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Four wheel drive torque vectoring of a Ferrari FF AWD system

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1 INTRODUCTION

This report is a study into the AWD torque vectoring systems and how the weight distribution affects the handling dynamics, the case this will be evaluated was Ferraris first AWD system on the FF which had an unconventional rear transaxle gearbox and front engined to improve the weight distribution. This report will be outlining and explaining the basics of AWD and why it is used, why Ferrari adopted for a brand new concept to the AWD system and how the AWD system can affect the handling dynamics of the car as well as briefly mentioning electronic handling control (ABS, TC)

2 BASE VEHICLE DATA

length	4907	mm
width	1953	mm
height	1379	mm
wheelbase	2990	mm
front track	1676	mm
rear track	1660	mm
kerb weight	1880	kg
weight distribution	47 front 53 rear	%

front tyre width	245	mm
rear tyre width	295	mm

max power	486	Kw
max torque	683	Nm
max rpm	8000	RPM
max speed	208	mph
0-60	3.7	seconds



These are main basic details of the Ferrari FF in order to calculate the COG as well as inertia in the z-axis to evaluate the dynamic index of the Ferrari which is way of characterising handling. There is brief mention of power and torque, but this will be expanded in more detail when calculating clutch pack power, torque and force.

3 INTRODUCTION TO GENERIC TORQUE VECTORING SYSTEMS

The purpose of torque vectoring systems are to control the amount of torque at each wheel in order to maximise the contact patch without overloading or underloading each tyre to maintain maximum grip, this can be done by using a differential. Under acceleration the differential can control the power output at each wheel across the axle. When cornering the outside tyre becomes overloaded from WT and when accelerating in an FWD car this will increase causing understeer. Therefore the differential will increase the power going to the inside wheel to reduce the load on the outside tyre and make the inside tyre work harder (closer to the slip curve) to reduce understeer.

