



THE ANALYSIS OF THE FOUR- WHEEL DRIVE TORQUE VECTERING SYSTEM OF THE 2011 FERRARI FF



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Abstract

For this report, the 4RM Torque Vectoring System of the 2011 Ferrari FF have been assessed, investigating the system's capabilities for improving vehicle performance laterally and longitudinally. It was found that the 4RM greatly improved both the vehicle's performance both longitudinally and laterally, proving the concept Ferrari applied to the FF despite inaccuracies as a result of limited information.

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Section 1 – Introduction

At the 2011 Geneva Motor Show, Ferrari revealed their successor to the 612 Scaglietti Grand Tourer, the Ferrari FF. The FF is fitted with Ferrari's first four-wheel drive (4WD) system, the 4RM. Designed by Ferrari themselves, the revolutionary 4RM system takes an abstract approach to the typical centre differential 4WD system in an attempt to save weight and preserve an optimal weight distribution (Motor Authority, n.d.).



Figure 1.1 – An image of the 2011 Ferrari FF (driving.co.uk, 2011)

In this paper, the dynamics of the Ferrari FF will be assessed, commenting on the overall design of the vehicle. Then, the aforementioned 4RM design will be analysed to investigate how the system will improve the overall vehicle dynamics.

Section 2 – Background Information

Section 2.1 – Vehicle Information

As mentioned in section 1, the dynamics of the FF and its 4RM system will be assessed in order to comment on the overall vehicle design as well as the improvements the 4RM system can bring to vehicle performance. The table below shows all the data (www.carfolio.com, n.d.) required for the analysis.

Name (Units)	Value
Wheelbase (millimetres)	2990
Front Track (millimetres)	1676
Rear Track (millimetres)	1660
Kerb Weight (kilograms)	1790
Weight Distribution (percent)	47 / 53
Torque (Nm)	683

Table 2.1 – Table showing the vehicle data relevant to the FF analysis

Section 2.2 – Torque Vectoring

Torque vectoring varies the torque applied to individual wheels depending on the current driving environment via the differential (Jonasson et.al, 2018). There are two different types of torque vectoring: via the brakes (TVB) and via the differential (TVD).

TVB makes use of the brakes as well as the existing differential on a 4WD car to create a cost-effective torque vectoring system. While cornering, the system applies the brakes to the inside wheels, creating a braking torque that enables the differential to apply a larger torque to the outside wheels. Applying more torque to the outside wheels during cornering improves the yaw rate and as a result reduces understeer (pistonhead.com, n.d.).

TVD uses a similar concept to TVB but rather than using the brakes to increase yaw, a system of planetary gearsets and clutch packs is used to vary the torque across the four wheels. While driving linearly, the clutch system is disengaged and therefore the torque is evenly distributed across all four wheels. While cornering, the clutch packs responsible for the outside wheels engages, redirecting drive from the central differential to the outside wheels, resulting in increased outside wheel speeds. This increase in wheel speed improves yaw without sacrificing cornering speed (pistonhead.com, n.d.).

Though complex, the TVD system is the more conventional torque vectoring option as yaw ability is improved without sacrificing cornering speed as well as brake wear. While using a different layout, the FF's 4RM torque vectoring system follows the same concept as the TVD system.

Section 2.3 – Lumped Mass Model

A lumped mass model, shown in figure 2.1, is a diagram showing where the individual masses of the vehicle are placed with regards to the centre of gravity (Blundell and Harty, 2015). From this, an accurate representation of a vehicle's moment of inertia can be calculated.

