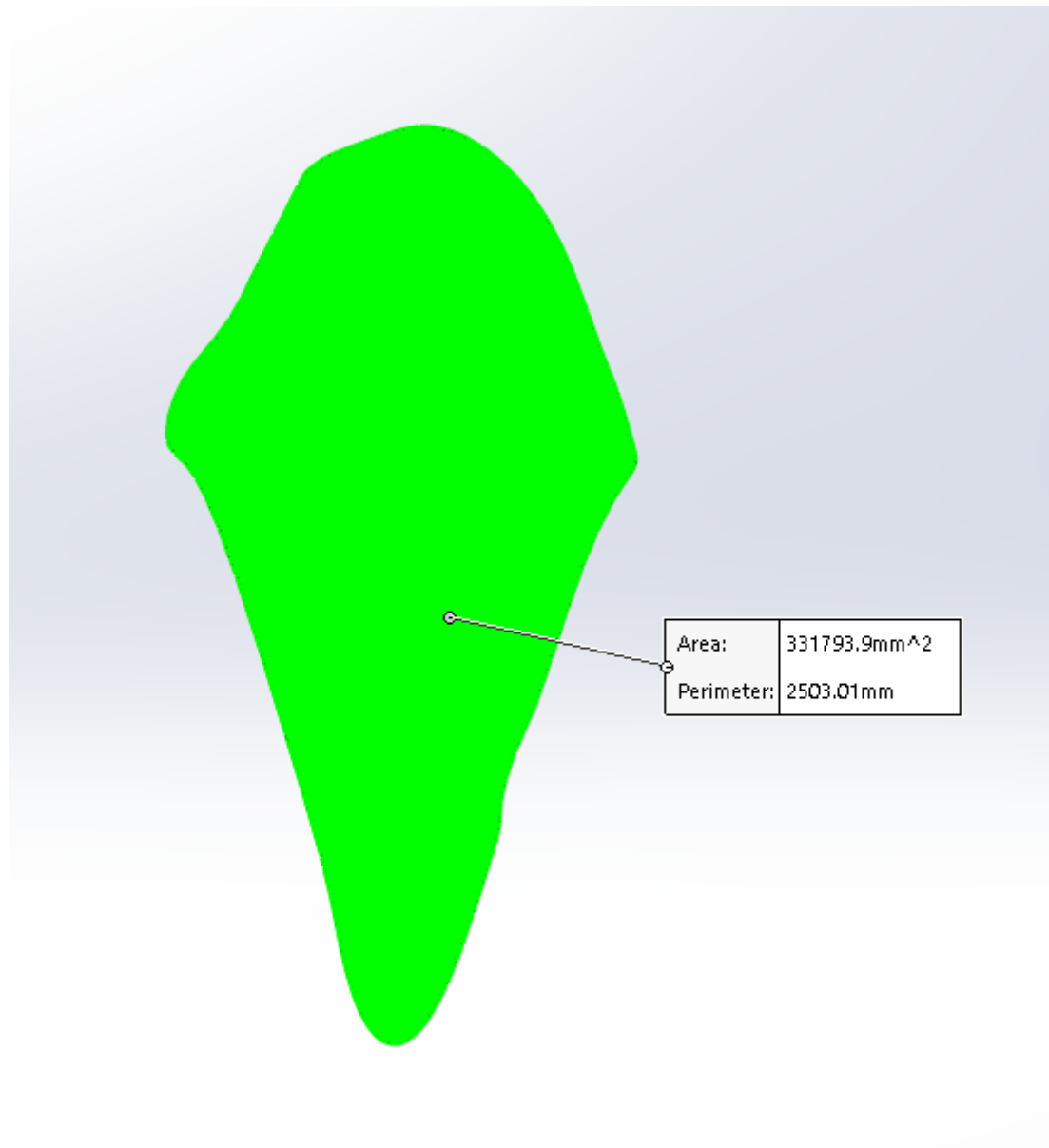


Figure 10: ZXR750 frontal area.

