



AWD Torque Vectoring

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Abstract

This report covers what torque vectoring is and how it can be used to improve a vehicle's dynamic. The vehicle chosen to demonstrate this system is the Ferrari FF. For this vehicle, the dynamic data is calculated for the scenario of 1 passenger to 4 passengers to show their effect on the vehicle. The front drive unit is analysed and the clutch forces are calculated. And finally, the added tractive force over a rear-wheel-drive system is calculated and compared.

Introduction.

This report will analyse a torque vectoring system and its application to vehicle dynamics. Analytical calculations will be applied to analyse the forces applied to the vehicle and how torque vectoring can be used to manage it.

Ferrari FF vehicle data

In 2011 Ferrari released the FF as its first attempt at a 'practical super car'. This featured 4 seats, a unique AWD system and a 6.3 litre V12 engine. The FF boasts a max torque figure of 683Nm and max power of 650bhp. This is enough to propel the FF to a top speed of 208mph. The FF has a kerb weight of 1880kg, a vast weight in comparison to the majority of super cars. The FF features 20-inch wheels front and rear and has a wheel base of 2990mm (2.99m).

Vehicle data as stated by (Ferrari, 2011) and (Parkers, 2011)

Torque vectoring

Torque vectoring is the process of manipulating the percentage of torque applied to each wheel of a vehicle. This has multiple uses to enhance the performance of a car. One such use is as traction control for providing drive in low grip situations. A torque vectoring system can distribute the drive torque to maximise the available traction.

One of the main uses of torque vectoring is for improving handling performance. Originally developed for combating understeer, torque vectoring is used to increase the yaw moment of the vehicle. This is done by distributing more drive to the outside wheels than the inside. This increases the yaw moment as the increased drive force on the outer wheels rotates the vehicle around its inside wheels. This will allow the car to drive towards the inside of the corner under power rather than pushing towards the outside. This is massively confidence inspiring for the driver as it minimizes the fear of understeer.

Brake vectoring is often talked about as the poor man's torque vectoring. This works by monitoring the required torque at each wheel and the torque supplied and then manages it by applying the brakes. By applying the brakes, the vehicle can manage the amount of torque that actually gets applied to the road. This is effective when managing oversteer and understeer as braking the inside wheels in a corner will increase the yaw moment of the vehicle. This is a similar concept to skid steer used in many tracked and heavy-duty vehicles where the inside wheels are stopped to force the outside to rotate the vehicle. This is considered less desirable for straight line performance as the braking force counters the drive force.

Jaguar use brake vectoring alongside electronic differentials "to improve the comfort and control of your drives" (Jaguar, 2020) this system allows the vehicle to manage the torque distribution through the differentials and the braking system. This gives it a larger ability to control the movement of the vehicle.

Calculations

Lump mass model of Ferrari FF

A lump mass model describes the distribution of mass across a vehicle. For the Ferrari FF the mass distribution of the kerb weight is known. The weight distribution is 47% on the front axle and 53% on the rear as stated by Evo UK (Dobie, 2011). This results in a mass of 883.6 kg on the front axle and 996.4 kg on the rear axle.

To complete the lump mass model, the masses of the passengers must be added. To determine the representative mass the average masses for a UK male and females was used. These masses were stated as 83.6 kg for an average male and 70.2 for an average female by (BBC, 2020). As it is undetermined the gender of the passengers an average of these two values were used which resulted as 76.9kg.

To determine the position of the passengers an official image was used to measure the seating position. The measurements were carried out by importing the vehicle image in to CAD and scaling it against a known measurement. This image was scaled to the size of the front brake disk. This is a known value of 398mm as stated by (Ferrari, 2011). Once the image is scaled the seat placement could be measured. This process is not exact as there is not a clear line of sight to the seats. Another variable is that the seats are sliding adjustable meaning the mass could be shifted forward or back depending on the operator's preference. The measurement process can be seen in Fig 1

