University of Wales Trinity Saint David

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Motorcycle Geometry Analysis and Dynamic Handling Investigation

Motorcycle Technology (ACHA 4027)

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1. Introduction

How a motorcycle handles and performs, is built up by a variety of geometric parameters, such as rake, trail, wheel base, spindle height, swingarm length and weight distribution, all these factors as well as many others can directly affect how a motorcycle handles and responds through its dynamic phases whilst in use.

This report will investigate a small group of motorcycles and their known handling characteristics and analyse how these may have been achieved by the manufacturer and how they differ for their desired application within different scenarios.

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2. Motorcycle Selection

Geometry data was acquired for the first two distinct types of motorcycle using a mixture of computer aided engineering (CAE) and mathematical calculations.

2.1 Yamaha FZR 400 RR SP Race Bike 1990

The first chosen motorcycle was a 1990 FZR 400 RR SP 3TJ2 race bike (Figure 1), the values for this are expected to be slightly different to the manufacturer numbers, due to this being fitted with a 1998 YZF 600 4TV engine, this engine mounts in the same place in the chassis however the engine sits 20mm higher than the standard engine, which will change the Centre of Gravity (CoG) measurements, alongside differing gear ratios.

The Frame type for this motorcycle ins an aluminium beam frame

2.2 GasGas TXT 300 Pro Racing 2017

The second motorcycle for the investigation is a standard 2017 GasGas TXT 300 Pro Racing (Figure 2); this offroad trials motorcycle has a vastly different usage application in contrast to the Yamaha, which should give a clear and apparent difference in results.

The frame type for this motorcycle is a steel tubular semi-trellis .

Figure 1 -Yamaha FZR 400 RR SP

Figure 2 - GasGas TXT 300 2017

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3. Geometry Measurements

The geometry for this investigation was obtained with both CAE and mathematical calculations as well as referencing the manufacturers published specifications, physical measurements such as wheelbase, yoke heights, wheel radius' and sprocket radius' were taken of the bikes to allow a chassis schematic to be represented in Microsoft Excel.

Images were also scaled and analysed using Fusion 360, software to find the rake angle and aid with validation of calculated values.

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3.1 FZR 400 Chassis Schematics

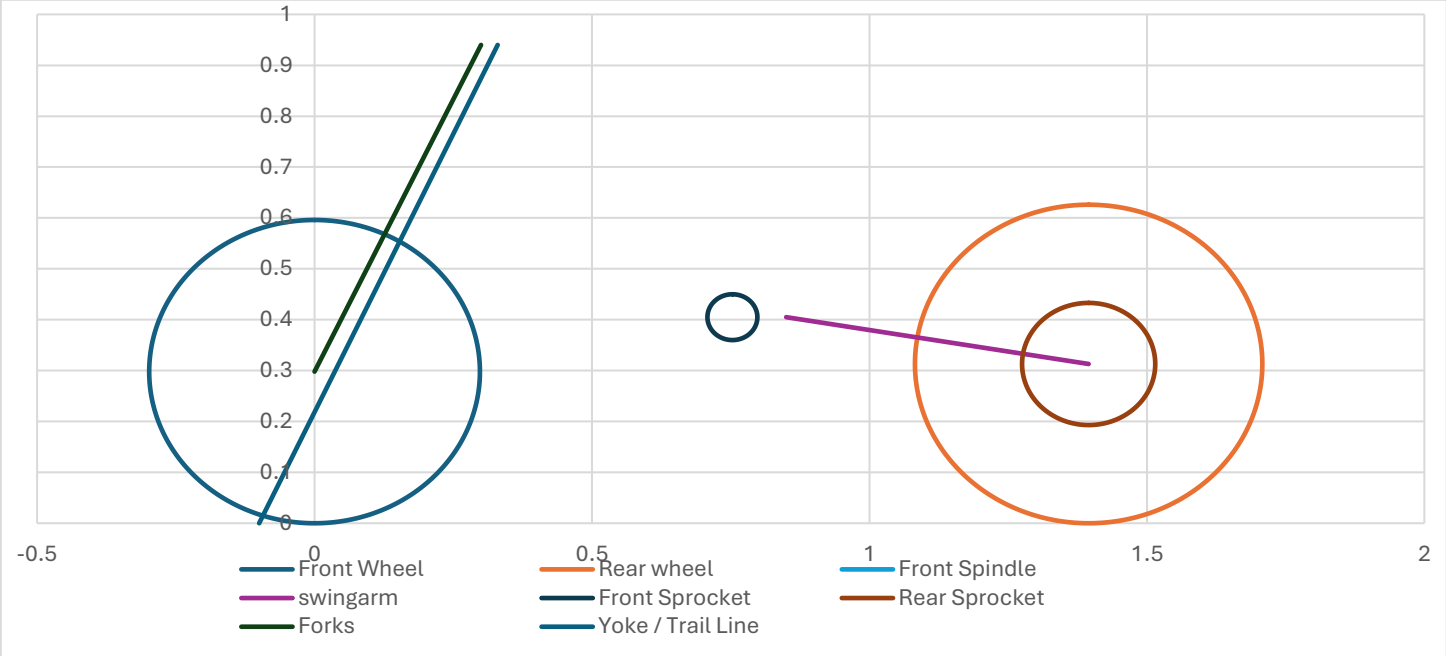

Figure 3 - FZR 400 Excel Schematics

Table 1- Measured Values for FZR

Positions	X (m)	Y (m)
Swingarm Pivot	0.85	0.405
Front Wheel Spindle	0	0.298
Rear Wheel Spindle	1.395	0.313
Front Wheel Radius	0.298	
Rear Wheel Radius	0.313	
Front Sprocket	0.753	0.405
Rear Sprocket	1.395	0.313
Front Sprocket Rad	0.045	
Rear Sprocket Rad	0.12	
Bike CoG	0.679	0.484
Bike + Rider CoG	0.740	0.657
Rake Angle (Degrees)	24	
Offset	0.03	
Trail	0.0998	

