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AWD Torque Vectoring

Advanced Vehicle Dynamics

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1 Introduction

This report will investigate the Ferrari FF. This car is a 4 seater, 4 wheel drive grand tourer.(Ferrari, 2011). This report will analyse the dynamics of the vehicle. This report will investigate why Ferrari used the systems that they have and how they affect the vehicles behaviour. Base statistics about the car will be used to calculated how it will potentially behave in real world conditions.

The overall geometry of the car and how this can affect performance will be analysed. The clutch system will be analysed to see why they have used the design that they have and if it works. These will be used to investigate how the car behaves in real world conditions such as driving on less than ideal surfaces.

2 Base Vehicle Data

The base vehicle data used to perform most of the calculations in this report can be seen in table X

Table 1 -Base Data

Length (mm)	Width (mm)	Height (mm)	Wheelbase (mm)	Front Track (mm)	Rear Track (mm)
4907	1953	1379	2990	1679	1660
Max Power (kw)	Max Torque (Nm)	Max RPM	Kerb Weight (kg)	Dry Weight (kg)	Weight Distribution
486	683	8000	1880	1790	47/53

All of this data has come directly from Ferrari and therefore can be trusted.(Ferrari, 2011). Other data was used in this assignment and these can be found in the submitted excel sheet.

3 Torque Vectoring

Simply put torque vectoring uses the cars differential to apply varied torque from the engine to individual wheels.(De Novellis *et al.*, 2015). The system works by monitoring the yaw moment being applied to each tyre, if the system detects some slip in one of the tyres it can restrict the amount of torque that wheel receives and shift it to another wheel. This will improve traction on the wheel that was losing grip, it will also shift the weight of the car as this tyre is having its torque restricted. By doing this the overall handling and stability of the car throughout a corner can be improved.

This system will allow a driver to corner faster and have more confidence as small amounts of slip are being solved by the torque vectoring system giving the driver the maximum amount of grip available. This system also helps the driver in difficult track conditions or with different surfaces. If the car travels over a puddle or a section of tarmac that has less grip the system can restrict torque to the specific wheel or wheels, this again makes sure the car has the maximum amount of grip available.

4 Lumped Mass Model

A lumped mass model was created for the car as this could be used to find the moment of inertia of the car. To find this the mass of the engine and the gearbox had to be found. No reliable source could be found for the exact mass of the engine although one website stated that it did weight 225kg.(*WebCars! Guide to the Ferrari Enzo*, no date). Therefore this mass has to be taken as unreliable data but it did show a value close to other V12 engines and therefore this mass was used.(Motor1, 2010). The gearbox was found to weight 81kg.

To find the distances of these masses on the car a picture of the car was imported to Solidworks. The picture was then scaled to match the length found in the cars specifications.(Ferrari, 2011). The distance from both the front of the car and the front axle was measured to the centre point of the gearbox and the engine. This allowed an inertia to be calculated using a basic mass model.