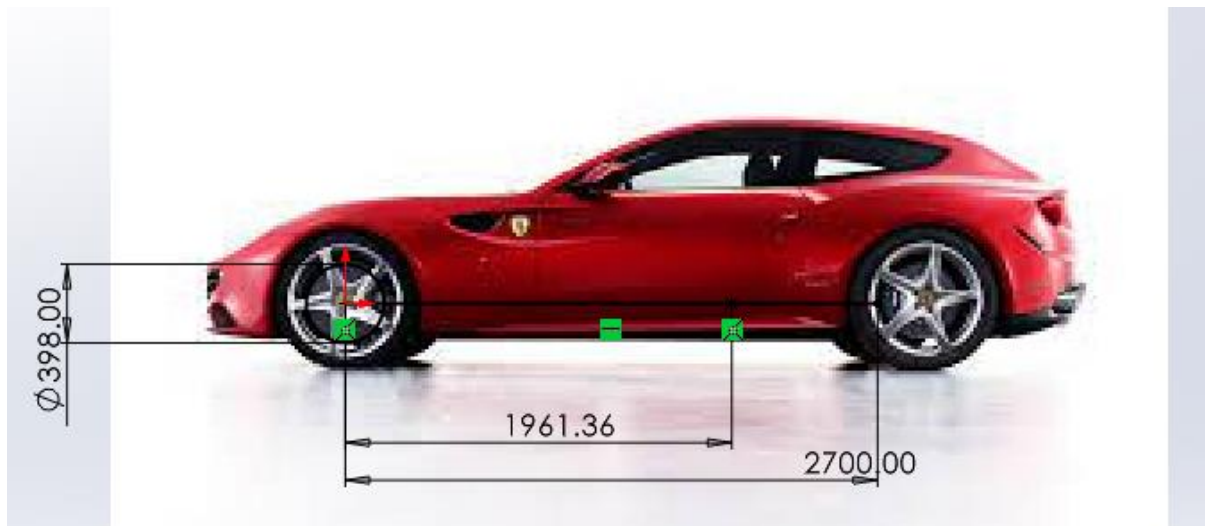


Figure 1 (Ferrari, 2011)

Calculated longitudinal Centre of Gravity position

Knowing the masses and their distribution across the wheel base, The centre of gravity position can now be calculated. The equation for which is as follows

$$CoG \text{ position} = ((Mass2 * Length2) + (Mass3 * Length3)) / (Total \text{ mass})$$

For this application this was calculated using an excel document. To account for the passengers sitting in the front or back of a vehicle, an if statement was used to determine the mass distribution. This dictated that the first 2 passengers' mass was acting at a distance of 1.961m and the second 2 at a distance of 2.7 m. The centre of gravity position was then calculated for the scenarios of 1 to 4 passengers. The results of which can be seen in Fig....

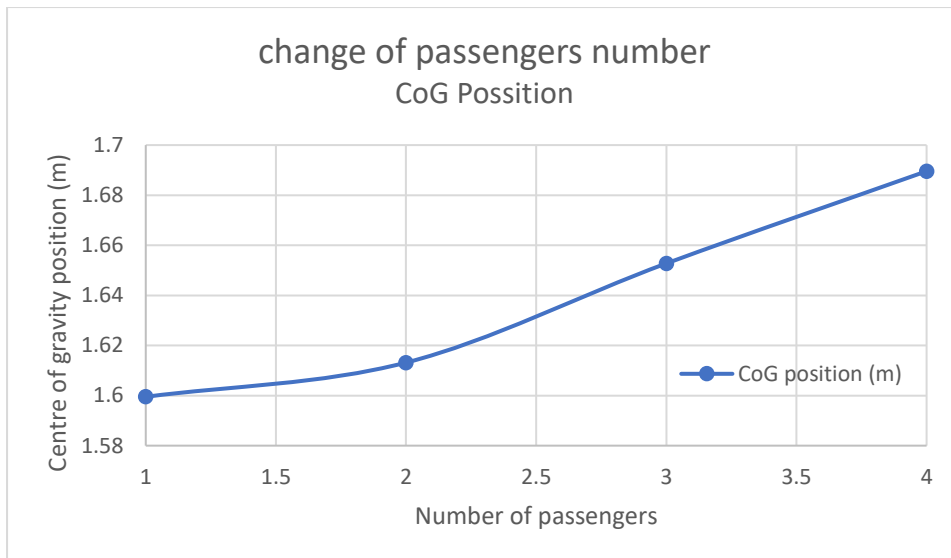


Figure 2

Fig 2 shows how the centre of gravity position shifts towards the rear of the car with the increase of passengers. This is to be expected due to the rear seats being placed close to the rear axle shifting the added mass rear ward.