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3.2 GasGas Txt Chassis Schematics

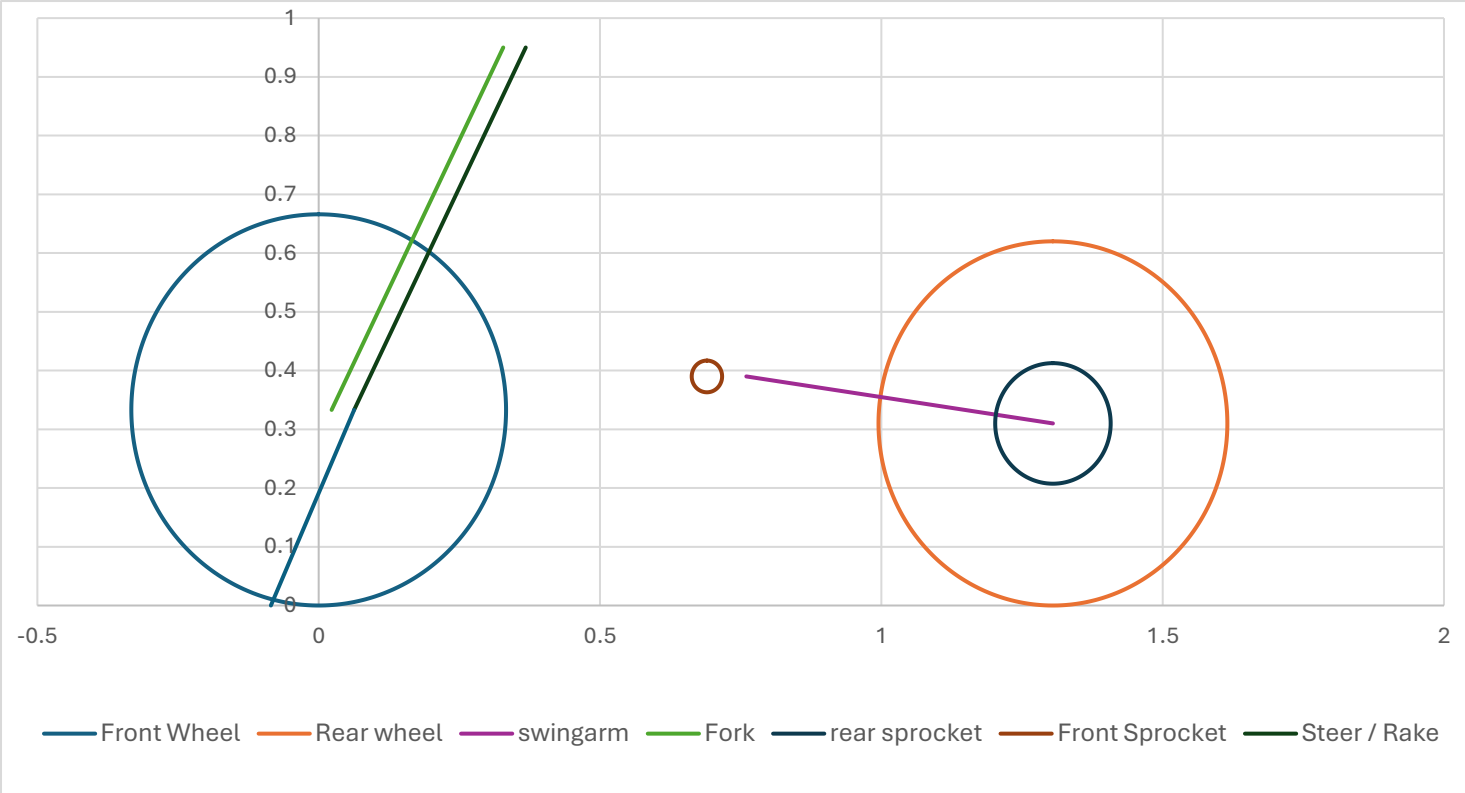

Figure 4 - GasGas TXT Excel Schematic

Table 2 – Measured Values for GasGas

Positions	x	y
Swingarm Pivot	0.76	0.39
Front Wheel Spindle	0	0.333
Rear Wheel Spindle	1.305	0.31
Front Wheel Radius	0.333	
Rear Wheel Radius	0.31	
Front Sprocket	0.69	0.39
Rear Sprocket	1.305	0.31
Front Sprocket Rad	0.027	
Rear Sprocket Rad	0.10261	
Bike CoG	0.655	0.445
Bike + Rider CoG	0.734	0.627
Rake Angle	21	
Offset	0.04	
Trail	0.085	
Trail mm	84.98	

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3.3 CAE / CAD Measurements

Figures 5 and 6 show the analysis of both motorcycles using Autodesk-Fusion CAD software, the photos are imported into the software and scaled using known measured real world values for example Figure 5 was scaled using the break disk diameter of 298mm, once scaled the photos can have reference geometry added and then measured, that is how their respective rake angles found and then used in the foregoing calculations.