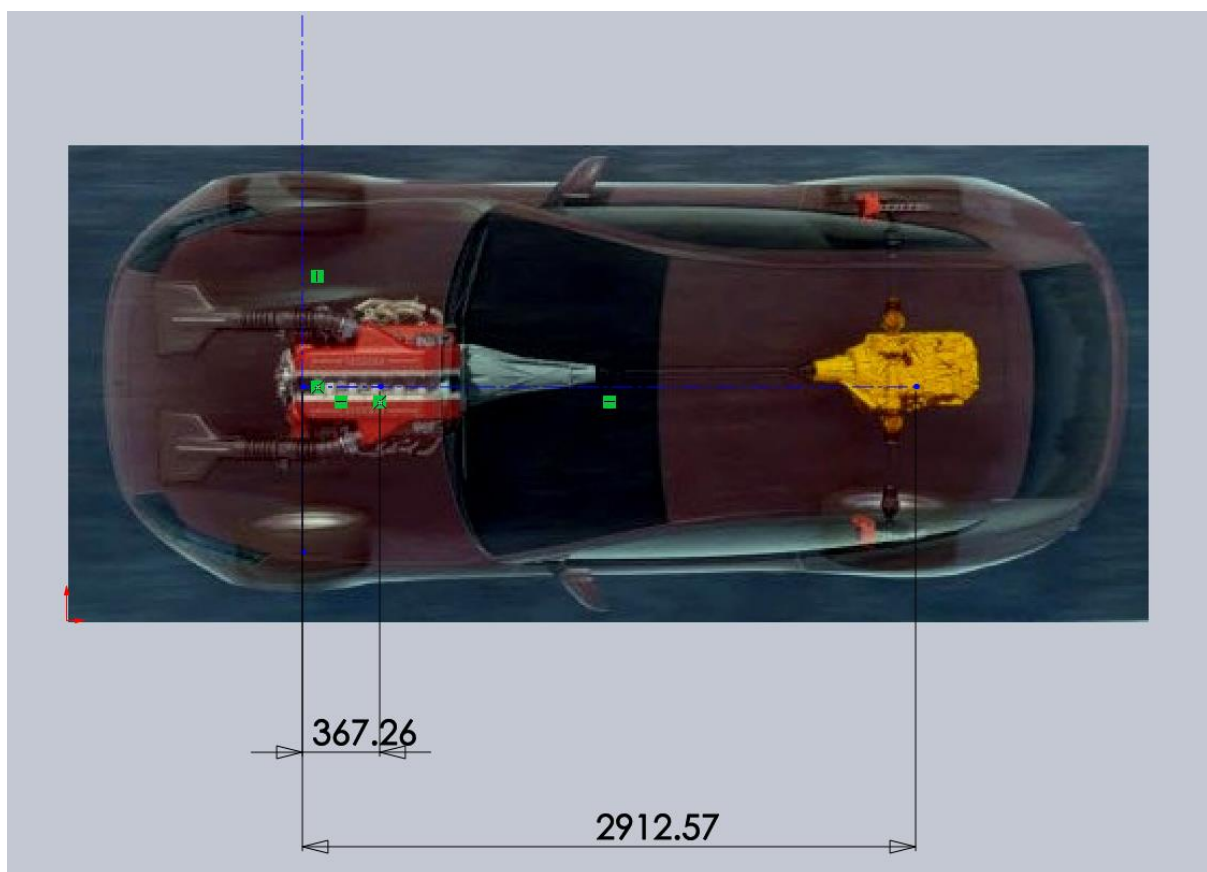


Figure 1 - Lumped Mass Model

5 Centre of Gravity

The centre of gravity (CoG) is a point at which the weight of a body is considered to act. (Katz, 1995).

The centre of gravity for the FF was found to act at 1.5847m behind the rear axle. This point can be used to calculate the moment of inertia. This point can be seen in figure x. This location is slightly behind the front seats and was calculated was no passengers in the car.

