

AWD Torque Vectoring

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Abstract – An investigation was conducted into the Ferrari FF AWD system in order to break it down and analyse why it was revolutionary at the time. A system in which few other vehicle manufacturers have been inspired to create their own version. A Notable example would be the Focus RS. (GKN Automotive, n.d)

1. INTRODUCTION

This Engineering Report details an investigation into the Ferrari FF vehicle All Wheel Drive systems in order to understand the effects on vehicle dynamics and potential control strategies from the torque vectoring front wheel drive system.

This is achieved via the gathering of the base vehicle data to calculate; A lumped mass model of the vehicle; the longitudinal C of G position; the vehicle's moment of inertia (about Z-Z axis); the position of the inertial conjugate; the 'dynamic index' of the vehicle and the mechanical torque path to the front wheels.

Further discussion is brought to the clutch packs torque capacity, approximate sizing's, axial force application values is achieved.

Finally, a discussion on possible control algorithms, sensors required, and potential vehicle dynamic improvements is given with focus on, on power and off power, straight line and cornering, on-limit lane change manoeuvres, and how the AWD system will inter-react with other vehicle dynamic control systems.

2. BASE VEHICLE DATA

Released in 2011 boasting 660hp it became Ferrari's most powerful production vehicle on par with the 2002 Ferrari Enzo. One of the innovations featured on the car was the patented four-wheel-drive system, called 4RM. The 4RM system allowed the FF to have a near perfect weight distribution with 53% over the rear axle. The vehicle also featured a magnetorheological self-adjusting damping system and Brembo Carbon-Ceramic brakes. (Reynal, 2011)

2.1 DIMENSIONS AND MASS

The dimension and mass data were gathered from 2 different sources in order to validate it. Table 1 and Figure 1 display this data.

Table 1: Ferrari FF Dimensions and Mass (The Car Guide, 2016)

Name	Measurement
Length	4,907 mm
Width	1,953 mm
Height	1,379 mm
Wheelbase	2,990 mm
Front track	1,676 mm
Rear track	1,661 mm
Weight	1,884 kg

Ferrari FF (2013)

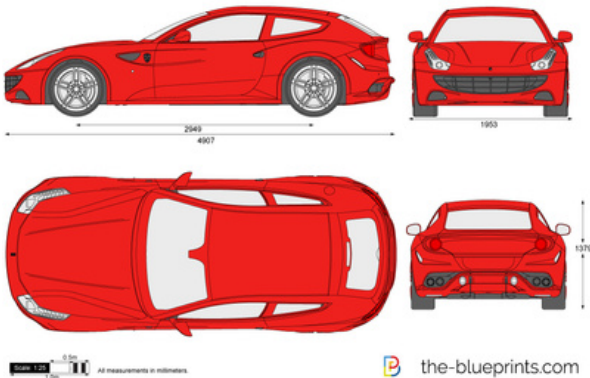


Figure 1: Ferrari FF Dimension (The Blueprints, n.d)

2.2 DRIVELINE LAYOUT

The Ferrari FF driveline layout was ground-breaking at the time as the 4RM system allowed for the retention of the mid-front engine architecture. Its 660hp V12 engine was positioned behind the front wheels and a Power Transfer Unit (PTU) ahead of the engine in order to aid in achieving near perfect weight distribution. The PTU managed the distribution of torque independently to the front wheels via the use of two separate multi-plate clutches and have a torque vectoring function. This innovation allowed for a 50% weight saving compared to a traditional 4WD system and ~30% faster activation time. Innovations continued with the addition of an n F1 dual-clutch gearbox with an E-Diff incorporated inside it. (Ferrari, 2011)

Unlike conventional 4WD systems the FF features 2 gearbox's with a conventional seven-speed gearbox on the rear axle, and a second gearbox (featuring 2 gears) inside the PTU. The PTU's gearing is slightly higher than the rear gearbox so to allow the front axle to match the rear the wet clutches continuously slip, or they can overspeed and utilize torque vectoring. (Strong, 2011)