On Figures 5-6 the Triangle represents the Cog with Rider and the Circle represents bike only.

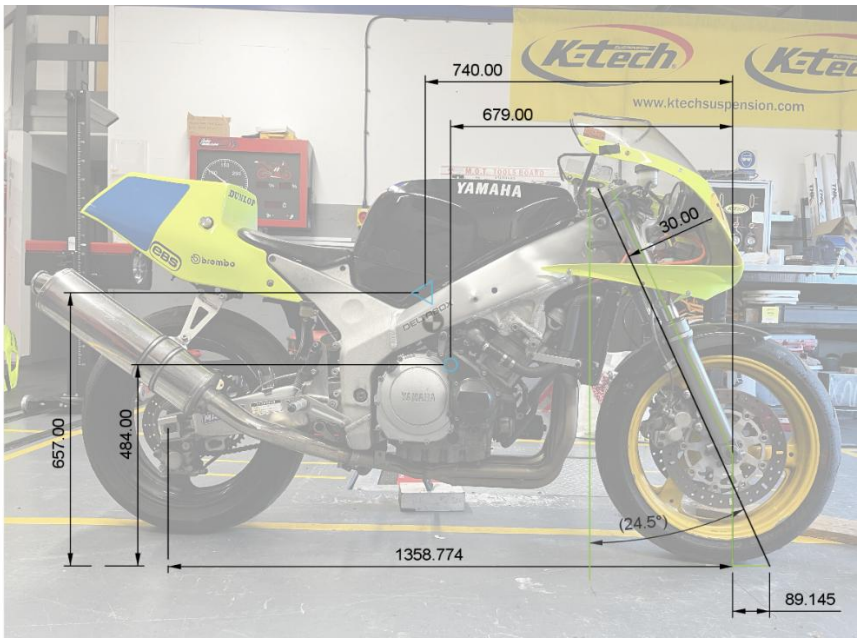

Figure 5 - FZR CAD Analysis

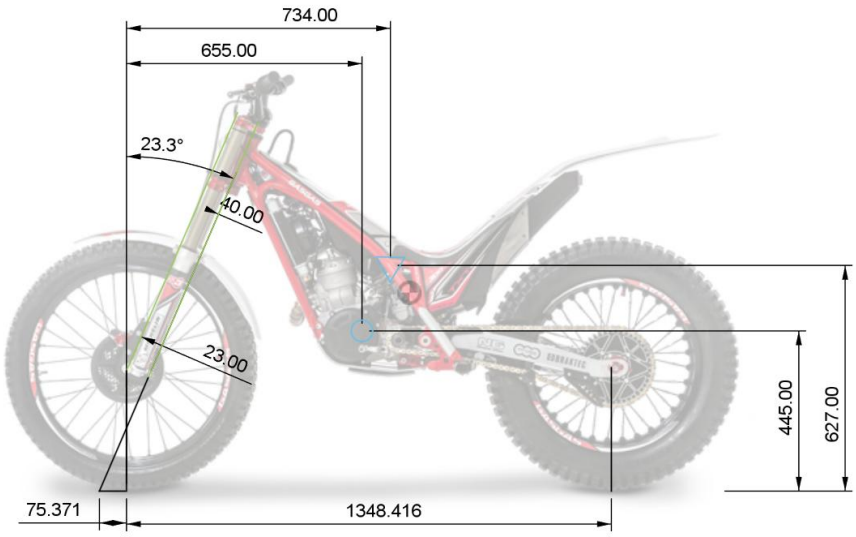

Figure 6 - GasGas CAD Analysis

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3.4 Geometry Table & Points of Error

Table 3 – Chassis Geometry Values

	FZR 400 Race Bike	GasGas TXT 300
Rake Angle Degrees (Calculated / Manufacturer / CAD)	ND / 24 / 24.5	ND / 23 / 23.3
Trail mm (Calculated / Manufacturer / CAD)	99 / 92 / 89	85 / ND / 75
Wheelbase mm (Measured / Manufacturer / CAD)	1396 / 1365 / 1358	1305 / 1330 / 1348
Ground Clearance mm (Measured / Manufacturer / CAD)	ND / 125 / ND	ND / 315 / ND
Tyre size (Fr / Rr)	120/60/17 160 / 60 / 17	69.85 / 100 / 21 101.6 / 100 / 18
Weight Kg (Measured / Manufacturer / CAD)	166 / 185 / ND	69.7 / 70.85 / ND

ND = No Data

There is variance between the investigated values and the manufacturer values, some of these such as the weight difference on the FZR is due to the fact that the factory manual is for the standard road bike whereas the machine measured is a race prepared bike which has had any unnecessary non race related items removed resulting in a lighter weight.

Looking at both motorcycles there is a +10mm difference in the measured trail over the CAD trail, this indicates that there could be a mathematical error within the trail calculation.