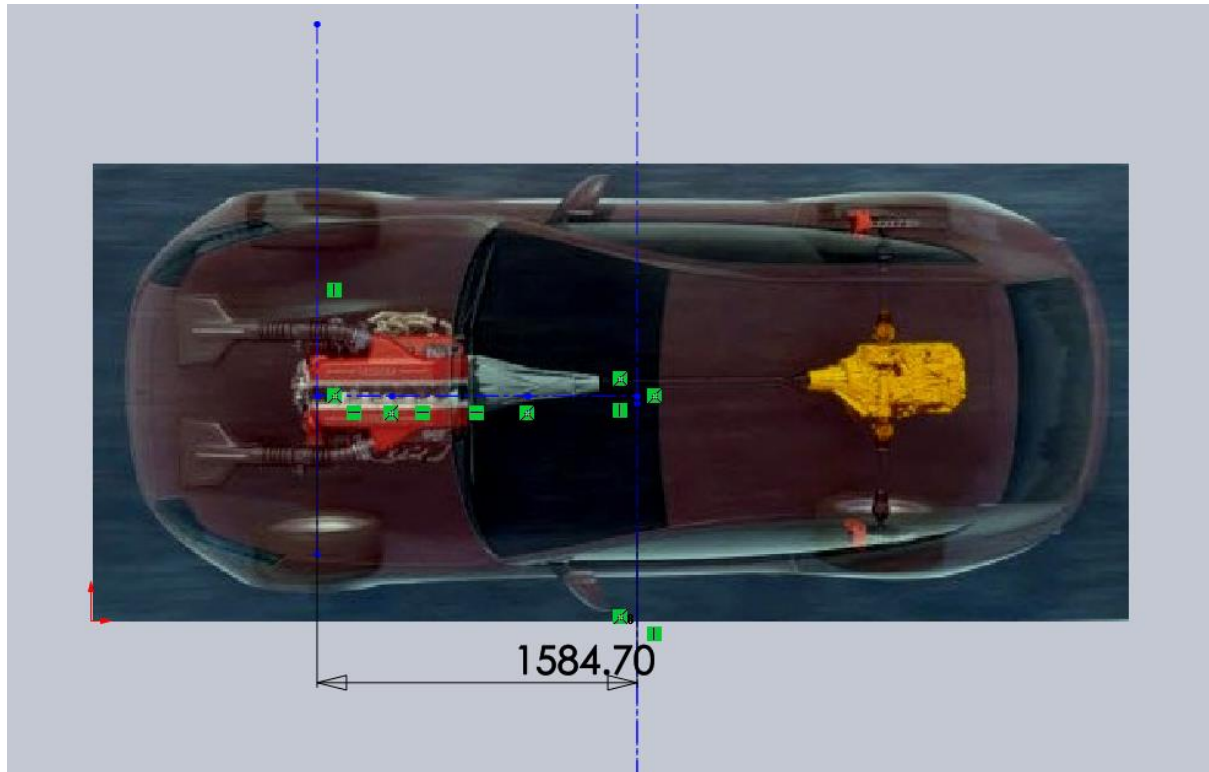


Figure 2 - CoG Point on Car

6 Moment of Inertia

The moment of inertia is dependant on how far the mass acts from the CoG. A car with a low moment of inertia will be able to turn quicker about its own axis, although, this can make it more unstable. A car with a large inertia will have a stronger opposition to change of direct but will be more stability in corners.

The moment of inertia was calculated around the z axis as there was not enough available data to produce a 3D inertia value. To calculate the inertia the following equation was used.

Equation 1 - Moment of Inertia

$$Inertia = \frac{Mass}{(Distance\ from\ font\ axle\ to\ CoG)^2}$$

Two distances are found (a and b) and these are found by multiplying the wheelbase by the weight distribution. 'a' was found to be 1.5847m from the front axle to the CoG and 'b' was found to be 1.4053m from the rear axle to the CoG.

The inertia was found to be 4721.2 kg.m² when there are no passengers in the car.

7 Inertial Conjugate

The inertial conjugate can sometimes be referred to as the radius of gyration. This is the distance from the axis of rotation where the total mass of the body is concentrated. The moment of inertia will act around this axis.(Stanford University, 2011)

The inertial conjugate was calculated as it is required to calculate the dynamic index. To calculate this the following equation was used.

Equation 2 - Inertial Conjugate

$$k = \sqrt{\frac{\text{Moment of Inertia}}{\text{Vehicle Mass} * \text{Distance from front axle to CoG}}}$$

The vehicle mass is in kg and the distance in m.

For the Ferrari FF, the inertial conjugate was found to be 1.259.