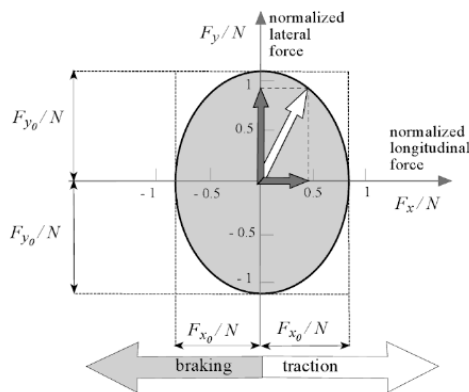


Figure 3-1 Tyre friction ellipse

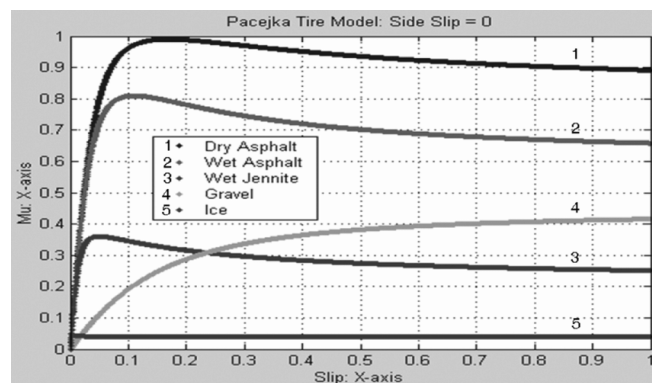
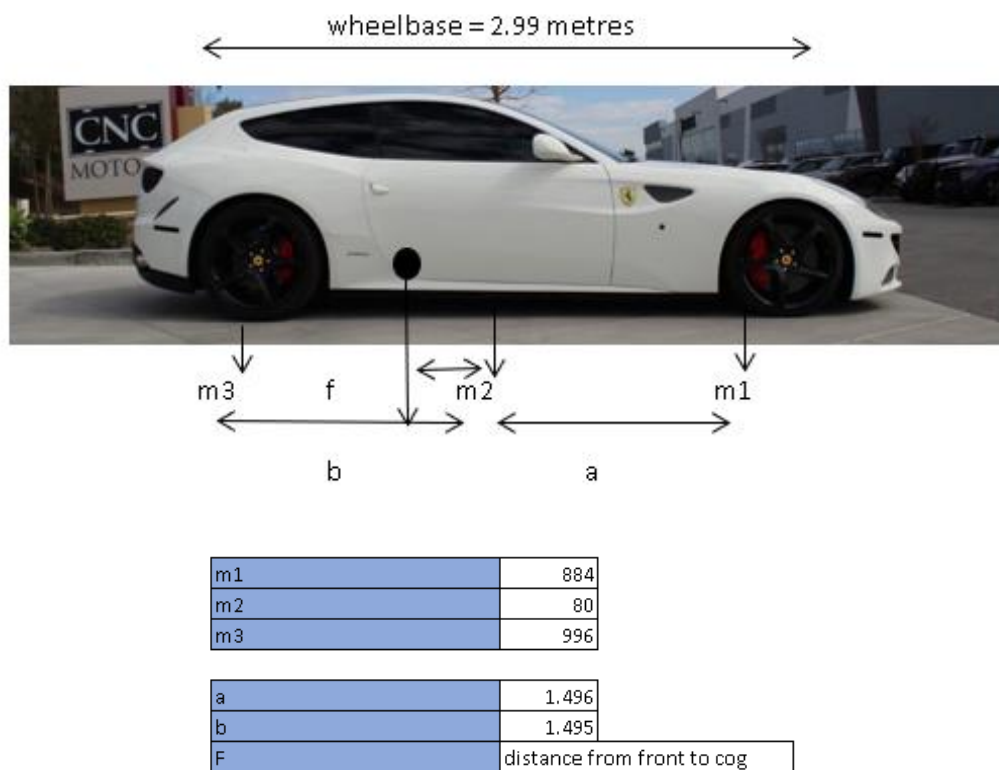


Figure 3-2 Tyre slip curve

To fully maximise each tyre an AWD drive system can control the torque and speeds of each wheel in dynamic driving, this is a 4 wheel drive system. The reason for this development is because if the torque vectoring system can control each wheel velocity it could control the Yaw angle and affect the handling balance. For example from a standing start conducting a 0-60mph test immediately of the line the rear tyres become overloaded from the WT shifting rearwards under acceleration, therefore you would like more torque going to the front wheels to make the tyres work harder at the front and reduce the load on the rear tyres. A 50/50 split front to rear will reduce this because the torque is been controlled front to rear to provide equal force on each tyre. The Subaru Impreza 4WD uses two different systems depending on the model with the WRX using a viscous centre differential, this would be an open differential using a 50/50 split front to rear. This would create a balancing handling characteristic. The 2nd system was similar to the Ferrari FF with an active torque split system. This is where if any traction is been lost at any axle, the clutch packs lock which increases the pressure and sends more torque to the axle that needs it. This system is more advanced than the viscous centre differential because its interacting with sensors whenever there is slip in order to keep maintaining as much traction as possible whereas the system on the WRX is more mechanical and relying on driver input more. (steering, braking, throttle application) (Fenske, 2017)