3 Motorcycle Gear Ratios

The below formulae are used in conjunction with data from manufacturer workshop manuals to provide a theoretical top speed, without external drag forces acting against the motorcycle.

Drag forces are calculated using data collected from the motorcycles. Using the drag force formulae alongside the theoretical speed calculator we can provide a more accurate calculation of motorcycle top speeds.

$$Speed = \frac{rpm(60) \left(\frac{GearIn}{GearOut} \right) \left(\frac{PrimaryReductionIn}{PrimaryReductionOut} \right) (Wheel\ Diameter)(\pi)}{1000} \left(\frac{SecondaryReductionIn}{SecondaryReductionOut} \right)$$

$$Drag\ Force = \frac{1}{2} (1.167) (Drag\ Coefficient) (Frontal\ Area) (Velocity)^2$$

$$Rolling\ Resistance = \mu(m)(g)$$

$$Road\ Plane\ Resistance = (m)(g)(\sin \theta)$$

3.1 Aprilia RS250

Note, there seems to be a mistake in 3rd gear where the in/out gear ratios have been swapped. The gearing calculator shows this mistake as a discrepancy in the form of a large jump in speed, rpm and incorrect rpm drop (figure 12). Swapping the ratio provides a more consistent result (figure 13).

TRANSMISSION

Clutch oil bath, multiple-disc,
with lever control on handlebars
Gear box 6-speed, direct drive
Gear change with pedal (L), 1st low,
other 5 high
Primary reduction Z = 23/59 (1 : 2,565)
Secondary reduction (chain) Z = 14/42 (1 : 3,000)
Total ratio (engine/wheel) 1 : 6,464
Gear ratios 1st-Z = 11/27 (1 : 2,454)
2nd-Z = 16/26 (1 : 1,625)
3rd-Z = 21/17 (1 : 1,235)
4th-Z = 22/23 (1 : 1,045)
5th-Z = 24/22 (1 : 0,916)
6th-Z = 25/21 (1 : 0,840)
Chain sealed, jointless,
DID model 520 V6

Figure 11: RS250 workshop manual transmission specs.

Gearing Calculator						
Primary Reduction	23	59				
Secondary Reduction	14	42				
Wheel Diameter (m)	0.6					
RPM	12000					
Gear Ratios			Speed (km/h)	Speed (mph)	RPM	RPM Drop
1st	11	27	71.85	44.91	7944	4056
2nd	16	26	108.53	67.83	5978	6022
3rd	21	17	217.85	136.16	15497	-3497
4th	22	23	168.69	105.43	10522	1478
5th	24	22	192.39	120.24	10996	1004
6th	25	21	209.95	131.22	12000	

Figure 12: Gearing ratios showing error.

Gearing Calculator						
Primary Reduction	23	59				
Secondary Reduction	14	42				
Wheel Diameter (m)	0.6					
RPM	12000					
Gear Ratios			Speed (km/h)	Speed (mph)	RPM	RPM Drop
1st	11	27	71.85	44.91	7944	4056
2nd	16	26	108.53	67.83	9122	2878
3rd	17	21	142.76	89.23	10156	1844
4th	22	23	168.69	105.43	10522	1478
5th	24	22	192.39	120.24	10996	1004
6th	25	21	209.95	131.22	12000	

Figure 13: RS250 gearing ratios.