Another point of error could be from the image scaling in the CAD software as in figure 5 the photo was not perfectly taken side on, this is shown by being able to see both fork legs meaning the correction for the reference geometry had to estimated.

The CAD values are closer to the manufacturer's values, supporting the argument that there may be an issue with the calculations.

The difference with the numbers being near but not aligning with the manufactures values is the

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way that the manufacturer may measure the bike in a different static scenario where the bike may have been suspended in air with no weight on the machine or with a simulated rider load.

All the manufacturer values obtained for these two machines were obtained from the Yamaha factory service manual and the GasGas owner's manual.

(Yamaha Motor Japan, 1990; Yamaha Motor, 1991)

3.5 Trail Calculation

Measured geometry can be used in the trail equation (Equation 1) to calculate the ground trail of a motorcycle, is the distance between the projected point where the steering axis intersects the ground and the centre of the contact patch of the front tyre. (Foale, 2002)

$$\boldsymbol{Trail} = \frac{(Front\ Wheel\ Radius * \ Sin\ (Rake\ Angle) - Fork\ offset)}{Rake\ Angle}$$

Equation 1 - Motorcycle Trail

Rake angle is the angle measured between the steering head axis and the vertical axis perpendicular to the ground, rake and trail are separate values but are strongly interlinked a decrease in rake will result in a decrease in trail. (Cossalter, 2006)

The rake angle used in the trail calculation is the CAE value for rake, calculated and manufacturer trail values can be seen in table 3.

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4.0 Centre of Gravity (CoG)

Centre of gravity of a motorcycle can have large impacts on the handling characteristics of a motorcycle, it is not set directly by the manufacturer as it can be described as the most concentrated point of mass within a body and is determined by the total mass and how it is distributed through the motorcycle, it would be extremely difficult if not near impossible to pinpoint a centre of gravity and build a whole motorcycle to achieve that chosen location, the CoG could be viewed as a dynamic measurement when a motorcycle is in operation, as it is largely changed but the rider position and chassis position of the vehicle due to squat, dive and lean angle.

In the sports bike category, a low central CoG is a desirable attribute as the lower the mass concentration the less offset the mass becomes at a given lean angle, it could be thought as an imaginary mass acting on a torque arm trying to rotate the motorcycle, it can also give more stability when in the braking phase to an extent, but has the drawback of reducing load transfer which can be desirable for some scenarios and riders. (ST Motosport, accessed 12/25; Cameron, 2020)

4.1 Centre of Gravity Measurement Method

For the chosen 2 motorcycles the Centre of Gravities were measured for the bike unladen and the bike mounted with a rider.

The Methodology for obtaining the Cog for the motorcycles is to weigh the front and rear end of the motorcycle simultaneously, then rise the rear end of the motorcycle by a known height, remembering to add in the weight of the raiser, depending on the layout for the apparatus (Figure 7).

These measurements are then repeated again with a rider mounted on the bike in a riding position with no external influence balancing the bike if possible, it important for the rider to maintain their position in both measurements to keep continuity.

Figure 7 - Raised with Rider Measurement position.

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4.2 Centre of Gravity Calculations

The centre of gravity of a motorcycle is calculated by the following two equations:

$$\boldsymbol{XCoG} = \frac{Load\ on\ Rear\ Wheel * \ Wheelbase}{Total\ Motorcycle\ Weight}$$

Equation 2 - X Centre of Gravity

$$\boldsymbol{YCoG} = \frac{Wheelbase * \ (Load\ on\ Rear\ Wheel - Raised\ Load\ on\ Rear\ Wheel\ )}{Total\ Motorcycle\ Weight * \ Tan(angle\ of\ lifted\ bike)} + Average\ Wheel\ Radius$$

Equation 3 - Y Centre of Gravity

The angle of lifted bike can be calculated using $\Theta = Sin^{-1} * \frac{Raised\ Height}{Wheelbase}$

Equation 4 – Bike Raised Angle

The measurements taken also allows to calculate for weight distribution percentage for both bike and bike with rider using the following.

$$Weight\ Distrobution\ Front = \frac{Front\ Wheel\ Load}{Total\ Mass} * 100$$

Equation 5 - Front Weigh Distribution

$$Weight\ Distrobution\ \ Rear = \frac{Rear\ Wheel\ Load}{Total\ Mass} * 100$$

Equation 6 - Rear Weight Distribution

It is taken that the centre of gravity falls on the midpoint of the Z axis of the bike.

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4.3 Yamaha FZR 400 RR SP Centre of Gravity Results

Center of Gravity	Bike	Bike + Rider
X Cog m	0.679	0.740
Y Cog m	0.484	0.657
Percentage Front	51.35	47
Percentage Rear	48.65	53

Motorcycle Information	
1990 FZR 400 RR SP	
Wheelbase (m)	1.395
Rw Radius (m)	0.313
Fw Radius (m)	0.298
Radius Avg (m)	0.306
Unladen Weight (Kg)	166.1

Rider information	
Name	Phil Smith
Date Weighed	23/11/2025
Rider Weight (Kg)	72.4
Riding Kit Weight (Kg)	0
Total Riding Weight (Kg)	78.7