4 MASS MODEL OF THE FERRARI FF



4.1 CALCULATION OF CENTRE OF GRAVITY

*Front mass = total mass * 0.47 (front weight distribution)*

*Rear mass = total mass * 0.53 (rear weight distribution)*

$$F = \left(\frac{m2 * a + m3 * wheelbase}{m1 + m2 + m3} \right)$$

$$F = 1.58 \text{ Metres}$$

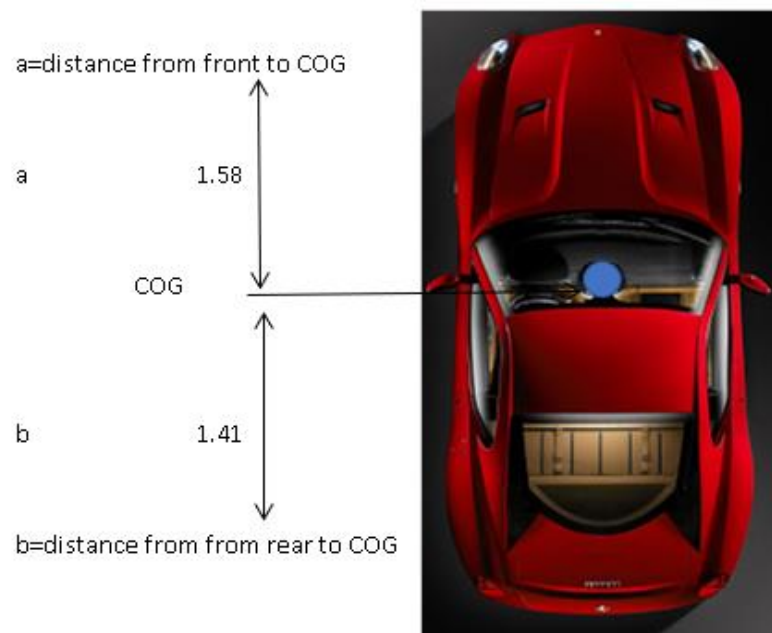
4.2 CALCULATION OF INERTIA ABOUT THE Z AXIS

$$Inertia \text{ z axis} = mk^2$$

$$Inertia \text{ z axis} = (m1 * f^2) + m2 * (a - f) + m3 * (wheelbase - f)^2$$

$$Inertia \text{ z axis} = 4172 \text{ Kgm}^2$$

4.3 CALCULATION OF THE DYNAMIC INDEX



$$\text{Dynamic Index} = \left(\frac{\text{Inertia z axis}}{\text{Total mass} * a * b} \right)$$

$$\text{Dynamic Index} = 1$$

4.4 CALCULATION OF THE INERTIAL CONJUGATE

$$K = \left(\frac{\text{Inertia z axis}}{\text{Total mass} * a} \right)$$

$$K = 1.32 \text{ metres}$$

5 ANALYSIS OF THE VEHICLE SPECIFICATION

The patented AWD system with a rear transaxle and front engine has created a more balanced weight distribution with a 47/53 split front to rear to achieve the ideal 50/50 split. This creates a more neutral handling balance as there is equal force on each tyre. The reason why Ferrari adopted the gearbox at the rear was that typically 4WD drive systems can increase understeer because there is more mass on the front axle as well as drive torque and steering input. This can be seen when examining the Subaru Impreza and Mitsubishi evo which have a weight distribution of 60/40 split front to rear split. By Ferrari putting gearbox at the rear this improves the balance as well as having a dynamic index of 1.

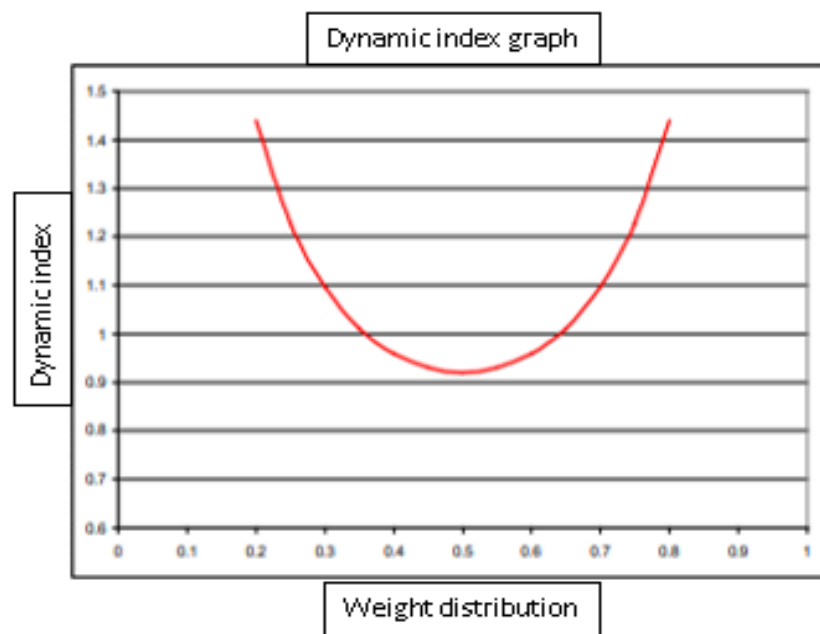


Figure 5-1 Graph showing the relationship between weight distribution and dynamic index