Key			
	Variable	Value	Unit
Mass	m	133.15	kg
Coefficient Drag	CdA	0.305	m ²
Velocity	v	209.45	km/h
Velocity	v	58.18	m/s
Gravity	g	9.81	m/s ²
Gradient (opposite)	opp	10	-
Gradient (adjacent)	adj	100	-
Angle	Θ	5.71	Degrees
Rho	ρ	1.167	-
Coefficient Friction	μ	0.02	-
Aero Drag Force	Fd		N
Rolling Resistance	Fw		N
Gradient Resistance	Fp		N
Frontal Area	A	0.387	m ²
Power needed to reach top speed			
	Variable	Value	Unit
Aero Drag Force	Fd	233.13	N
Rolling Resistance	Fw	26.12403	N
Forces Total	FT	259.26	N
Power	P	15083.83	W
Power needed to reach top speed up a 10% slope			
	Variable	Value	Unit
Aero Drag Force	Fd	233.13	N
Rolling Resistance	Fw	26.12403	N
Gradient Resistance	Fp	130.19	N
Forces Total	FT	389.45	N
Power	P	22658.20	W

Figure 14: RS250 drag and power calculations.

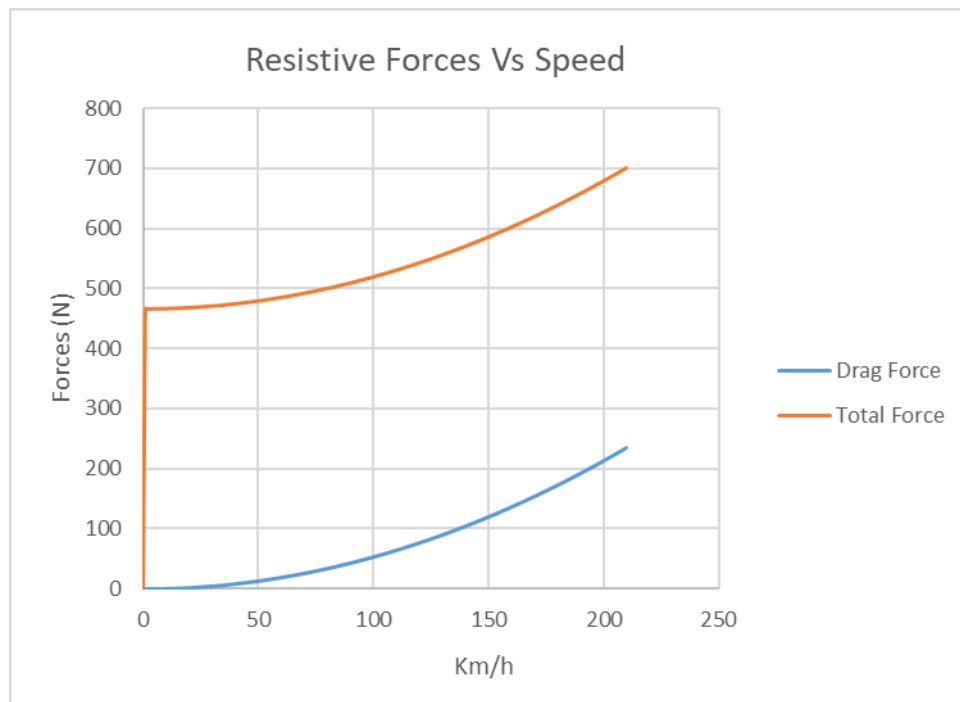


Figure 15: Resistive forces increase (found in figure 14) relating to speed increase.