Calculated vehicle moment of inertia (Z)

Knowing the centre of gravity position, the yaw inertia can be calculated. The equation for which is as follows

$$\text{Yaw inertia} = \text{Mass1}(\text{CoG position}^2) + \text{Mass2}(\text{length2} - \text{CoGposition}^2)$$

This was calculated using the 4 masses for each circumstance of 1 to 4 passengers. The result of which can be seen in Fig 3

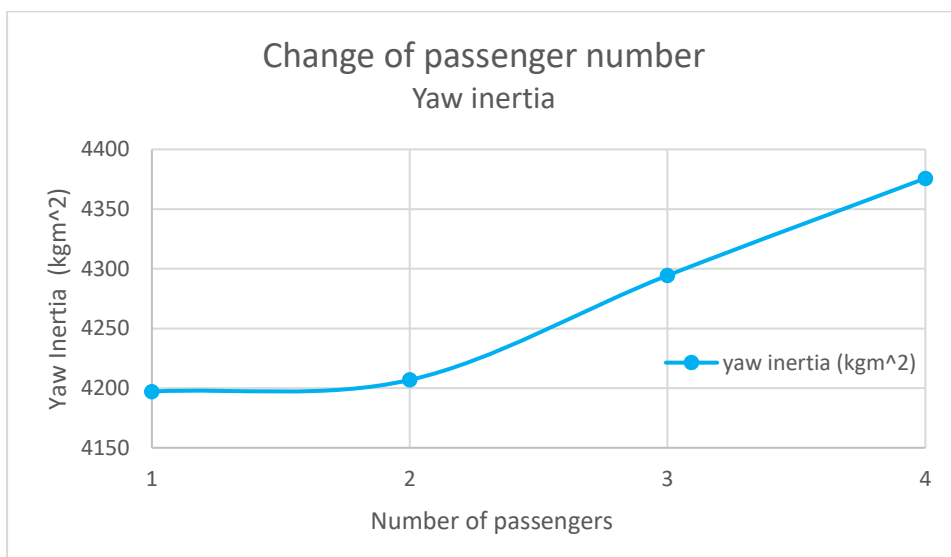


Figure 3

Fig 3 shows that the Yaw inertia increases with the number of passengers. This is expected as the added mass will increase the inertia force experience by the vehicle. The large increase due to the

rear passengers is due to their added distance from the front of the car giving them a larger moment of inertia.

Establish the inertial conjugate

Now that the yaw inertia has been established this can be used to calculate the inertial conjugate. For equation for which is as follows.

$$\text{Inertial conjugate} = \frac{\left(\frac{\text{Yaw inertia}}{\text{Total mass}} \right)}{\text{Centre of Gravity position}}$$

Once again this was calculated for each scenario of 1 to 4 passengers using the previous values. The results can be seen plotted in Fig 4

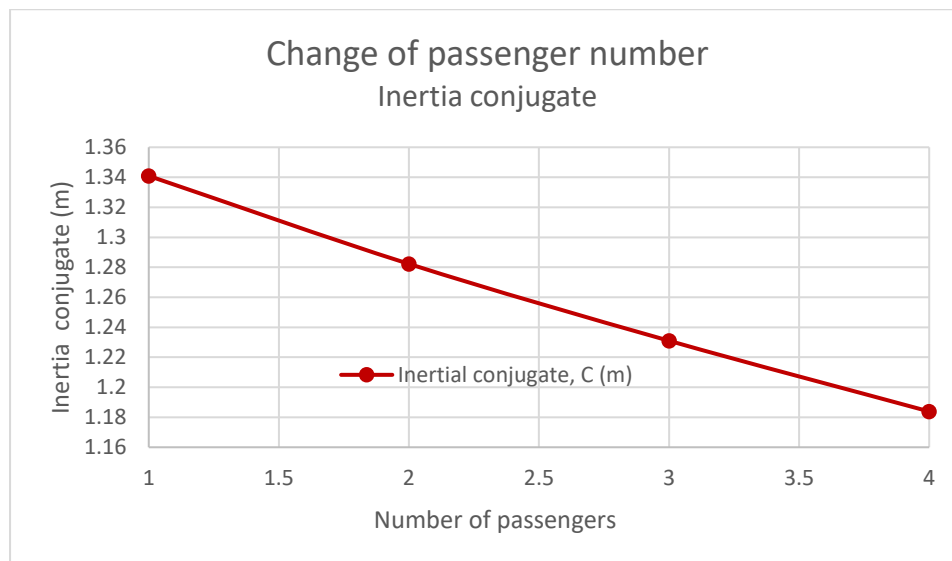


Figure 4

Fig 4 shows that the inertia conjugate decreases with the increase of passengers. This is expected as the added mass of the passengers in front of the rear axle. This shifts the weight distribution further forward compared to the Ferraris rear bias at kerb mass. This means the point at which the car rotates around moves forward, away from the rear axel of the car.