Measured Weight (Kg)					
	Level	**Level+Rider**	**Raised**	**Raised + Rider**	**Riser Weight**
Front	85.3	114.6	91.2	131.1	-
Rear	80.8	129.8	75.3	113.8	0

Risen Height	0.35
Risen Angle°	14.53

Combined Weight (Kg)	244.8

Table 4 - FZR 400 RR SP Race Bike Centre of Gravity Results`

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4.4 GasGas TXT Pro Racing 300 Centre of Gravity Results

Center of Gravity	Bike	Bike + Rider
X Cog	0.655	0.734
Y Cog	0.445	0.627
Percentage Front	49.78	44
Percentage Rear	50.22	56

Motorcycle Information	
2017 GasGas Txt 300	
Wheelbase (m)	1.305
Rw Radius (m)	0.31
Fw Radius (m)	0.333
Radius Avg (m)	0.322
Unladen Weight (Kg)	69.7

Rider information	
Name	Lucy Morris
Date Weighed	23/11/2025
Rider Weight (Kg)	65.7
Riding Kit Weight (Kg)	0
Total Riding Weight (Kg)	65.7

Measured Weight (Kg)					
	Level	**Level+Rider**	**Raised**	**Raised + Rider**	**Riser Weight**
Front	34.7	59.2	36.4	64.1	-
Rear	35	76.2	33.5	69	0

Risen Height	0.289
Risen Angle°	12.79

Combined Weight (Kg)	135.4

Table 5 - GasGas TXT Pro Racing 300 Centre of Gravity Results

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5.0 Top Speed and Resistance to Motion

Gear ratio and final drive selection has a substantial influence on a motorcycles behaviour and response and is an aspect that gets tailored to the motorcycles desired application and in competition machines changed dependant on location and conditions.

Final drive ratios can affect the squat and anti-squat behaviour of a motorcycle, increasing the front sprocket diameter will decrease anti-squat.

Figures 8 and 9 show the calculation data for the discussed motorcycles such as gearbox ratios, reduction ratios, and tyre size, to calculate rpm drops and top speeds for each gear at a given RPM.

Gearbox Calculator

Primary	48	82
Final	14	47

Mph On

Diameter	0.631
RPM	13000

Ratios			Speed Kmh	Speed Mph	Revs Rpm	Next Gear Rpm	Fall Rpm
1st	13	37	94.7	58	13000		
						8895	4105
2nd	19	37	138.4	86	13000		
						10317	2683
3rd	22	34	174.4	108	13000		
						11216	1784
4th	21	28	202.2	125	13000		
						11607	1393
5th	21	25	226.4	140	13000		
						11729	1271
6th	27	29	251.0	155	13000		

Figure 8 - FZR 400 Gearbox Data Calculator

Wheels And Tyres		
Width	Height	Rim Size"
160	60	17

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Gearbox Calculator								
Primary	27	75					Mph On	
Final	11	42						
Diameter	0.668							
RPM	10000							
Ratios				Speeds Kmh	Speed Mph	Revs Rpm	Next Gear Rpm	Fall Rpm
1st	1	2.996		39.6	24	10000		
							8581	1419
2nd	1	2.571		46.2	28	10000		
							8506	1494
3rd	1	2.187		54.3	33	10000		
							9657	343
4th	1	2.112		56.2	34	10000		
							5327	4673
5th	1	1.125		105.5	65	10000		
							7298	2702
6th	1	0.821		144.6	89	10000		

Wheels And Tyres		
Width	Height	Rim Size"
101.6	100	18

Figure 9 - GasGas Gearbox Data Calculator

It is worth noting, that this is the theoretical top speed at the rear wheel of the motorcycle not accounting for resistance to motion or drivetrain losses, all values come from their respective manuals.

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5.1 Top speed with resistance to motion (calculations)

The calculated theoretical top speeds are not necessarily achievable, due to the motorcycle having to work against resistances such as rolling resistance and aerodynamic drag, calculations can be done to assess if these may be achievable.

5.2 Theoretical Rear wheel speed:

$$= RPM * 60 * \left(\frac{main\ gear}{Counter\ Gear}\right) * \left(\frac{Primary\ in}{Primary\ out}\right) * \left(\frac{Wheel\ Diameter * Pi}{1000}\right) * \left(\frac{Front\ Sprocket}{Rear\ Sprocket}\right)$$

Equation 7 – Theoretical Rear Wheel Output Speed

Rolling resistance from mass:

$$= 0.02 * Total\ Mass * Gravity$$

5.3 Aerodynamic Drag:

$$= \frac{1}{2}\rho * Drag\ Coefficient * Area * Velocity^2$$

Equation 8 - Aerodynamic Drag

ρ = Air density of 1.167 Kg/m^3

5.4 Resistance Due to Gradient (Road Plane)

$$= mass * gravity * Sim\ Angle\ of\ Road\ PLane$$

Equation 9 - Resistance due to gradient

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6.0 Speed Calculations vs Resistance to Motion

Using the calculated information a plot of driving force against speed and total resistance against speed can be made to gauge how optimally the motorcycles are geared within terms of the bike's terminal velocity due to resistance.
Coefficient of drag values were unavailable for the chosen motorcycles and reliable values were difficult to find, these would be multiplied by the frontal area of the motorcycle in the drag equation, the values used in figures were CdA values taken from Page 93 of Motorcycle Dynamics Second Edition By Vittore Cossalter (2006), in the calculations the area is set to 1 due to the values being used being a CdA value.