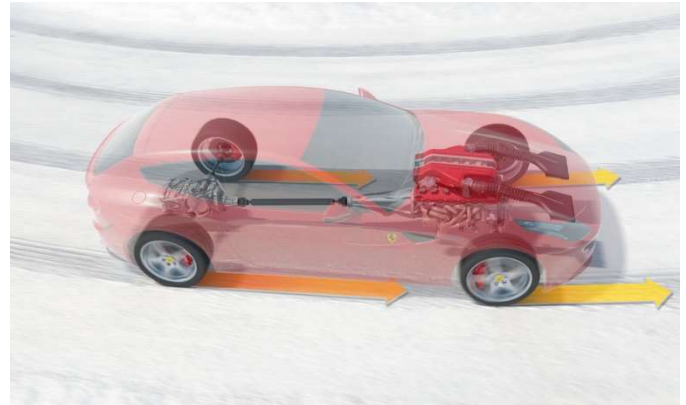


Figure 2: Ferrari FF Driveline Overview (Pulman, 2021)

3. TORQUE VECTORING SYSTEMS

Torque Vectoring's main principle is to improve handling and steering response by changing the distribution of torque between the wheels. This seems to be similar to a Limited-slip Differential (LSD) at first glance however, torque vectoring is much more advanced. (Shah, 2021)

The main difference between the two is that an LSD is a mechanical, reactive system whereas torque vectoring is a holistic predictive system utilizing a combination of mechanical hardware and electronic software. Rather than just limiting the amount of slip torque vectoring could allow for a small amount of power to be sent to a slower wheel or vice-versa. Another benefit of torque vectoring is the ability to increase the yaw effect when cornering by distributing the engine power to rotate the car more easily. (Shah, 2021)

Torque vectoring operations differ widely from vehicle to vehicle. Performance cars typically use a mechanical, differential system whereas standard conventional vehicle tend to use a brake-based system. In some cases, vehicles use a combination of the two. (Shah, 2021)

3.1 DIFFERENTIAL AND CLUTCH BASED TORQUE VECTORING

Differential based systems tend to have an open differential with multi plate clutch packs on either side along with wheel speed sensors and pitch and yaw sensors. The clutch packs aren't always engaged and when not in use the car functions as if it had a standard open differential;. If any of the clutch packs engage they work by increasing or reducing the amount of torque provided to a certain wheel. (Shah, 2021)

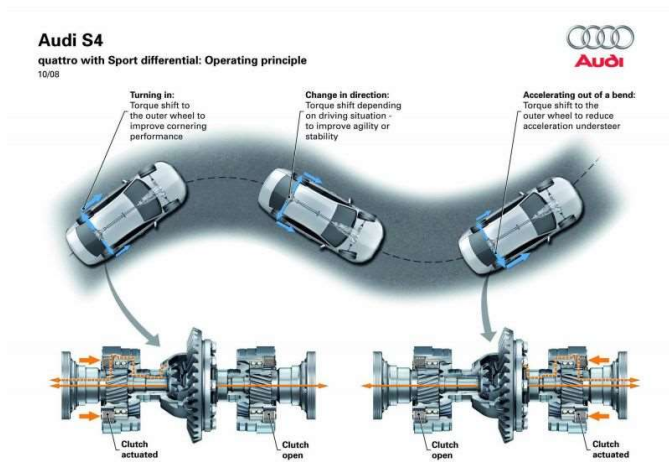


Figure 3: Audi S4 Quattro Torque Vectoring (Shah, 2021)

3.2 BRAKE-BASED TORQUE VECTORING

Brake-based torque vectoring aims to replicate the features of differential based torque vectoring by applying the brake to one of the wheels to mimic the function of an open differential with multi plate clutches. In the case of a turn, the inside wheel would have the brake applied creating a speed difference between it and the outside wheel in turn increasing yaw. The main disadvantage of this is its speed and durability, applying the brakes instead of hydraulically or electronically engaging a clutch is much slower. However, it is a lot cheaper and much

more suitable for road vehicles where lap times are not essential. (Shah, 2021)