A low dynamic index increases agility making the car feel more nimble but can also become unstable and twitchy if excessively low, the same affects would be in the opposite direction as a high dynamic index can be sluggish and slow to respond, more likely in a SUV or 4x4. Most sporty cars have a dynamic index between 0.8-0.95 as this is the ideal compromise between agile and stability. The Ferrari FF 47/53 weight distribution has increased stability with a higher dynamic index, and this could be because the FF weighs 1880 kg. This is higher than other front engined Ferraris such as the F12 and 812 which weigh between 1700-1670kg which would result in a lower dynamic index with the extra mass to accommodate for the 4WD system. (Anon., 2019)

6 IDENTIFYING THE MECHANICAL TORQUE PATH TO THE FRONT WHEELS

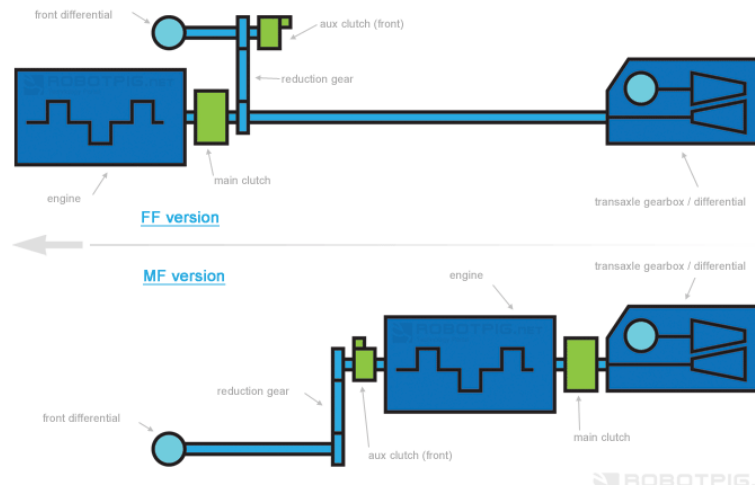


Figure 5-1 Diagram showing the difference between Ferrari FF AWD compared to RWD

Figure 6-3 shows the front gearbox of the Ferrari FF to provide power to the front wheels as there are two gearboxes with the main gear box at the rear to maintain the weight distribution of an RWD car. This means to reduce weight to front gearbox is much smaller with only 2 gears and can only control 20% of the torque which still drive like an RWD car with oversteer on acceleration. As the largest gear in the front gearbox is 6% larger than the 4th gear in the main box the 4WD system shuts off in 5th gear meaning all the power goes to the rear, as you are less likely to have wheelspin in fifth gear on tarmac this should be controllable for the driver. Figure 6-3 also shows the clutch packs at the front controlling the amount of torque being applied to front wheels which is a system that relies on sensors similar to an active torque split system which constantly change depending on the driver input. As the FF was marketed that it could go off road the sensors would be reliable in controlling the wheel torque compared to a mechanical differential system of a viscous central differential. (Ferrari FF 4wd system , n.d.)