The horsepower figures were extracted from dynamometer runs done by third parties, there could be a source of error here as the values were taken in different locations at in different environments and were also read off of a graph. (Performance Ivans, no date; Oldar, 2020)

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6.1 FZR Shift point Data

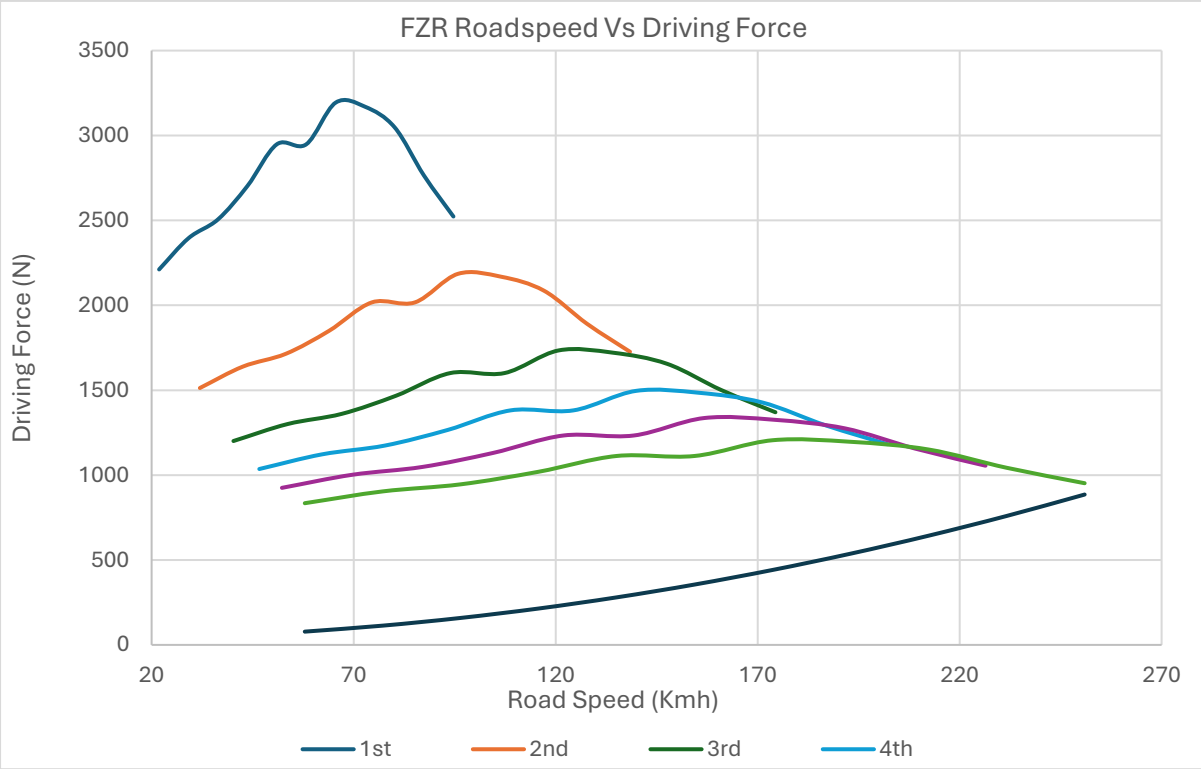

Figure 10 - FZR Shift Point Data

The Information displayed in the graph shows that the FZR within terms of the final gearing is that it is very near the intersect point but does not meet which means it **should** be able to achieve its geared top speed, the graph also shows that the first gear ratio could be significantly longer as there is a long way between the ratio and for short circuit use first gear is extremely short, you could also argue that the final drive could be a bit longer to help this and achieve a slightly higher top speed