Figure 4: Land Rover Discovery Sport Torque Vectoring (Shah, 2021)

3.3 ELECTRIC TORQUE VECTORING

The increased activation speed of electronic motors allows for the foundation of all-wheel torque vectoring. By placing an electric motor on each wheel, each wheel can be independently controlled via an ECU. Torque and power levels can be adjusted on the fly and can also combine with regenerative braking to give greater control during acceleration and braking. (Shah, 2021)

Electric Torque vectoring also allows for greater control of the vehicle by allowing the driver to make the vehicle to oversteer, understeer, or have a neutral handling balance. (Shah, 2021)

4. CENTRE OF GRAVITY

In order to calculate the Centre of Gravity of the FF a Lumped Mass Model was created (fig 2).

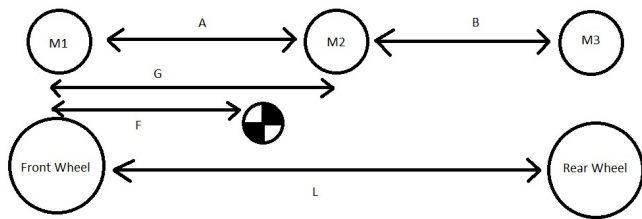


Figure 5: Simplified Lumped Mass Model

To calculate the Centre of Gravity (F) the following equation was used:

$$F = (M2 * G) + (M3 * L) / M1 + M2 + M3$$

Where:

M1 = Mass over the front axle

M2 = Mass of Driver

M3 = Mass over the rear axle

G = Distance to Driver from front axle

L = Wheelbase

4.1 DERIVATION OF VARIABLES FOR COG

M1 and M2 were easily calculated as the weight distribution of the vehicle was researched indicating that 53% of the vehicle's weight is over the rear axle which gives us a value of 998.52 kg for M3. From this we can deduce that 47% of the weight is over the front axle which gives us 885.48 kg for M1. The final Mass Variable is the driver. The average weight of a man globally is 61 kg, so this was the weight chosen for M2. (Gill, 2018)

The variable L was once again achieved through research which gave a value of 2.99m. (The Car Guide,

2016). The final variable to find was G which is the Distance to Driver from front axle. This required some more in-depth research to be calculated.

Firstly Figure 1 was imported into Solid Works and a 160mm line was drawn from wheel to wheel. Then a 110mm line was drawn from the centre of the front axle to roughly where the driver would be seated. From this it can be deduced that the driver sits 68.75% along the wheelbase. As the real wheelbase is known to be 2.99m the driver can be deduced to be at 68.75% of this value which gives a G value of 2.05m.

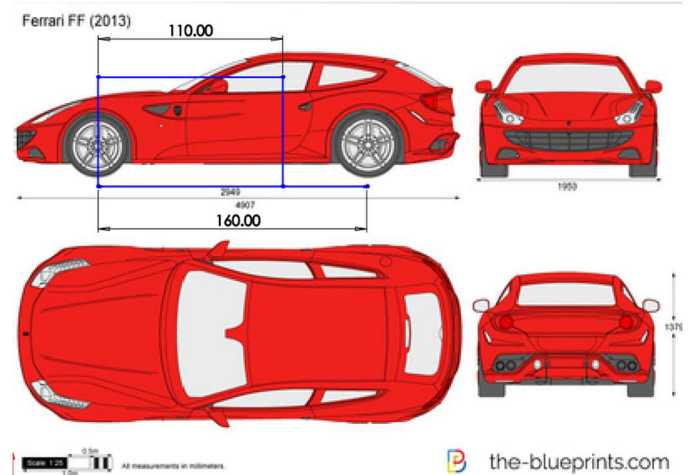


Figure 6: Ferrari FF Driver Position Estimation (The Blueprints, n.d)

From this the CoG equation can be solved which presents the Ferrari FF's CoG at 1.6m between its wheelbase.