Establish dynamic index

Finally, the dynamic index was calculated using the previous values. The equation used to calculate the dynamic index is as follows.

$$Di = \frac{\text{Yaw inetira}}{\text{total mass} * \text{CoG position} * (\text{WB} - \text{CoG position})}$$

This was calculated for each scenario of passenger numbers 1 to 4 to show the effect of mass distribution. The results can be seen plotted in Fig 5

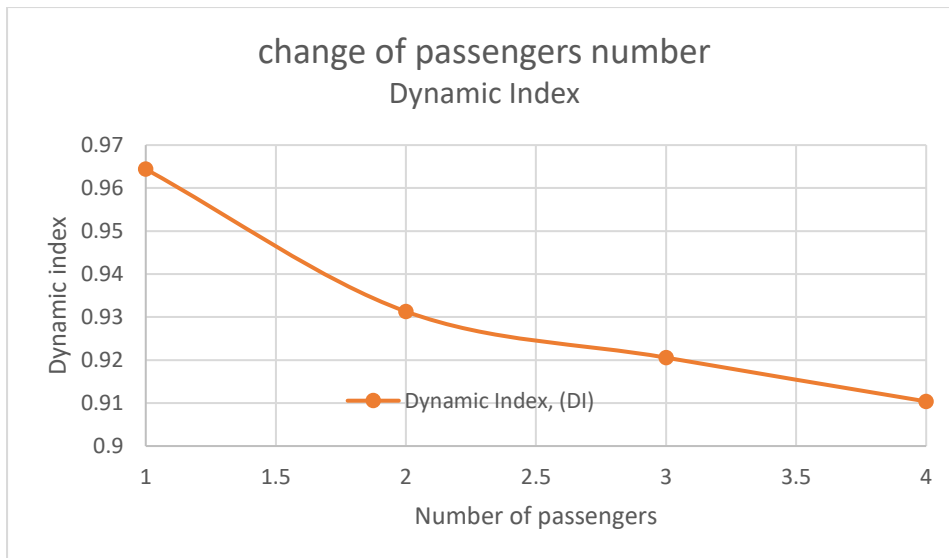


Figure 5

Fig 5 shows that the dynamic index decreases with the increase of passengers. This means that inertia conjugate is moving forwards, away from the rear axle. This is expected as the added mass of the passengers is in front of the rear axle and shifts the inertia conjugate towards the front axle. The dynamic index ranges from 0.96 to 0.91, this indicates that the Ferrari has a good compromise between stability and agility. Stability is generally associated with a dynamic index equal or higher than 1. Being a high output super car Ferrari would want the car to be stable and predictable as this gives the customer and driver confidence. As the inertia conjugate moves forwards with the added passengers, the dynamic index reduces. This implies that the FF gains a slight increase in agility with its new weight distribution. However, what the car gains from is point of rotation moving forward, is almost defiantly lost from the added inertia force of the passengers.

The mechanical torque path to the front wheels

The Ferrari FF uses an unconventional system to send torque to the front wheels. Most all wheel drive systems on a longitudinal engine use a transfer box after the gear box to split the torque between the front and rear. This is a bulky system that requires 2 prop shafts to transfer the torque to each end of the car. This is a heavy system that requires a lot of space under the chassis for packaging. This compromises the vehicle that it is applied to.

To avoid compromising the performance characteristics of the FF, Ferrari developed a new path of sending torque to the front wheels. This involves a second gear box mounted to the front of the engine purely for driving the front wheels. 'This is driven by a conical gear off the nose of the crankshaft, the front transmission is a helical gearset with two forward speeds plus reverse' (Austin, 2011). The 2-speed gear box is geared so that the 1st gear covers 1st and 2nd of the rear gear box and the 2nd front gear covers the 3rd and 4th rear gears. However, this means from 5th to 7th the Ferrari FF can only operated in rear wheel drive.

The FF splits the front torque between the two wheels using a torque vectoring differential. This is aptly named the "Power Transfer Unit" or PTU for short. This operates using clutch pack to transfer the torque or disengage the drive. This system uses a clutch pack for each of the front wheels to give it the ability to control the wheels individually. The FF only ever sends a maximum of 20% of its overall torque to the front wheels.