8 Dynamic Index

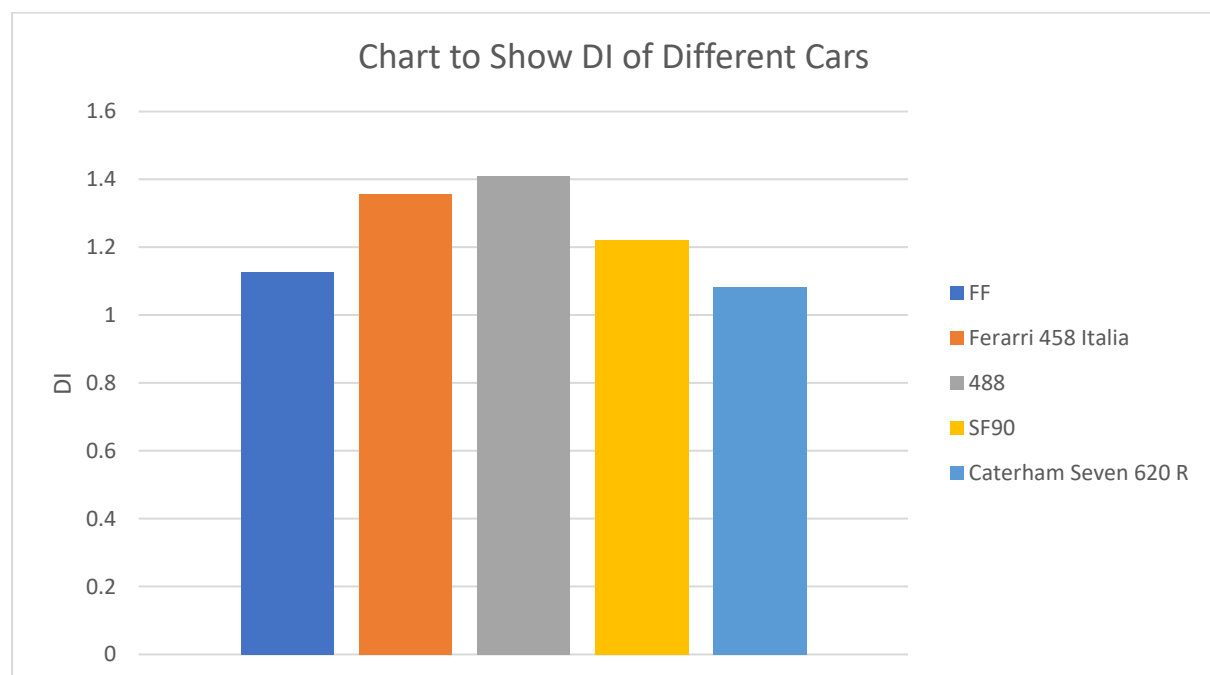
The dynamic index is a value that can be used to measure the responsiveness of a car when turning. If the value is less than 1 the car will be very twitchy but responsive to steering inputs, if the value is greater than 1 then the car will be more stable but less responsive to steering inputs.(Johns and Cole, 2015)

The dynamic index is typically known as a ratio between the radius of gyration and the distance from the CoG. The following equation can also be used to find the dynamic index.(Gillespie, 1992)

Equation 3 - Dynamic Index

$$DI = \frac{\text{Moment of Inertia}}{\text{Mass} * a * b}$$

The dynamic index of the Ferrari FF is 1.128. This would suggest that the car is slower to respond to steering inputs compared with a sports car.



Graph 1 - Dynamic Index of Different Cars

Graph 1 shows the dynamic index values for different cars. The FF has a lower dynamic index compared with other Ferraris. This is possible due to these values being calculated with no passengers inside the car. If these values were calculated with the cars at maximum capacity it would be expected that the FF would then have a greater dynamic index than the other Ferraris tested. This is because the FF is able to seat 4 people and with the rear seats being located behind

the CoG the dynamic index would increase as the weight distribution would move further rearwards. The other Ferraris tested are all mid engined meaning their weight distribution is further rearwards than the FF.

One possible reason for the other Ferraris having a larger dynamic index would be that they are powerful sportscars designed for both track and road. When driving these cars on the road having a larger dynamic index makes them more predictable to drive and therefore safer for the average driver. When driving on the track the driver would be able to slow the car down in a straight line, allow the car to rotate in the mid corner phase and finally after the apex utilise the power of the car to power out of the corner with the maximum grip available.

This could explain the difference between the Ferraris and the Caterham that was tested. The Caterham while being road legal was mainly designed for the track. The Caterham has under half the horsepower compared with the FF but is nearly 3 times as light. This car would require a different driving style to be fast around a track. It would be more efficient to carry the speed around the corner making use of its lack of weight as it does not have as much power to gain the speed at corner exit. The driver would have to slow the car down as it turns into the corner, making use of the lower dynamic index to turn more effectively, and try to carry the speed through the mid corner and exit the corner with a greater velocity.

This would explain why light weight track focused cars have a lower dynamic index as they rely on the quick cornering response to be fast around a track. It would have been interesting to find the index of the 458 or 488 GT3 spec race cars to see if they have the expected lower dynamic index value, which they could have as racing cars can be less stable since they are solely designed to go quick around a track and are driven by skilled drivers. Unfortunately, Ferrari or customer teams do not publish the required data to find the dynamic index and it is therefore just speculation.

9 Base Vehicle Specification

If 2 front passengers are located in the car the CoG moves much further forwards making the weight distribution slightly front biased. If there are both front and rear passengers in the car the CoG still moves slightly further forward but still remains rear biased.