5. MOMENT OF INERTIA (ABOUT Z-Z AXIS)

The Yaw Inertia is calculated via the use of the Inertia Equation seen below:

$$I = M * r^2$$

Where:

M = Mass

r = radius i.e., the CoG

As the vehicle has 3 lumped mass' in this model the Inertia Equation is applied to all 3 mass'.

$$I = (885.48 * 1.6) + (61 * (2.05 - 1.6)^2) + (998.52 * (2.05 - 1.6 + 0.94)^2)$$

$$I = 4208.42 \text{ kgm}^2$$

6. Inertial Conjugate

Inertial Conjugate or Centre of Percussion (CoP) is easier visualised in the form of a bat hitting a ball. When the bat is displaced from a point of equilibrium gravity will try and return that object back to its equilibrium point while its inertia will cause it to overshoot similar to a pendulum. Due to the interplay of these forces the object will repeat this cyclic motion for an amount of time. The amount of time depends on the objects mass, the location of the CoG relative to its pivot point, the rotational inertia, or Yaw Rate about its pivot point and finally the force of gravity.

In the case of baseball bats, manufacturers and governing bodies position the pivot point 6 inches away from the end of the bat to start to solve the CoP. The CoP can be calculated simply via

$$\frac{\text{Inertia}}{\text{Mass} * \text{Distance from Pivot Point to CoG}}$$

In this case the pivot point of the car would be the front axle. To solve the CoP the formula can be populated as so.

$$\frac{4208.42}{1945 * 1.6} = 1.35 \text{ m}$$

7. DYNAMIC INDEX

The Dynamic Index (DI) of a vehicle is the output of the Inertia Match Theory. The Inertia Match Theory Describes "the relationship between a vehicles Centre Of Gravity position (COG), the vehicles wheelbase and then it's yaw inertia (mass squared)." (Sam, 2007)

A 50:50 weight distribution will always produce the best DI for a given yaw inertia. The DI indicates the way the chassis will behave when manoeuvred on a ground plane. (Sam, 2007)

If the $DI < 1$ then the rear of car moves outwards, and the inertial effects add to the rear tyre slip angle. If the $DI > 1$ then the effects are reversed. An example of a vehicle with a lower DI is the Classic VW Beetle. This vehicle has a DI of around 0.48 and are the opposite of a nimble vehicle and can be uncontrollable when at the grip limit. (Sam, 2007)

7.1 FERRARI FF DI CALCULATION

The DI of the FF was calculated via the following equation:

$$DI = \frac{I}{m * a * b}$$

Where:

I = Inertia in the ZZ axis

M = Total mass of the vehicle

A = Distance from M1 to CoG

B = Distance from M3 to CoG

In the case of the FF the equation is as follows:

$$DI = \frac{4208.42}{1945 * 1.6 * 1.39} = 0.97$$

The DI of the vehicle is more or less equal to 1 which is expected due to the near perfect weight balance of the vehicle which would suggest a DI of close to 1. This DI makes the FF an agile and nimble vehicle despite its weight and wheelbase size. (Sam, 2007)

8. MECHANICAL TORQUE PATH TO THE FRONT WHEELS

This section utilises 2nd hand research to help explain the mechanical torque path from the engine to the front wheels.

In 2007 Ferrari filed a patent titled "Connectable Four-Wheel drive vehicle" (US2007/0221427). The patent describes the system publicly known as 4RM.

Figure 7 displays the general layout of this system.

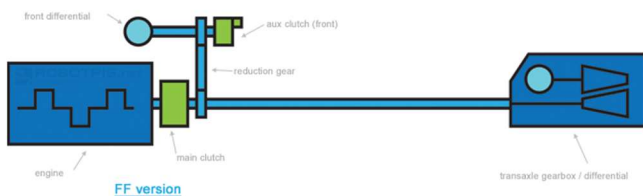


Figure 7: Ferrari FF Driveline Sketch (RobotPig, 2011)

The Torque is transferred from the crankshaft through the main clutch and flywheel where it then travels through the prop shaft into the rear transaxle gearbox / differential. In most cases a secondary prop shaft would then be required to transfer the remaining torque to the front differential. (RobotPig, 2011)