Clutch packs

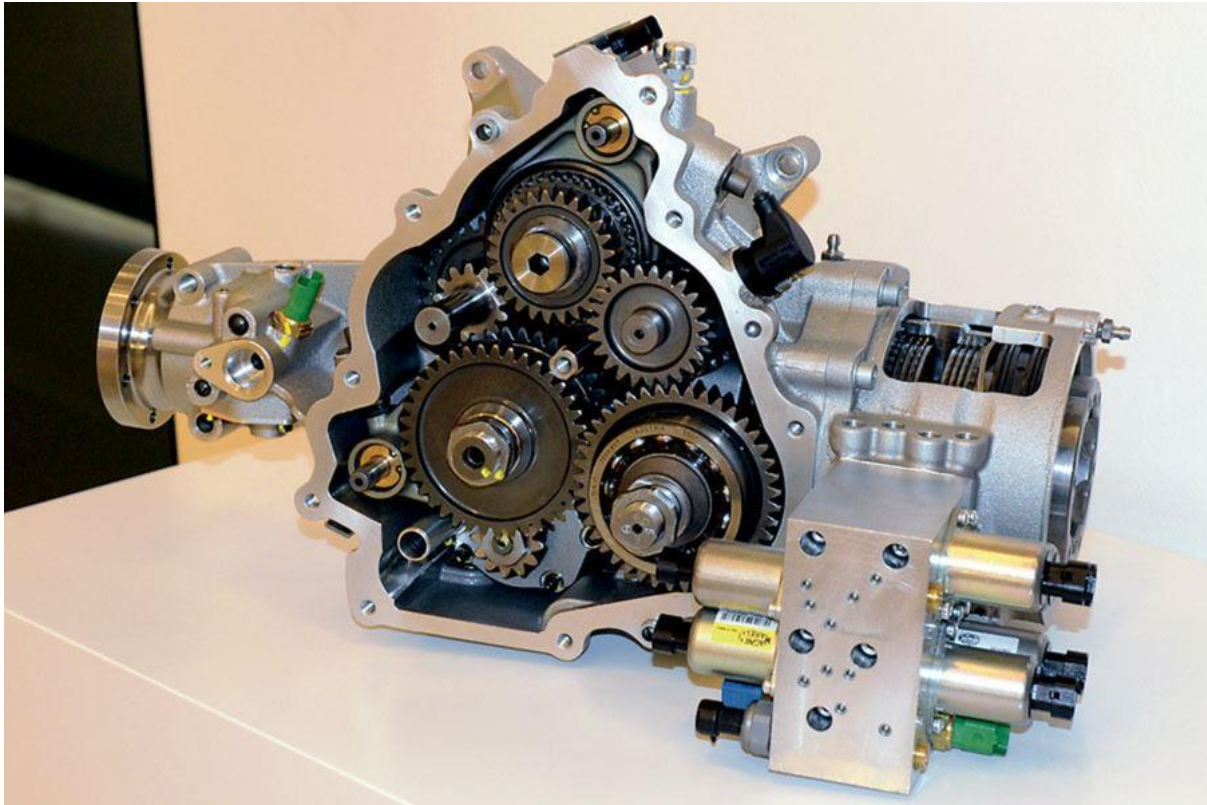


Figure 6 (Jenkins, 2011)

Fig 6 shows the front drive unit of the Ferrari FF. the power transfer unit (PTU) on the right of the picture has a section removed to reveal its internals. From Fig 6 it is determined that there are 8 clutch discs in the PTU (4 discs per clutch pack). This system uses 4 clutch discs to distribute torque to each of the front wheels.

The size of the clutches used in the PTU is not stated anywhere. This is something Ferrari will want kept a little quiet to protect their engineering advancements. However, these sizes are needed for the following clutch calculations so some investigative engineering was needed to estimate the size of the clutch disks. once again this involved using official photos of the drivetrain imported in to CAD and scaled against a known component size. Luckily a photo was obtained with the front disk brakes in the shot. Knowing the diameter of the front disks being 398mm as stated by (Ferrari , 2011), the image was enlarged to scale. From Fig 6 the clutch disks can be seen to be slightly smaller than the PTU housing. From this the PTU housing can be measured in Fig 7 and an educated estimate can be made on the clutch out side diameter. This is determined as 140mm as seen in fig 7. The inner diameter of the clutches isn't seen in either photo meaning this had to be assumed. The value chosen was 90mm.