The mass distribution of the car with no passengers is 47/53. It is often referred that a 50/50 weight distribution is somewhere close is the ideal for most cars.(Gillespie, 1992). For a car with a large engine located in the front this is a good weight distribution and the engineers at Ferrari would have put it a lot of effort to get a four seater, AWD, front engine car to have this weight distribution.

10 Mechanical Torque Path

The '4RM' system is around 50% lighter than a standard AWD system and can provide power to each of the wheels independently. The system works by having a second gearbox that is attached to the engine. This gearbox contains two forward gears and one reverse gear. The forward gears are 2nd and 4th but with a ratio that is 6% taller than the same gears in the main gearbox.(English, 2011). When the main gearbox is using 1st or 2nd the front gearbox uses its first gear. When the main gearbox is in 3rd or 4th the front gearbox uses its second gear. After that, no torque is given to the front wheels.

The front gearbox in the FF is only able to transmit 20% of the engines torque to the front wheels, this is done as the front drive shafts would not be able to handle more of the torque. This system allowed for a relatively low weight setup for front of the car to compensate for the engine being placed at the front, allowing for greater weight distribution.(Fedeli, 2011). One main advantage of this system is that it is easy to manufacture.

Ferrari have also recently produced a patent for an electric vehicle which uses a similar AWD system but with electric motors on the front and on the rear. The system uses two separate 'electric powertrain systems'(Francesco, 2020), one for the front wheels and one for the rear wheels. These systems are designed to act independently from one another.

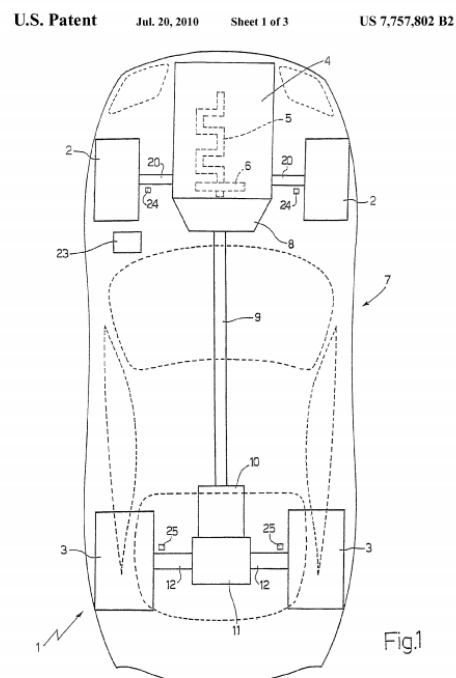


Figure 3 - Patent Drawing of Transmission

11 Clutch Packs

The Ferrari FF uses multiple clutches inside a clutch pack. This is done for a few main reasons, the first being a clutch pack is able to withstand higher torque values compared to a normal transmission with a single as the torque transmitted can be shared by the multiple clutches. This can also be done since there are a greater number of friction plates to share the torque load. The second advantage is size, since there are multiple clutches the overall diameter of these clutches can be reduced when compared with a normal clutch, this allows for more compact packaging which in a sports cars where space can be limited. With the FF this allows more room in the rear of the car letting Ferrari place 2 rear seats that can comfortably seat 2 adults. With the clutches in the FF being wet clutches the overall friction loss with the transmission is reduced as there is less friction with a wet clutch system compared with a dry clutch system.

One big disadvantage of a multiple clutch system is price, this is why it is not seen in cheap cars. But with the Ferrari costing around £250,000 new the extra cost of this system is only a fraction of the overall cost of the car and therefore the advantages outweigh the extra cost of the system.

The transmission in the FF has been assumed to be 97% efficient. The μ value of the wet clutch where the material has been assumed as carbon is 0.075. The dimensions of the clutch for the FF could not be found and therefore the dimensions of the Ferrari 348 clutch were used, where the inner diameter is 148mm and the outer diameter is 215mm.(John K, 2004). Although it is possible that the actual clutch sizes are smaller due to the FF having a newer more sophisticated system these are the only clutch sizes for a Ferrari that could be found and was therefore used. The force acting on the clutch was calculated using both the constant pressure and constant wear equations which can be seen below.