However, in the FF's case there is an electronically controlled clutch which allows power to be transferred directly from the crankshaft to the front differential (PTU). (RobotPig, 2011)

The Torque reaches the rear wheels through the conventional path of a gearbox/differential combination but, there is a set gear ratio for the front. Typically, the front auxiliary clutch will be disengaged allowing 100% of the available Torque to sent to the rear axle. In the case that Torque vectoring is required and is determined via the wheel speed sensors the front clutch will engage sending up to 20% of the available torque to the front wheels. (RobotPig, 2011)

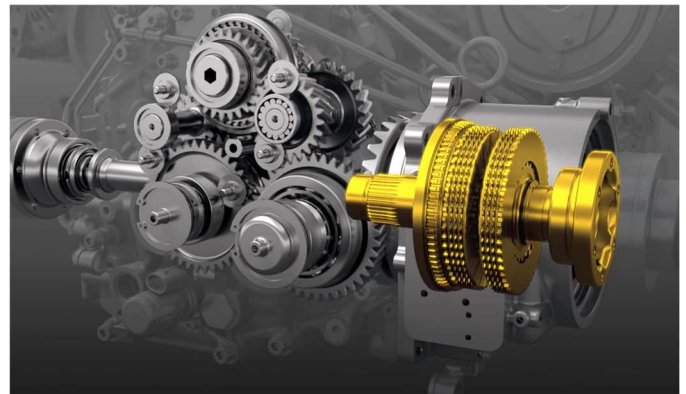


Figure 8: Inside view of the PTU (Ferrari, 2011)

The image above displays the helical reduction gears displayed in Figure 7 in more detail. The Torque is fed through these gears and into the 2 sets of clutch packs (1 for each wheel) in order to help stabilize the vehicle when cornering. (RobotPig, 2011)

9. CLUTCH PACK INVESTIGATION

The FF features a gearbox situated above its rear axle which houses a series of wet clutches for each wheel. This section aims to evaluate these clutches with regard to their torque capacity and the axial force applied to them.

As much of the FF's data is confidential and covered by my Intellectual Property laws the clutch sizes are estimations gathered from 2nd hand research and via the scaling of known parts to determine the clutch pack size.

9.1 SCALING

The Ferrari FF's brake rotor size is known and is 398mm. (FerrariLife, 2014). Figure 9 displays a skeletal version of the FF's chassis with the brake rotor on display. This was then imported into Solidworks and scaled so that the brake rotor matched the 398mm researched diameter. From this the external diameter of the wet clutches could be determined.

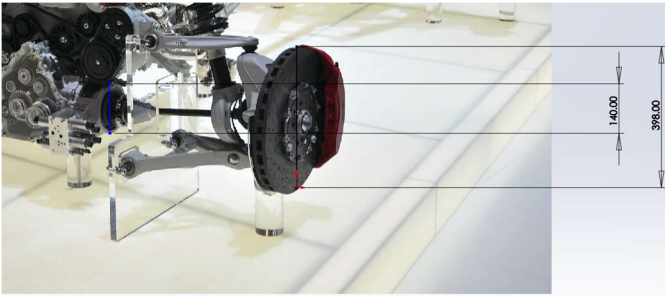


Figure 9: Ferrari FF Chassis (Reddit, 2015)

Now that the external diameter has been estimated the thickness and inner diameter can be calculated from another researched and scaled image.

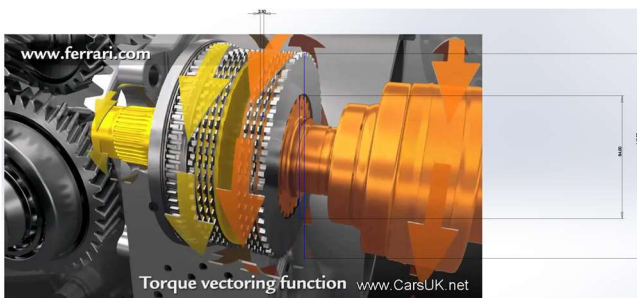


Figure 10: Ferrari FF Clutch Pack (CarsUK, 2011)

From this scaling the inner diameter of the clutch can be estimated to be 84mm and the thickness to be around 2.5mm and there are 4 clutches per wheel. Full size images can be seen in Appendix A and Appendix B.