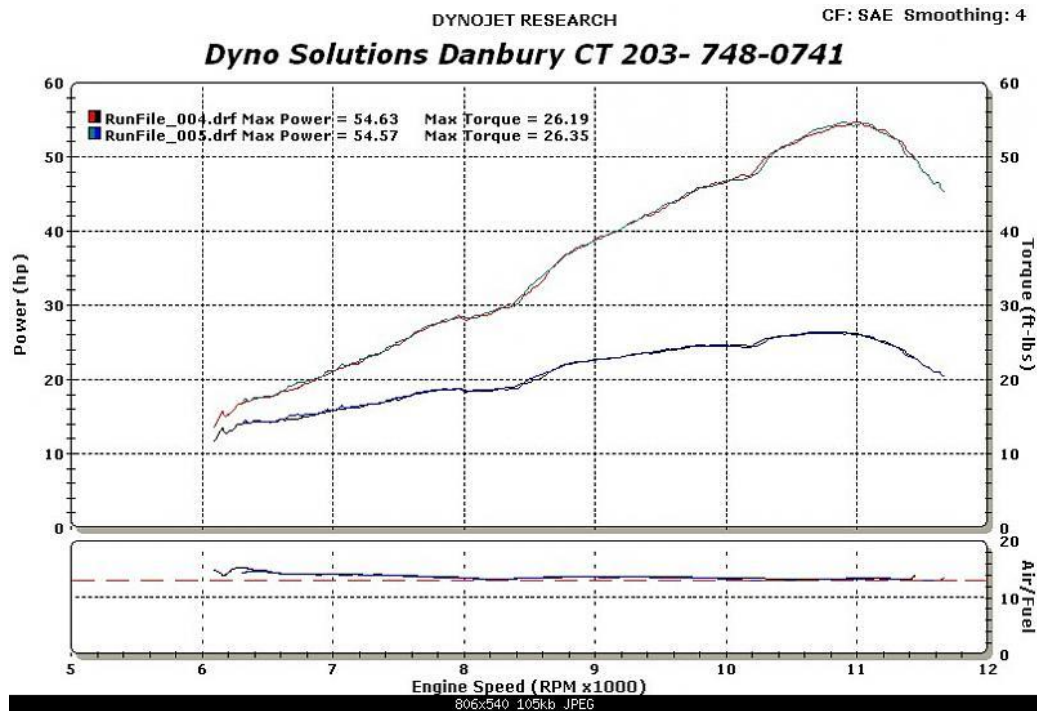


Figure 16: RS250 dyno run results (www.apriliaforum.com).

Figure 14 shows a dyno run on a stock RS250 with a max power output of 54.63 hp equating to 40737.58 watts. Providing enough power to reach top speed whilst overcoming drag and inclination forces.

Figure 14 shows a maximum incline of 35% before the forces overcome the power produced by the motorcycle.

Power needed to reach top speed up a 35% slope			
	Variable	Value	Unit
Aero Drag Force	Fd	233.13	N
Rolling Resistance	Fw	26.12403	N
Gradient Resistance	Fp	439.77	N
Forces Total	FT	699.02	N
Power	P	40669.61	W

Figure 17: RS250 maximum incline the motorcycle could climb.

3.2 Kawasaki ZXR750

TRANSMISSION		
Transmission Type	6-speed, constant mesh, return shift	
Clutch Type	Wet, multi disc	
Driving System	Chain drive	
Primary Reduction Ratio	1.754 (93/53)	
Final Reduction Ratio	2.750 (44/16)	* 2.562 (41/16)
Overall Drive Ratio	5.324 (Top gear)	* 5.395 (Top gear)
Gear Ratio: 1st	2.857 (40/14)	* 2.375 (38/16)
2nd	2.055 (37/18)	* 1.894 (36/19)
3rd	1.650 (33/20)	* 1.619 (34/21)
4th	1.391 (32/23)	* 1.409 (31/22)
5th	1.222 (33/27)	* 1.291 (31/24)
6th	1.103 (32/29)	* 1.200 (30/25)

Figure 18: ZXR750 workshop manual transmission specs.

Gearing Calculator						
Primary Reduction	53	93				
Secondary Reduction	16	44				
Wheel Diameter (m)	0.6					
RPM	12000					
Gear Ratios			Speed (km/h)	Speed (mph)	RPM	RPM Drop
1st	14	40	98.44	61.52	8633	3367
2nd	18	37	136.82	85.52	9632	2368
3rd	20	33	170.46	106.53	10119	1881
4th	23	32	202.15	126.34	10542	1458
5th	27	33	230.11	143.82	10834	1166
6th	29	32	254.88	159.30	12000	

Figure 19: ZXR750 gearing ratios.