Equation 4 - Constant Pressure Theory

$$F = \frac{T}{\left(\frac{2}{3}\right) * \mu * \left(\frac{r_2^3 - r_1^3}{r_2^2 - r_1^2}\right)}$$

Equation 5 - Constant Wear Theory

$$F = \frac{2 * T}{\mu * (r_2 + r_1)}$$

The T represents the torque transmitted through the clutch; the torque value was divided by 12 as it has been assumed the system contains 12 clutch plates from the original patent.(Cimatti, 2010)

When the constant wear theory is being used, the force applied to the clutch was found to be 7635.6N and when the constant pressure theory was being used the force was found to be 7783.5N. It would be expected that the constant pressure theory would allow for more force as this is the theory used when the clutch is new and breaking in, the constant wear theory is used once the clutch has been broken in.

12 Longitudinal Acceleration

For this section, the longitudinal acceleration was calculated for the car in full RWD mode and the car transmitting 20% of the torque to the front wheels. This was done with the car on dry tarmac and also with the car on ice to see how the AWD system can improve the acceleration on slippery surfaces.

To calculate the acceleration the torque being transmitted first had to be calculated. The torque at the shaft was calculated using the following equation.

Equation 6 - Torque at Shaft

$$\text{Torque at Shaft} = \text{Engine Torque} * \text{Transmission Efficiency} * 1\text{st Gear Ratio}$$

Where the 1st gear ratio is 3.4:1. The torque to the rear wheels could then be calculated using the following equation.

Equation 7 - Torque at Rear Wheels

$$\text{Torque at Rear Wheels} = \text{Torque at Shaft} * \text{Efficiency} * \text{Final Ratio}$$

Where the final ratio is 4.38:1. Before the acceleration could be found the force first needed to be found, this was done using the following equation.

Equation 8 - Force on wheels

$$\text{Force} = \frac{\text{Torque at Rear Wheels}}{\text{Rolling Radius}}$$

The rolling radius had to be calculated for both the front and rear wheels. The FF uses 20 inch wheels. On the front the FF uses 235/35/20 tyre sizes and 295/35/20 on the rear.(Ferrari, 2011). Therefore, the side wall of the tyre is 35% of the width. This means for the front the rolling radius was 339.75mm and 357.25mm for the rear. This was calculated using half of the wheel diameter (508mm) and adding this value to 35% of the side wall size (85.75mm for the front and 103.25mm for the rear.) The acceleration could be calculated using the following equation.

Equation 9 - Acceleration

$$\text{Acceleration} = \frac{\text{Force}}{\text{Mass of Car}}$$

When all the torque was going to the rear wheels the maximum acceleration was found to be 14.25 m/s. However, the maximum acceleration was found to be 5.2 m/s. This means if the car accelerated at the maximum possible rate the wheels would end up spinning. When 20% of the torque was transmitted to the front wheels the maximum acceleration was found to be 13.44 m/s. This is a

slightly lower value as there is more mechanical resistance reducing the amount of torque being transmitted overall. However, when there is torque being transmitted the possible amount of acceleration is increased to 9.81 m/s. Therefore, when torque is being transmitted to the front wheels the car will be able to accelerate quicker even though the maximum amount of acceleration was reduced.

If the rear tyres were placed on ice with a μ value of 0.1 where 100% of the torque is being transmitted to the rear wheels the acceleration is dramatically decreased. The maximum acceleration decreased to only 1.34 m/s. This is because the driven wheels have been placed on a surface with low grip, thus they are not able to transmit the torque from the engine to drive the wheels efficiently without spinning them.

If the front tyres are on dry tarmac while the rear tyres are placed on ice the maximum acceleration is increased to 3.18 m/s. This is because 20% of the engines torque is being applied to the front wheels which are placed on a surface with a high μ value and therefore are able to grip even though the rear wheels would still spin. This shows that in difficult condition including a wet or icy road, the AWD system would allow the car to have more grip which would make the car safer on the road as it would have more available grip when compared with an RWD sports car. It would also make the car faster around a track as it would be able to utilise any available grip across all 4 wheels.

13 Yaw Rate Increase

By utilising the AWD system the FF is able to increase the yaw rate over a standard RWD car. It is able to do this using the electronic AWD which constantly measures the amount of slip for each wheel. If one wheel begins to slip, which in normal cornering would be the front inside wheel, the amount of torque to this wheel can be reduced and more can be provided to the outside wheel. This is done since the outside wheel has more mass acting on it due to the yaw of the vehicle and therefore would have more available grip.