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6.2 GasGas Shift Point Data

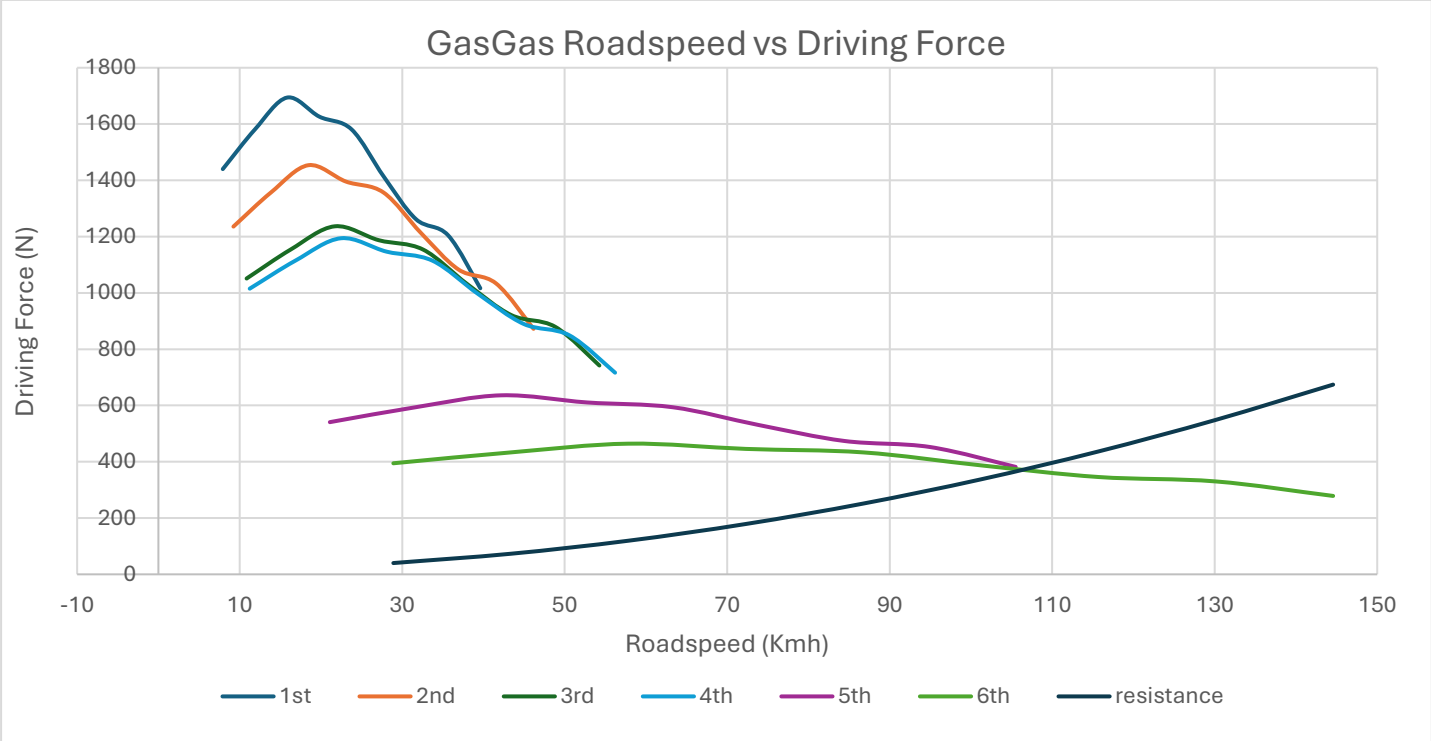

Figure 11- GasGas Shift point Data

This graph shows that the GasGas will **not** hit its top speed, due to the early intersect with the resistance, it can almost hit the top speed in 5th, it also show that the first 4 gears are extremely short this is a requirement for the trials sports to make the bike agile to launch over obstacles, the last two long gears are to be able to travel at speed at low RPM between sections of the course.

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7.0 Analysis

The Rake angle for the FZR is 24 degrees which is in the supersport and racing range of values encouraging a shorter trail relationship, this gives the bike a keen and fast tip in to encourage a tight turning radius and high lean angle, which supports the category of the 400cc machines being about flow and corner speed.

Rake angle for the GasGas is 23 degrees which is starting to move the extreme end of the scale, this is to allow the bike to have a very accurate and responsive feel to the machine allowing for an extremely tight turning circle to traverse severe terrain, the bike is designed for low speeds, as shown in 6.2, so high speed stability is not an issue and is offset but the flat square aspect of the rear tyre .

(Bradley, 2003; Lindemann, 2015)

7.1 Trail

The trail of the Gasgas and Fzr are 92mm and 75mm respectively, the FZR has a larger trail falling just in the sports-tourer category, which is unusual for the type of race bike, this could be to allow for stability to balance the steep rake. (Cossalter, 2006), the Gasgas has an extremely short trail, to allow for tight turns and wheel placement for trials manoeuvres such as splatters.

Part of the Gasgas' short trail is thanks to its axle led front forks offsetting the wheel spindle 35mm infront of the fork legs moving the front contact point closer to the projected line of the steering reducing the trail.

7.2 Wheelbase

Both machines assessed had a similar wheelbase both falling in the extremely short category continuing the theme of the both chassis having a rapid responsive feel, and a tight turning circle, this short wheelbase could be the reason the FZR has such a large trail value for a SuperSport bike in a bid to gain some stability within an agile chassis.

The Gasgas also boasts a longer swinging arm to boost stability and reduce wheelie whilst riding steep inclines.

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7.3 Centre of Gravity & weight distribution

Both bikes have a Very centred XCog moving rearwards by similar values, when the rider is mounted having this relatively even weight distribution allows for good tyre grip throughout the dynamic riding phases under both applications , the rearward shift under the rider weight is useful to grip under acceleration, also taking weight off of the front to aid turning and lifting the front in the case of the GasGas.

The Y Cog increases as expected on both motorcycles, when the measurements were taken, the Gasgas caused some error when rider mounted the YCoG decreased, this is believed to be due to the nature of the soft suspension and compression of the tyres from only having 4PSI in each, so the rider weight compressed the vehicle down to the ground plane with such severity that the loaded centre of gravity decrease .

The solution to this was to maximise the pre load front and rear, close the compression damping and inflate the tyres to negate compression, once these changes had been made the calculations resulted as expected.