Key			
	Variable	Value	Unit
Mass	m	191.9	kg
Coefficient Drag	CdA	0.305	m ²
Velocity	v	254.88	km/h
Velocity	v	70.80	m/s
Gravity	g	9.81	m/s ²
Gradient (opposite)	opp	10	-
Gradient (adjacent)	adj	100	-
Angle	Θ	5.71	Degrees
Rho	ρ	1.167	-
Coefficient Friction	μ	0.02	-
Aero Drag Force	Fd		N
Rolling Resistance	Fw		N
Gradient Resistance	Fp		N
Frontal Area	A	0.332	m ²
Power needed to reach top speed			
	Variable	Value	Unit
Aero Drag Force	Fd	296.17	N
Rolling Resistance	Fw	37.65078	N
Forces Total	FT	333.82	N
Power	P	23634.72	W
Power needed to reach top speed up a 10% slope			
	Variable	Value	Unit
Aero Drag Force	Fd	296.17	N
Rolling Resistance	Fw	37.65078	N
Gradient Resistance	Fp	187.63	N
Forces Total	FT	521.45	N
Power	P	36918.93	W

Figure 20: ZXR750 drag and power calculations.

Research suggests that the max power at the rear tyre of the ZXR750 comes to 112.3hp at 11400 rpm equating to 83742 watts.

Max Power Rear Tyre	112.3 hp / 83.7 kW @ 11400 rpm
---------------------	--------------------------------

Figure 21: ZXR750 max power at rear tyre (www.motorcyclespecs.co.za).

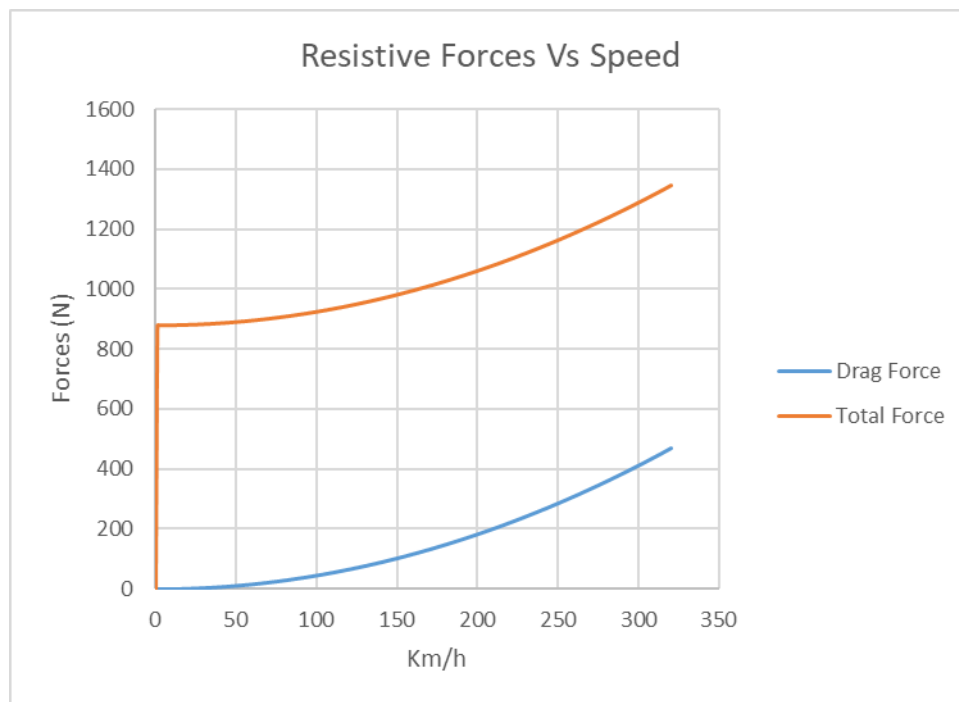


Figure 22: Resistive forces increase (found in figure 20) compared to speed increase.