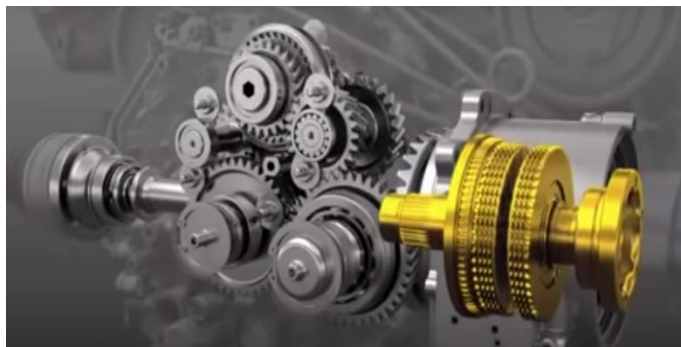


Figure 6-3 Ferrari front gearbox and clutch packs of the FF

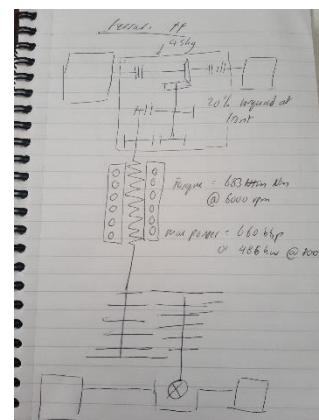


Figure 6-2 Basic illustration of the AWD system

7 CALCULATING CLUTCH PACK TORQUE CAPACITY, CLUTCH SLIP AND POWER LOSS

Gear	gear ratio	Final drive	overall	Front gear ratio	RPM rear wheel speed at 1000	RPM front wheel speed at 1000
1	3.4	4.38	14.89	9.01	67.15	111.01
2	2.18		9.55	5.33	104.73	187.60
3	1.63		7.14		140.07	
4	1.29		5.65		176.98	
5	1.03		4.51		221.66	
6	0.84		3.68		271.80	
7	0.63		2.76		362.40	

1st gear front box is 6% taller than 2nd gear in the main box

2nd gear in the main box is 6% taller than 4th in the main box

tyre circumference	2.245	
20% torque at front	136.6	nm
torque at 6000RPM	683	nm
max power at 8000	486	KW

Clutch plate dimensions	
coefficient of friction	0.4
outer radius	0.1 metres
inner radius	0.05 metres
surfaces	4

The clutch plate dimensions were assumed of a larger clutch from a race car which means that they would be slightly too powerful for the Ferrari FF front gearbox which decreases the clutch axial force meaning that the clutch will wear more and produce less force the more the FWD system is been used to control the torque, over time this will increase clutch slip.

$$\text{Front 1st gear ratio} = \left(\frac{\text{2nd overall gear ratio}}{1.06 (6\%)} \right)$$

$$\text{Front 2nd gear ratio} = \left(\frac{\text{4th overall gear ratio}}{1.06 (6\%)} \right)$$

$$\text{wheel speed RPM} = \left(\frac{\text{RPM}}{\text{Overall gear ratio}} \right)$$

$$\text{Difference between front to rear} = \text{front wheel speed} - \text{rear wheel speed}$$

$$\text{Torque Nm} = \text{Front torque} * \text{front gear ratio}$$

$$\text{Power of clutch packs at front Watts} = \text{Torque} * \frac{\text{front} - \text{rear wheel speed} * 2\pi}{60}$$

$$\text{Slip across clutches \%} = \frac{\text{front wheel speed}}{\text{rear wheel speed}} * 100$$

$$\text{Axial force} = \frac{\frac{2}{3} * \frac{\text{torque}}{\text{coefficient of friction}} * \frac{(r_2^2 - r_1^2)}{r_2^3 - r_1^3}}{4}$$

$$r_2 = \text{outer radius of clutch plate}$$

$$r_1 = \text{inner radius of clutch plate}$$

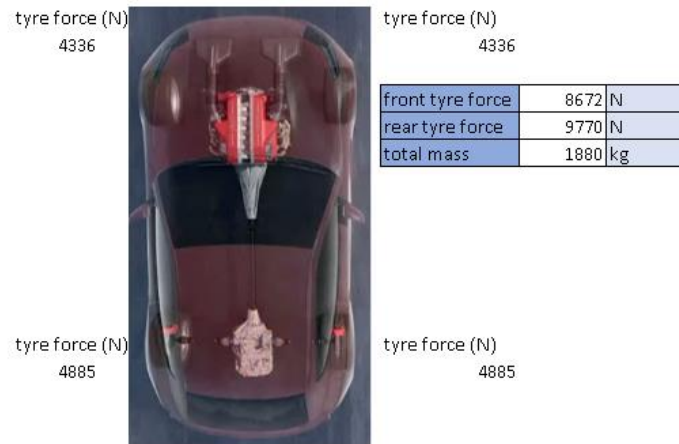
max power at clutches in 1st gear in main box and 1st gear in front box			
wheel speed at front	666.08	rpm	69.752 rad/sec
wheel speed at rear	402.90	rpm	42.192 rad/sec
difference between front and rear	263.18	rpm	27.56 rad/sec
Torque at front	1230.48	nm	
Power of clutch packs at front	33912.19	watts	
Axial force	9887.81	N clamp load	
slip across clutches	1.65	65.00	%