9.2 TORQUE CAPACITY

The FF's torque output is 683Nm at 6000 RPM. (Ze Perf, 2020) Its reported that the PTU can handle up to 20% of that torque which equates to 136.6 Nm. (Austin, 2011)

From this the Axial force on the clutches can be determined.

9.3 AXIAL FORCE

The following equation was used to determine the axial force on the clutch packs.

$$W = \frac{T}{2n\mu(r1 + r2)}$$

Where:

T = Torque

2n = Number of Plates

W = Axial Force

r1 = Outer Diameter

r2 = Inner Diameter

μ = Coefficient of Friction

$\therefore$

$$W = \frac{136.6}{8 * \mu * (0.14 + 0.084)} = 252.98 \text{ N}$$

10. VEHICLE DYNAMICS IMPROVEMENTS

Vehicles are complex systems which involve multiple dynamics. On one hand you have the perceived and subjective comfort and on the other you have the objective safety dynamics. Typically, these two dynamics are decoupled with comfort dynamics typically relating to suspension systems and the safety dynamics relating to steering and braking systems. (Poussot-Vassal et al., 2010)

10.1 ABS

One of the most widely used dynamics improvement over recent years is ABS. Under normal braking conditions ABS is not active. However, when the ABS senses a wheel is about to lock up (tyre loses traction) the brake force is regulated by the ABS. It has 3 stages. Stage 1 is Pressure Increase. More brake fluid is passed through the brake cylinder to increase braking pressure. Stage 2 is Pressure Sustained. This stops any more hydraulic fluid running to the brake piston, which holds the current level of braking. If this is not enough Stage 2 is initiated. Stage 3 is Pressure Reduction which reduces the amount of brake force being applied to avoid wheel lock up. (AUTODIAGNOS, n.d)

A wheel will lock up when the tyre cannot absorb the lateral forces acting upon it. When a wheel locks up and stops moving, there is a difference in velocity as the car is still moving. This is known as 'Slip Coefficient' or 'Slip'. 0% slip means the car is free to roll whereas 100% slip the wheel is locked and the car is still moving. The maximum slip coefficient of a modern car is ~20% depending on tyre and road surface. (Alfa Romeo, n.d)

Speed sensors in the wheels determine if a wheel is about to lose traction and lock up. There is a sprocket on the wheel and a sensor (typically a hall effect sensor or a magneto resistive) attached to the car. The

signal is then converted to a digital signal. (Automotive Engineer, 1999)

ABS aims to achieve the optimal control of wheel acceleration and slip angle. A modern ABS has several different states which include: "Initialize, Hold Brake Pressure, Increase Brake Pressure, Fast Increase Brake Pressure, Step Increase Brake Pressure, Decrease Brake Pressure, Step Decrease Brake Pressure and Exit Braking." (Khanse et al., 2015) Each wheel can be in a different state at one time all working in unison to increase traction. A typical ABS on a modern vehicle is capable of control all 4 wheels with a single unit. The brake pressure is regulated by solenoids in the Hydraulic Control Unit. (Khanse et al., 2015)

10.2 ABS and AWD

ABS's main purpose is to allow steering while under braking. Not too dissimilar from the purpose of Torque Vectoring which allows for enhanced vehicle control while steering. As such the systems could share certain sensors such as wheel speed, steering angle, acceleration, and brake sensors to name a few. The interaction between these sensors would need to be managed carefully via software to determine whether ABS intervention is required or Torque Vectoring.