Power needed to reach top speed up a 48% slope			
	Variable	Value	Unit
Aero Drag Force	F_d	296.17	N
Rolling Resistance	F_w	37.65078	N
Gradient Resistance	F_p	842.47	N
Forces Total	F_T	1176.30	N
Power	P	83281.86	W

Figure 23: ZXR750 maximum incline the motorcycle could climb at top speed.

4 Handling Dynamics

4.1 Rake and Trail

Trail allows for a castor effect when steering, castor is the action of moving the wheel back into its center line once displaced (Coombs, 2002). Foale, 2002, mentions the typical trail of motorcycles range from 50-100mm, further mentioning that the increase in positive trail increases the castor effect and therefore provides increased steering stability. Rake is directly proportionate to trail and works in conjunction with castor as the steering moves to provide a steering feel.

Data acquisition on the Aprilia RS250 (RS) provided a positive trail measurement of 95mm, tending towards the longer, or more stable end of the range. This is a difference of 8mm when compared with data gathered from the Kawasaki ZXR750 (ZXR) that provided a trail measurement of 87mm. The ZXR750 still has stability characteristics but may feel lighter or more responsive to weight distribution and through corners.

4.2 Wheelbase

Wheelbase measurements are taken between the two axles, the length is determined by the setup of suspension and steering geometry, it is also under constant change as the motorcycle moves through space. A longer wheelbase allows for increased stability in a straight line but decreases the sensitivity of cornering, whereas a shorter wheelbase allows for quick, nimble turning but reduced stability in a straight line (Coombs, 2002).

The measurement gathered for the RS shows a wheelbase of 1360mm, slightly shorter than that of the ZXR which provided a measurement of 1440mm. This would suggest that the ZXR is more stable in a straight line but slower to handle around corners.

4.3 Centre of Gravity

Centre of gravity (CoG) is defined as a point through which the mass of the bike acts (Foale, 2002). The position of the CoG greatly determines the handling characteristic of a motorcycle especially when accelerating, braking, and cornering (Coombs, 2002). A higher CoG enables better load transfer but increases the chance of the front or rear wheel losing contact during acceleration or braking and a lower CoG allows for better stability but causes front or rear wheel slip under acceleration or braking.

From the data collected (figure 4 & 9) we can visualise the CoG of the RS and ZXR (Figure 1 & 6). CoG is measured from the front wheel contact patch and as can be seen are both relatively central, tending towards the front of the motorcycles on the x-axis and again relatively central on the y-axis. These figures show that the manufacturers have opted for a more stable geometry option.

However, the CoG position is greatly dependent on the rider. Figure 4 & 9 shows x & y coordinates for a rider on the same two motorcycles and suggests the CoG position moves both backwards and higher. The position of a rider and the use of their body weight has a large effect on the CoG position. The use of bodyweight to change the CoG position is often seen in motorsports where a rider will position themselves largely over the fuel tank, towards the front of a bike at the start of a race, to move the CoG as close the front wheel as possible to prevent too much front wheel contact loss.

4.4 1G Acceleration Line

The 1G acceleration line is shown for the two motorcycles in figures 2 and 7. To prevent looping under a constant acceleration of 1G, the CoG needs to be positioned ahead of and below a line extending 45 degrees from the rear contact patch (Foale, 2002).

Comparing the two images shows that the RS250 has a CoG closer to the 1G line than the ZXR750 suggesting that it would be easier to bring the front wheel up. Of course, the CoG position will differ with a rider and can be positioned to suit depending on the riding position, to either counteract or assist the front wheel lifting.

4.5 Squat and Anti-Squat

Squat is the act of load transfer to the rear wheel causing compression of the rear suspension and in turn extending the front steering geometry whilst removing load from the front wheel, negatively affecting handling. Driving forces from the chain and wheel produce the opposite effect, anti-squat, is the extension of the rear suspension and is used to counteract the effects of squat (Datamc, 2023).