A coefficient of friction of the clutch plates was assumed to be 0.07. This is a typical coefficient of a wet clutch as stated by (Rensselaar, 2020). The front drive only sees 20% of the Ferraris max torque meaning the clutch plates experience 136.6Nm (20% of the max 683Nm).

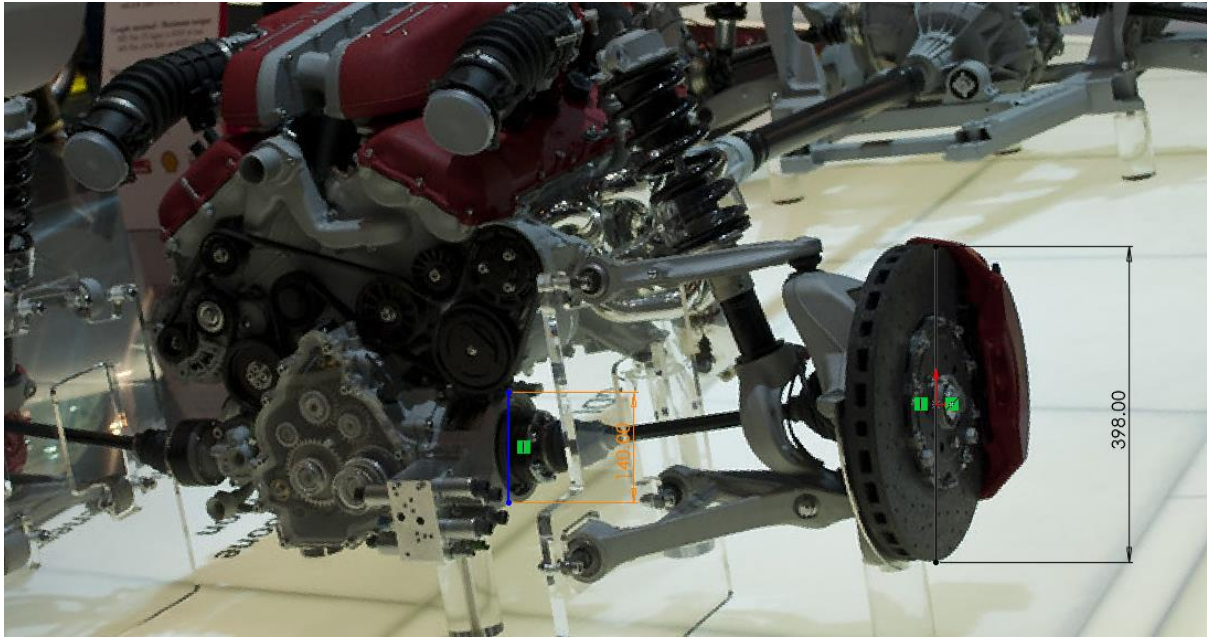


Figure 7 (Jenkins, 2011)

With the data collected on the clutch packs the axial forces were calculated.

$$\begin{aligned} & \text{(Total) Axial Load(uniform pressure)} \\ &= \frac{(3 * \text{Torque Front}) * (\text{outer radius}^2 - \text{inner radius}^2)}{(2 * \text{coefficient of friction}) * (\text{outer radius}^3 - \text{inner radius}^3)} \end{aligned}$$

$$\text{Axial Load (uniform pressure)} = 33411.56$$

$$\begin{aligned} & \text{(Total) Axial Load (uniform wear)} \\ &= \frac{2 * \text{Torque Front}}{\text{coefficient of friction} * (\text{outer radius} + \text{inner radius})} \end{aligned}$$

$$\text{Axial Load (uniform wear)} = 33937.89$$

Calculate potential longitudinal accel improvements on a variety of surfaces

The potential acceleration improvements of the all-wheel drive system over the conventional rear wheel drive configuration Ferrari is used to were then compared. To do so the tractive force applied to each wheel was calculated. The process this was calculated by is as follows

$$\text{Force applied to wheel} = \text{Coner mass} * \text{gravity } 9.81$$

$$\text{Wheel Traction force} = \text{Force applied to wheel} * \text{surface friction } \mu$$

This was calculated for each corner of the car applying the individual corner masses. This allowed for different road surface frictions to be applied to each wheel to analyse the performance in split mu conditions.