For the car to be in equilibrium through a corner the total force acting on the front should equal the total force acting on the rear wheels. If the car had an open differential the wheels can rotate at different speeds but only 50% of the torque would go to each wheel. The AWD system can 'lock' the differential and therefore the torque can be transmitted to the required wheel if the other one begins to slip.

14 Control Algorithms

Many control systems are used on the FF some are for safety, some for driving enjoyment and some for both. The FF makes use of wheel speed sensors in each individual wheel, this is used to determine how much torque should be provided to each wheel when driving. X, Y and Z acceleration sensors can be used to confirm the vehicles acceleration.

The FF also has electronic stability and anti-lock brakes. These are both used together to determine how much slip the car is allowed before they begin to intervene. This can also be dependant on the mode the car is set in. If it is set into comfort mode these system will react quickly and allow only minor amounts of slip to keep the car in control at all times. If the mode is set to sports mode the car will be allowed to slip more as it is now assuming that the driver wants to drive quickly so they will only switch on when the situation starts to become dangerous.

When the car is on power through a corner the ESP and ABS will work together to try and use the maximum available grip. When the car is off power they will again work together, although this time they will be making sure that the car doesn't begin to over rotated when cornering. This can be done by applying a small breaking force to any wheel that beings to lose traction.

When performing the 'moose test' also known as a lane change test, the systems in the car will try and stop the car from over rotating and thus spinning out. As if this had to be done in an emergency these systems will allow the driver to have some control over the car during the incident and to recover safely.

15 Conclusion

As seen in the report many elements can impact the vehicles static and mobile handling characteristics.

Changing the mass distribution of the car to lead to completely different handling characteristics. The position of major components had a large impact on the mass distribution of the car and therefore a large impact on how the car behaves. Ensuring the control systems work together is essential in maintaining a car that is both fun and safe to drive. Allowing the driver to have a setting to change how much of an impact these systems have, such as having a comfort and sports mode can allow the driver to be safe and comfortable when they want to be but also allow them to drive fast and have fun, while still remaining fully in control.

The use of the AWD system allows the car to accelerate faster as it has more available grip. It also allows the car to corner faster and harder as it provide each wheel with the maximum possible grip available.

The opinion of the car was mainly positive with people being happy that the car can seat 4 adults, while still being fun to drive. It was seen as a better alternative to a sporty SUV as it was more of a sports tourer rather than a utility vehicle. This allowed the drivers to remain comfortable on long journeys while still being able to have fun when a twisty road was there.(Autocar, 2011; Clarkson, 2011; English, 2011)

Motor1 (2010) *Lamborghini reveals new V12 Engine with 700 horsepower [videos]*. Available at:
<https://www.motor1.com/news/24803/lamborghini-reveals-new-v12-engine-with-700-horsepower-videos/>

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De Novellis, L. *et al.* (2015) 'Direct yaw moment control actuated through electric drivetrains and friction brakes: Theoretical design and experimental assessment', *Mechatronics*. Elsevier Ltd, 26, pp. 1–15. doi: 10.1016/j.mechatronics.2014.12.003.

Stanford University (no date) *Radius of Gyration*. Available at: https://ccrma.stanford.edu/~jos/pasp/Radius_Gyration.html (Accessed: 20 May 2020).

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17 Appendix

	Length	Width	Height	Wheelbase	Front Track	Rear Track	Kerb Weight	Dry Weight	Weight Distribution	
	4907	1953	1379	2990	1679	1660	1880	1790	47/53	
	Engine	CC	CC per cylinder	Max Power (kw)	Max Torque (Nm)	Max RPM	Rf/r	Kerb Force	Final Gear Ratio	
	V12	6262	521.8333333	486	683	8000	254	18442.8	4.38	
	Front Weight (kg)	Rear Weight (kg)	a	b	k	lzz	D.l			
	883.6	996.4	1584.7	1405.3	1.25884868	4721.195289	1.127659574	0.711591831		
	Force									
	8668.116	9774.684								
	Front to Engine	Front to Gearbox		Engine mass	Gearbox mass					
	1351.72	3820.52		225	81					
	Axle to engine	Axle to gearbox								
	367.26	2912.57								

Figure 4 - Excel Base Data

[illegible]

Figure 5 - Excel Clutch

Figure 6 - Excel Acceleration

Figure 7 - Excel 458 Italia