Using Figure 2 and 7 we can find the instantaneous force centre and calculate the anti-squat angle, the higher the anti-squat angle the better. Despite the differing geometry data throughout the two bikes the anti-squat angle is identical for both, although this is likely to change with a rider due to weight split differences and a change in CoG. Gearing changes influence anti-squat angle and so this can be tailored to suit but will also influence acceleration and top speed. Another way to change the anti-squat angle would be to change the ride height and therefore swing arm angle.

5 Geometry Data (Modern Motorcycles)

5.1 Honda RC213V-S

Honda's RC213V-S is a road legal MotoGP replica of their RC213V model. Potter, provides a range of geometry data for the RC213V-S, listed below.

Table 1: RC213V-S geometry data (bennetts.co.uk).

Geometry	Measurement
Wheelbase	1465mm
Rake	24.6°
Trail	105mm

When compared with the RS250 and ZXR750 the wheelbase measurement does not differ a large amount. The trail measurement however is longer than the two, this no doubt allows for increased stability in a straight line due to the potential speeds that the motorcycle can reach.

The CoG position is low as seen on figure 24. This provides improved stability.

The RC213V-S has a larger rear tyre no doubt to assist with grip due to the considerable power the engine produces (Figure 25).

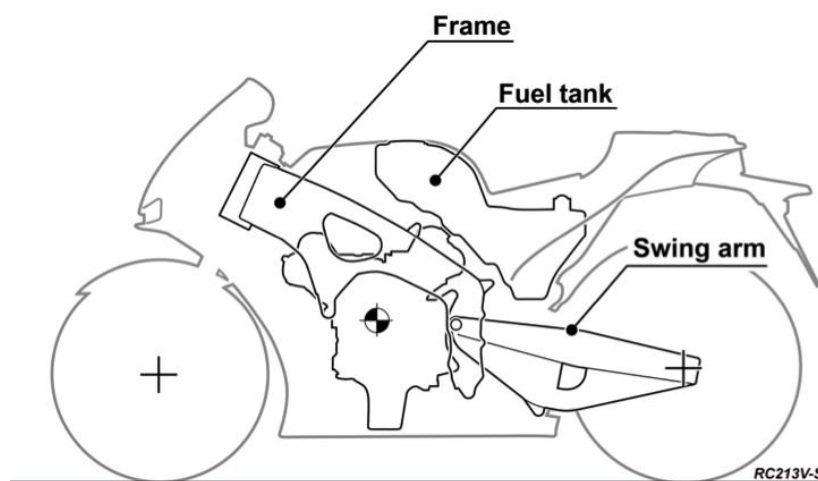


Figure 24: RC213V-S CoG position (image courtesy of Honda).

Interestingly the RC213V-S has a smaller anti-squat angle (figure 24) when compared with the KTM 450 Rally (figure 26). However, the swing arm length is considerably larger which pushes the CoG forward and will assist with keeping the front wheel contacting the ground.