Equal mu surface

Initially an equal mu comparison of AWD and RWD was equated to compare the added tractive force of the AWD system. This was calculated for the mu values of 1, 0.5 and 0.1 to simulate the available tractive force on tarmac, grave/dirt and ice.

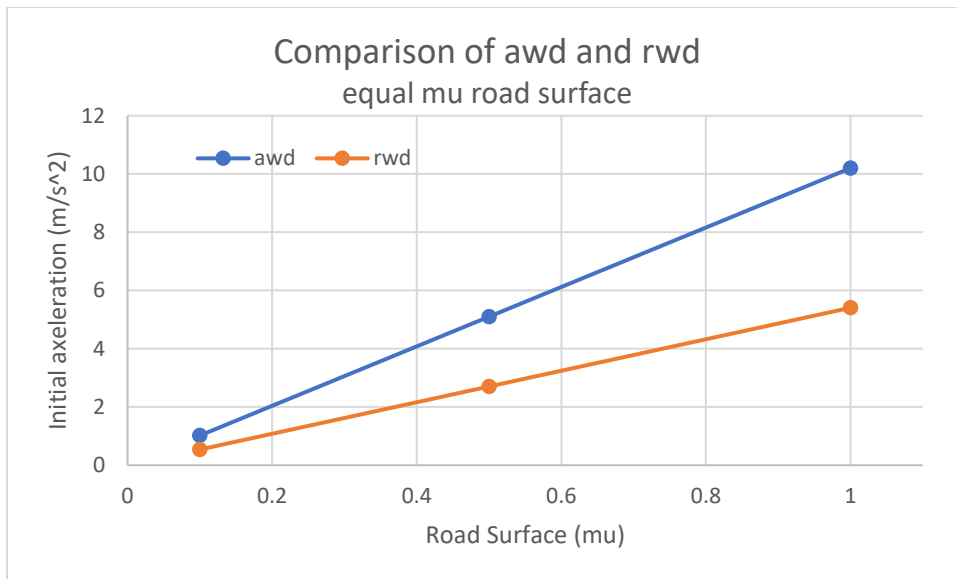


Figure 8

Fig 8 shows that throughout the range of surface friction, the AWD system provides double the maximum initial acceleration compared to the RWD system. However, despite the added tractive force of the AWD system. The initial acceleration on ice (μ of 0.1) is drastically small at $1.02m/s^2$

Split mu surface

The initial acceleration of the vehicle was then calculated for a split mu surface. This means that half the car is on a lower mu surface than the other side. For this calculation the lower mu was stated as 0.1 (Ice) and the other side was calculated for a range of surface friction from 1 to 0.1.



Figure 9

Fig 9 continues the trend of the AWD system providing double the maximum initial acceleration when compared to a RWD system on the same surfaces.

control algorithms,

To talk about the control systems, the actions to be controlled must first be discussed.

The first dynamic use of torque vectoring is its use as a traction control system. This application is used when the road surface is suboptimal, compromised or non-existent meaning each wheel may experience a difference in available tractive force. Torque vectoring can be used to distribute the torque to the wheels with the most available tractive force. Wheel speed sensors can be used to monitor this by analysing the velocity of each wheel and comparing it against the expected value. Wheels with higher velocity's than expected will be in slip conditions meaning there is less tractive force available. An advance way of monitoring this would be to compare against a GPS speed sensor. This would allow all wheel velocity to be compared against an accurate vehicle velocity.

The second dynamic use of torque vectoring is for improved handling by increased yaw rate. This one is a little harder to monitor the effectiveness of however the trigger inputs are simple. For the system to know how much torque to distribute and where it must analyse the inputs of the driver. These being steering wheel angle and throttle position. From these inputs the system can calculate the driver's request and distribute the torque between the wheels. In an advanced system, G force sensors mixed with GPS and wheel speed sensors could be used to analyse in real time the effectiveness of the torque vectoring output. However, this would require a large amount of on-board computing power and drastically increase the manufacturing cost thus bumping up the sale price of the vehicle.

Summary and conclusion.

To conclude, in this report the torque vectoring system of the Ferrari FF has been analysed. The initial dynamic forces were calculated for a range of passengers. The front drive unit and its operation was analysed using investigative engineering. The forces applied through the PTU were estimated. And finally, the added tractive force of the all-wheel drive system was compared to a standard rear wheel drive system. From this it is clear that a torque vectoring all wheel drive system provides dynamic improvements to a vehicle.

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