max power at clutches in 2nd gear in main box at 1st gear in front box			
wheel speed at front	666.08	rpm	69.752 rad/sec
wheel speed at rear	628.38	rpm	65.804 rad/sec
difference between front and rear	37.70	rpm	3.9482 rad/sec
Torque at front	1230.48	nm	
Axial force	9887.81	N clamp load	
Power of clutch packs at front	4858.21	watts	
slip across clutches	1.06	6%	

max power at clutches in 3rd gear in main box at 2nd gear in front box			
wheel speed at front	1125.62	rpm	117.88 rad/sec
wheel speed at rear	840.41	rpm	88.007 rad/sec
difference between front and rear	285.22	rpm	29.868 rad/sec
Torque at front	728.13	nm	
Axial force	5851.04	N clamp load	
Power of clutch packs at front	21747.68	watts	
slip across clutches	1.34	33%	

max power at clutches in 4th gear in main box at 2nd gear in front box			
wheel speed at front	1125.62	rpm	117.88 rad/sec
wheel speed at rear	1061.91	rpm	111.2 rad/sec
difference between front and rear	63.71	rpm	6.6722 rad/sec
Torque at front	728.13	nm	
Axial force	5851.04	N clamp load	
Power of clutch packs at front	4858.21	watts	
slip across clutches	1.06	6%	

8 LONGITUDINAL ACCELERATION ON A VARIETY OF SURFACES



For a comparison between rear wheel to the FF 4WD only 20% of the front tractive effort would be applied because the front gear box can only handle 20% of the torque. This means that if all of the tractive effort were considered the acceleration would represent a 50/50 torque split which can accelerate faster in reality. (Anon., n.d.)

$$\text{Tractive effort front} = \text{front tyre force} * 0.2 \text{ (20\% power)} * \mu$$

$$\text{Tractive effort rear} = \text{rear tyre force} * \mu$$

$$\mu = \text{coefficient of friction}$$

Assuming open differential

$$\text{Torque left} = \text{torque right}$$

8.1 TARMAC

$$\mu = \text{coefficient of friction} = 1$$

$$\text{Tractive effort front} = 8672 * 0.2 * \mu$$

$$\text{Tractive effort front} = 1734 \text{ N}$$

$$\text{Tractive effort rear} = 9770 * 1$$

$$\text{Total tractive effort} = 11504 \text{ N}$$

$$\text{Longitudinal acceleration} = \left(\frac{\text{Force}}{\text{total mass}} \right)$$

$$\text{Longitudinal acceleration} = 6.1 \text{ ms}^{-2}$$

8.2 GRAVEL

$$\mu = \text{coefficient of friction} = 0.6$$

$$\text{Tractive effort front} = 8672 * 0.2 * \mu$$

$$\text{Tractive effort front} = 1040N$$

$$\text{Tractive effort rear} = 9770 * 1 * \mu$$

$$\text{Total tractive effort} = 5862 N$$

$$\text{Longitudinal acceleration} = \left(\frac{\text{Force}}{\text{total mass}} \right)$$

$$\text{Longitudinal acceleration} = 3.67 \text{ ms}^{-2}$$

8.3 ICE

$$\mu = \text{coefficient of friction} = 0.1$$

$$\text{Tractive effort front} = 8672 * 0.2 * \mu$$

$$\text{Tractive effort front} = 173N$$

$$\text{Tractive effort rear} = 4885 * 1 * \mu$$

$$\text{Total tractive effort} = 662 N$$

$$\text{Longitudinal acceleration} = \left(\frac{\text{Force}}{\text{total mass}} \right)$$