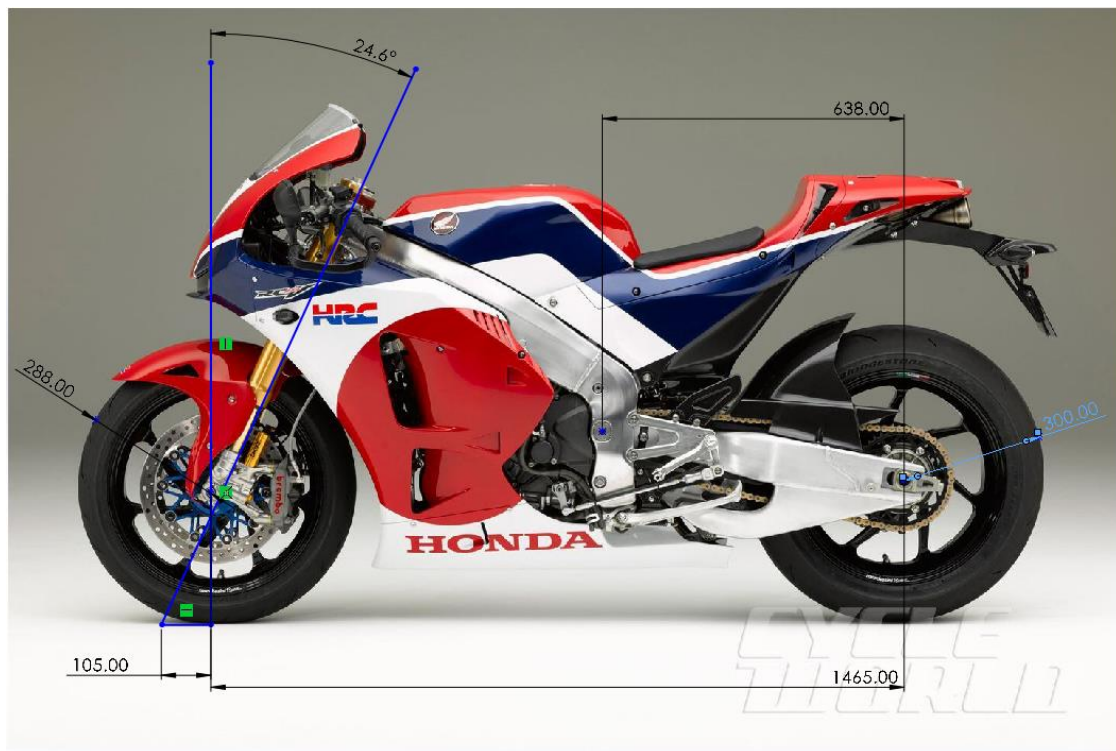


Figure 25: RC213V-S geometry data (image courtesy of www.cycleworld.com).



Figure 26: RC213V-S anti-squat angle (image courtesy of www.cycleworld.com).

5.2 KTM 450 Rally

The KTM 450 Rally is designed for use off road and is a popular choice in the Paris Dakar. It's seen to have a slightly longer wheelbase when compared to the RC213V-S. Due to the nature of the Paris Dakar and the terrain encountered a longer wheelbase is desirable for increased stability and because there is a lack of need for sharp, precise cornering the bike benefits from a larger rake angle further assisting with stability (A. Dowds).

Table 2: KTM 450 Rally geometry data (wheelbase taken from motorcyclespecs.co.za).

Geometry	Measurement
Wheelbase	1535mm
Rake	27°
Trail	54mm
Swingarm Length	578mm
Front Wheel Radius	346mm
Rear Wheel Radius	333mm
Anti Squat Angle	31°



Figure 27: KTM 450 Rally geometry (image courtesy of www.amsmoto.co.uk).



Figure 28: KTM 450 Rally anti-squat angle (image courtesy of www.amsmoto.co.uk).

Compared with the RC213V-S the KTM has a slightly larger diameter front wheel to assist with stability in loose terrain and a larger anti-squat angle to assist with keeping the front wheel contacting the ground for increased control and steering ability.

6 Recommended Alterations

The Aprilia RS250 has a positive trail measurement of 95mm, reducing this could improve responsiveness when entering corners but runs the risk of reducing stability in a straight line. From figure 2 we can see the CoG of the bike is near the 1G line. Moving the CoG forwards and down would allow for more controllable race starts.

The RS250 could benefit from an increase in anti-squat angle to assist with exiting corners during acceleration but it needs to be considered whether the bike has enough power to cause enough squat to benefit from this change.

Ultimately changing one piece of geometry may have a positive effect on handling it directly relates to but may also negatively affect other handling aspects.

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