11. CONCLUSION

In conclusion its clear to see that the Ferrari was ahead of its time with its development of the 4RM system, A system in which few other vehicle manufacturers have been inspired to create their own version. A Notable example would be the Focus RS. (GKN Automotive, n.d) This may be down to quality control issues that have been raised by many Ferrari owners. (Furlonger, n.d). Nevertheless, the Ferrari FF featured an amazing AWD system which allowed for lightning speed actuation and tremendous weight savings.

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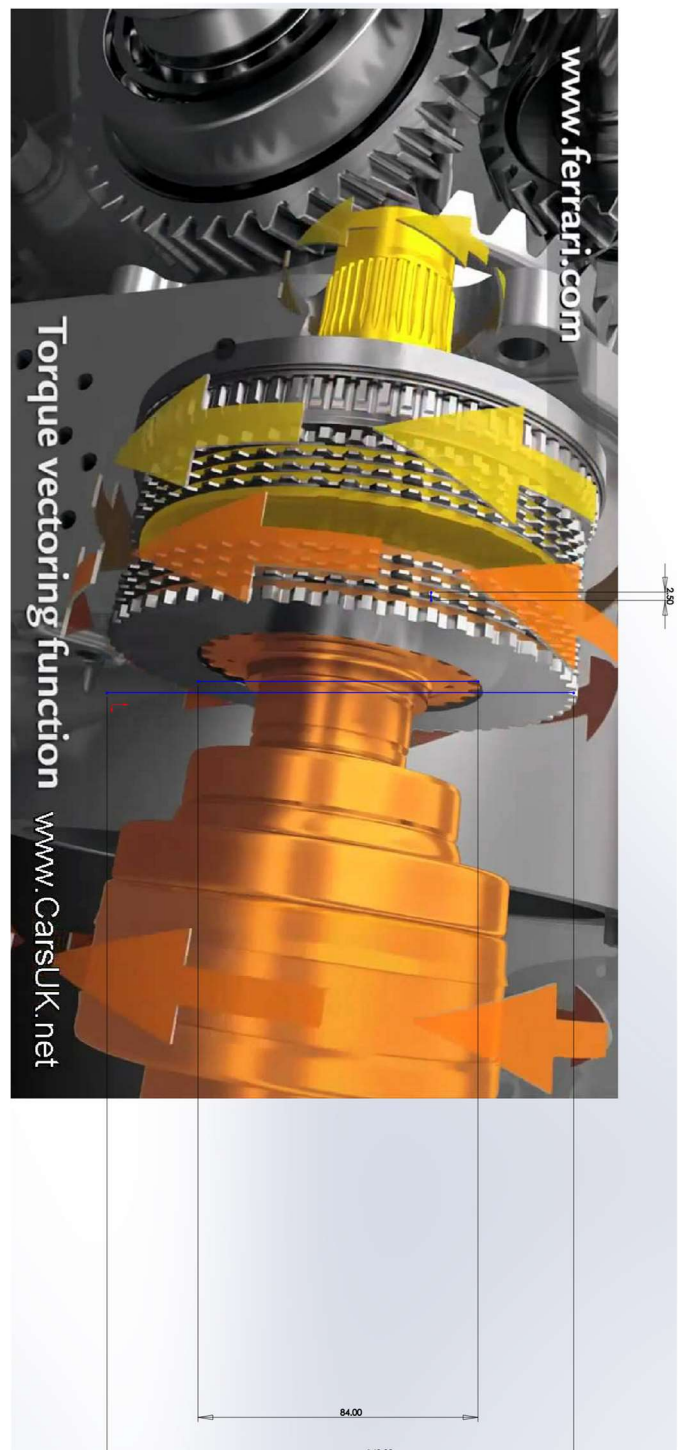
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13. APPENICES

APPENDIX A



APPENDIX B



APPENDIX C

1	m1	m2	m3	g	I	f	Yaw Inertia	Dynamic Index
2	885.48	61	998.52	2.05	2.99	1.599293	4208.42082	0.97282758
3								
4								
5								
6	1.390707							
7								
8	1945							
9								
10	0.94							
11								
12								
13	a	1.599292956						
14	b	1.390707044						
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