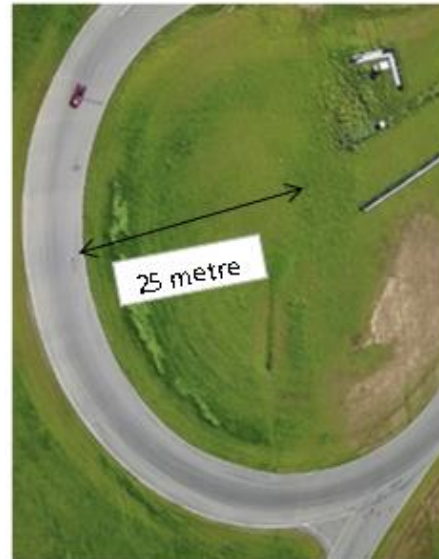
$$\text{Longitudinal acceleration} = 0.61 \text{ ms}^{-2}$$

9 POTENTIAL YAW RATE GAIN

Driving clockwise		
Velocity	14	ms ⁻¹
Lat accel	7.84	ms ⁻²
corner radius	25	m

mass	1880	kg
mass front axle	883.6	kg
mass rear axle	996.4	kg
track width	1.66	m
COG height	0.45	m

cd	0.5
density of air	1.3
area	2.5



$$WT = COG\ height * \left(\frac{1880}{2}\right) * \left(\frac{velocity}{track\ width}\right) = 1997\ N\ per\ axle$$

$$Left\ outer\ wheel = 4336 + 1987 = 6324\ N$$

$$Right\ inner\ wheel = 4336 - 1987 = 2349\ N$$

$$Drive\ force\ at\ 14\ ms^{-1}$$

$$Rolling\ resistance = mass * 9.81 * 0.1 = 1844.28\ N$$

$$Aero = 0.5 * cd * area * density\ of\ air * velocity^2 = 159\ N$$

$$Total\ drive\ force = 2003\ N$$

$$Lateral\ force\ each\ axle = \left(\frac{Total\ mass}{2}\right) * velocity = 7332\ N$$

$$Left\ outer\ load = \left(\frac{Left\ outer\ load}{Axle\ force}\right) = 73\%$$

$$Right\ inner\ load = \left(\frac{Right\ inner\ load}{axle\ force}\right) = 27\%$$

$$Lat\ force\ resist\ outer\ load = 73\% * 7332\ N = 5352$$

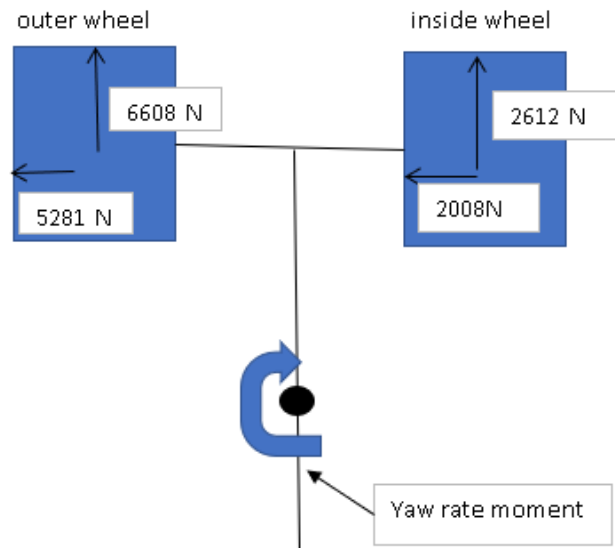
$$Lat\ force\ resist\ inner\ load = 27\% * 7332\ N = 1979$$

$$\text{Available drive force} = \sqrt{(2349^2 - 1949^2)} = 1265 \text{ N}$$

$$\text{Total drive force} = \left(\frac{2003}{2}\right) = 1001 \text{ N per inside wheels}$$

$$\text{Additional drive force to inside wheel} = 1265 - 1001 = 264 \text{ N}$$

$$\text{Yaw Rate gain} = \frac{\text{Force}}{\text{mass}} = 0.14 \text{ ms}^{-2}$$



9.1 AFFECT ON HAND WHEEL POSITION

The increased yaw rate increases the rotation of the car which does not require as much steering input as the car is more likely to oversteer as the inside tyres are working harder providing more grip. Increasing hand wheel movement will induce more load onto the outside tyres and increase understeer or more likely to increase the yaw rate moment, therefore less steering angle would be required.