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8.0 Modern Motorcycles & Applications

8.1 CBR 1000 RR R SP British Superbike

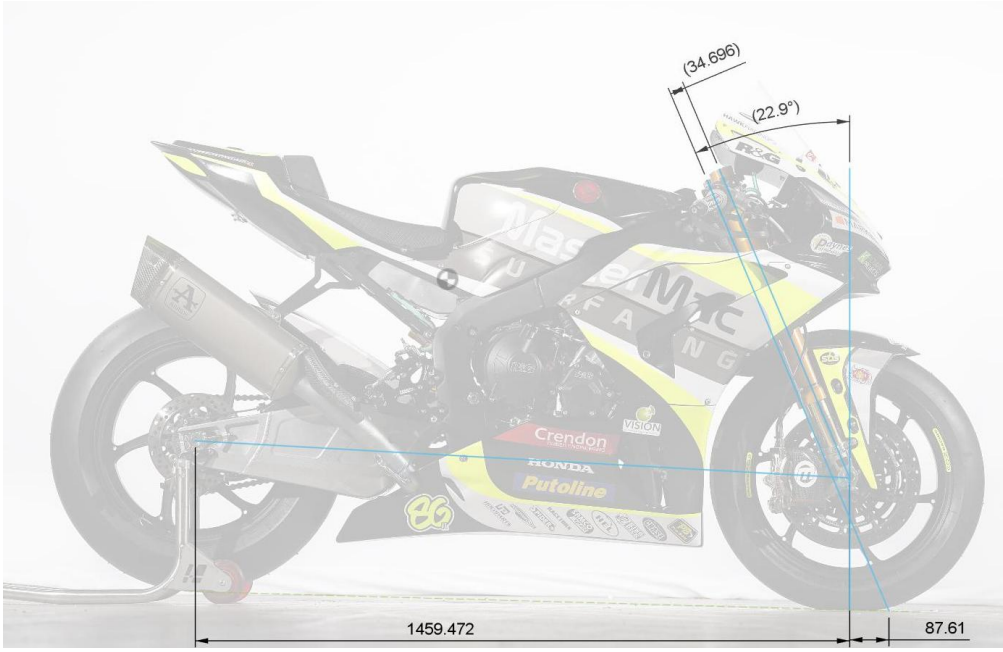

Figure 12 - Hawk Racing CBR1000 RR R SP 2024 (Hawk Racing, no date)

This Fireblade has a relatively steep rake angle and short trail for the motorcycle to be able to change direction quickly for short circuit racing, the wheelbase is longer to allow for stability and reduce wheelie, measurements are not final for this bike due to it having variable swingarm and headstock inserts to alter the geometry depending on environment.

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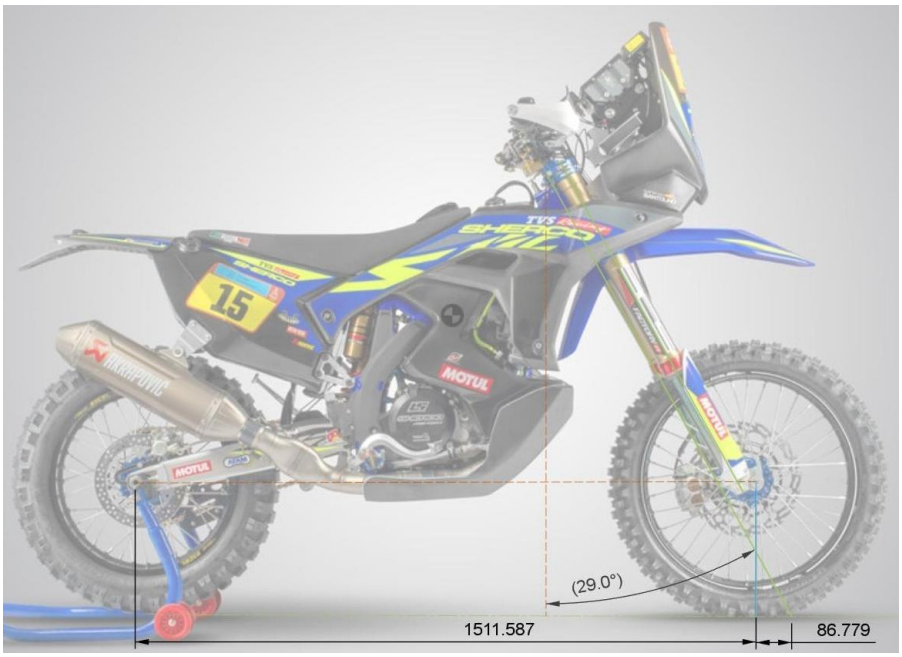
8.2 Sherco 450 SEF Rally Factory Dakar Bike



This Sherco boast a large 29˚ Rake angle providing a large stability for when the front wheel pushed through the sand on Dakar stages, combined with a short trial given by the axle led forks to allow for direction change in the sand, a long wheelbase also aids stability, alongside a large front wheel than rear to allow the motorcycle to traverse over uneven terrain.

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9.0 Alterations

The FZR would benefit from lowering its centre of gravity to tailor it better to its racing category, allowing the bike to yaw less under breaking and stand up easier out of a corner, the centre of gravity for this bike is high, due to the 600 engine being slightly heavier but also sitting 20mm higher in the frame than the original, this could be aided but fitting something such as a kit ignition rotor, removing sprung weight and reducing inertia, to help tip in and exit.

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11.0 Acknowledgement

A thanks to KSR Performance Isle of wight for allowing the use of their workshop space and time to obtain centre of gravity measurements and geometry data for the motorcycle