10 SENSORS REQUIRED TO IMPROVE VEHICLE DYNAMICS

As advancement in electronics and a desire to control the vehicles handling there have been more sensors on vehicles with a decrease in mechanical systems controlling the vehicles handling. This means that engineers can calibrate the system for how they expect the vehicle to be drove and how they can make the vehicle predictable for high performance cars such as the Ferrari FF.

10.1 ON AND OFF POWER

To control the torque output to the wheel's traction control is designed to control wheel spin and reduce slip and make the car more predictable under accelerating, especially important on the Ferrari FF which produces 600 BHP. If the throttle was on a throttle by wire system which be calibrated to make the throttle progression more progressive so that the torque is less instantaneous and less likely to cause wheelspin. (Throttle control , n.d.)

10.2 STRAIGHT LINE AND CORNERING

For straight line scenarios such as driving along motorways autonomous systems such as lane holding and lane change have been developed with sensors monitoring the vehicles position in respect to the lane limit, when cornering the ground speed sensor interacts with the steering input the so the steering input speed and angle is safe, for example very fast quick steering input can be unpredictable which could lead to the car rolling from the sudden WT. Whenever there is violent steering input stability control such as ESP can reduce slip and by controlling the throttle and more importantly brake input because in real life driving on the road when cars start to slip it is under braking. The ESP system monitors wheel speed as well as driver input based on the yaw angle and can apply the brake to control the wheel speed in order for the tyres to regain traction overriding the driver inputs.

10.3 ON-LIMIT LANE CHANGE MANOEUVRES

Active anti – roll bars were developed to dynamically control roll to increase the inside tyre contact patch when cornering. In order for the system to work the sensors need to be able to predict the roll angle from the yaw and ground speed so that the system knows what the roll angle will be to apply torque to the ARB, This is the system Audi use on the SQ7. (Active sway bar suspension explained , 2015) Adjustable damping settings are installed on performance production cars such as the “*manettino dial*” on the Ferrari which makes the dampers stiffer on the sport setting reducing roll and improving change of direction on a race track on in lane change manoeuvre, this however is controlled by the driver and not from sensors affecting the damping behaviour. (Anon., 2016)

10.4 HOW THE AWD SYSTEM WILL INTER-REACT WITH OTHER VEHICLE DYNAMIC CONTROL SYSTEMS

The way AWD systems can interact with systems such as ABS and ESP is that the active torque split system can affect the amount of torque at each wheel to balance the car under acceleration just like a TC control system, this can give the car a more mechanical feel because if the 4WD reduces the torque there be less chance of wheelspin and using the traction control less which will feel more mechanical which some consumers may prefer. The differentials can also control the wheel speed under braking and turning with the coast setting which can manipulate yaw rate under change of direction relying less on the ESP. For example on the rear if you have a 3-1 locking differential on the coast setting and you turn into a corner the outside wheel will rotate faster than the inside increasing the yaw moment, which increase oversteer and cause the ESP to interact and slow down the outside wheels by applying the brakes, therefore if your programmed the differential so that it was more open under braking there will be a decreased yaw moment and less reliance on the ESP system. With the 2001 Subaru Impreza WRX there was less reliance on ESP and ABS by developing a more advanced torque vectoring system so the AWD system would control the vehicle dynamics. (Prodrive ATD system on subaru impreza, 2012)

11 CONCLUSIONS

The reason why Ferrari designed this system was to develop an AWD system that had a low centre of gravity and an even 50/50 split weight distribution that hadn't been done before as most 4WD systems in Audis and Range rovers had the gearbox and engine up the front which increased the COG height at the front, increased mass on the front axle which increased understeer and caused undesirable handling characteristics. Therefore Ferraris idea of using the RWD concept with a small gearbox at the front was to keep the balance of an RWD car but straight line grip of a 4WD car. The designed has not been copied to the same extent as systems used in Audis because torque capacity of the front gear box would be insufficient for a car with 300BHP and because of the 20/80 power split the car would still drive like a RWD car and off road a 50/50 power split would be more predictable to drive. Also because of the size of the front gearbox is small to reduce mass and engine at the front the components could be fragile and more likely to break and with a car with 2 gearboxes the overall mass increases that the dynamic index increases which can compromise handling performance.

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