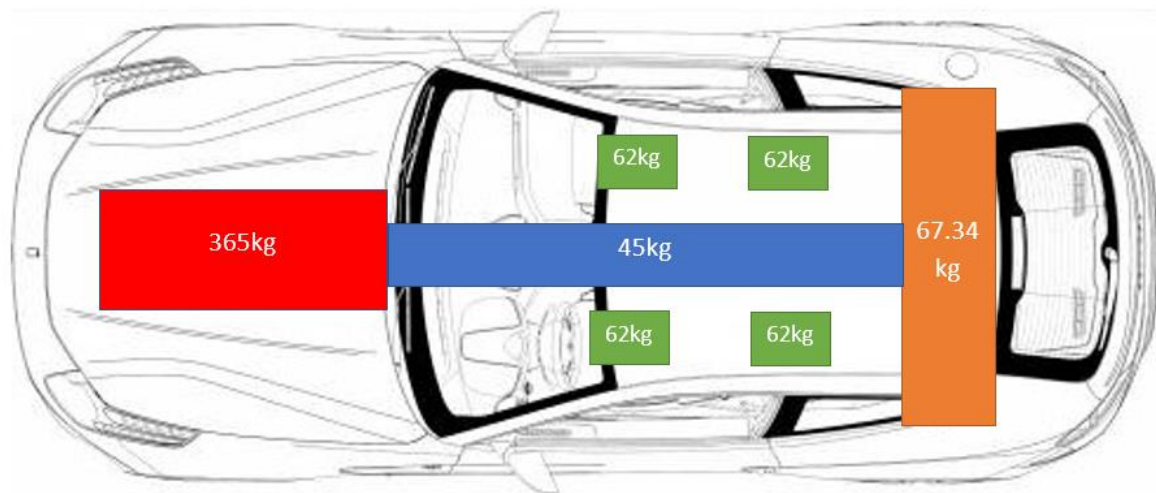


Figure 2.1 – Lumped Mass Diagram of the Ferrari FF

Due to a lack of available information for the component's masses of the FF, major assumptions of these masses have been made to create the model above. The engine and gearbox, shown in red, has been assumed as 365kg (nadascientific.com, n.d. and auto123.com, n.d.). As the FF is a four-seater vehicle, the green boxes represent the vehicle at full capacity, where one box corresponds to one average human with a mass of 62kg (Walpole et. Al, 2012). Ferrari state a fuel tank capacity of ninety-one litres (car.info, n.d.). With this in mind, and that the mass of petrol per litre is 0.740kg (engineeringtoolbox.com, n.d.), the mass of a full fuel tank is 67.34kg. Finally, the 4RM differential system is quoted to weigh 45kg by Ferrari (car.info, n.d.).

Section 3 – Vehicle Analysis

Section 3.1 – Longitudinal Centre of Gravity

The longitudinal centre of gravity is a metaphorical point on a vehicle where all of the mass acts about (Solmaz, Akar and Shorten, 2006). Calculating the longitudinal position of the centre of gravity enables an engineer to understand the handling capabilities of a vehicle, where a more central point gives better vehicle cornering performance. To calculate this position, the equation below must be used.

$$Long\ CoG\ Position = W \times \%mass \quad (1)$$

Where, W is the vehicle's wheelbase and %mass is the weight distribution from the front or the rear. Therefore, using equation one gives the centre of gravity position of 1405.3mm from the front axle.

Section 3.2 – Pitch Moment of Inertia

Ritzel.edu describes the pitch moment of inertia as 'the force felt in acceleration or braking around the horizontal axis of a vehicle' (ritzel.siu.edu, n.d.). Understanding the pitch moment is important to understanding the front to back weight transfer of a vehicle under braking and acceleration. With this in mind, the equation for calculating the pitch moment of inertia is shown below.

$$I_{pitch} = \sum m \times r^2 \quad (2)$$

Where m is the mass of the component and r is the distance between the component and the centre of gravity. Without a Ferrari FF being available, the true distance between a component and the centre of gravity cannot be measured. Therefore, it will be assumed that the mass acting over the front and rear of the car is acting above their respective axle. Consequently, the equation used to calculate the pitch moment of inertia of the FF is:

$$I_{pitch} = \sum (m_f \times a^2) + (m_r \times b^2) \quad (3)$$

Where a is the distance from the front axle to the longitudinal centre of gravity, which is 1405.3mm with regard to the FF, and b is the distance from the rear axle to the longitudinal centre of gravity, which is 1584.7mm for the FF. The mass at the front of the vehicle (m_f) is 47% of the overall mass, which is 883.6kg, and the mass at the rear of the car is 53% of the overall mass, which is 996.4kg, due to the weight distribution of the FF. Therefore, the overall pitch moment of inertia for the Ferrari FF is 4244.27kgm².

Section 3.3 – Dynamic Index and the Position of Inertial Conjugate

The dynamic index is a product of the inertial match theory, which describes the relationship between a vehicle's centre of gravity, inertia, and its wheelbase (Blundell and Harty, 2015). Calculating the dynamic index enables a vehicle designer a vital insight into chassis behaviour during a cornering scenario. From the dynamic index, the inertial conjugate can be found. Blundell and Harty, 2015 describe the inertial conjugate as 'the location at which no translation occurs when a free body with finite mass and inertia properties is loaded in a direction that doesn't pass through its centre of gravity'. A dynamic index larger than one means that the distance c , which is the distance between the centre of gravity and the position of the inertial conjugate, is larger than the distance b and vice versa for a dynamic index smaller than one. Therefore, the position of the inertial conjugate from the centre of gravity can be calculated by multiplying the dynamic index by the distance b .

With this in mind, to calculate the dynamic index of the FF, the equation below has been used.

$$DI = \frac{I_{pitch}}{mab} \quad (4)$$

Where I_{pitch} is the pitch moment of inertia, m is the vehicle mass in kilograms, a is the distance from the front axle to the centre of gravity in metres and b is the distance from the rear axle to the centre of gravity in metres. Using equation 4, the dynamic index was calculated to be 1.014, meaning that the position of the inertial conjugate (c) is 1606.17mm from the centre of gravity.

Section 3.4 – Base Specification Assessment

As shown in section 2.1, the weight distribution is 47% front and 53% rear, making the centre of gravity roughly central along the wheelbase. The weight distribution of a vehicle gives an early indicator of how a car will handle. The optimal weight distribution is 50-50, which means that all of the vehicle's mass is evenly distributed across the four wheels, meaning there is no grip loss across the wheels. Having a weight distribution with a larger forward percentage than rear, such as 55% front and 45% rear, results in the front tyres reaching the limit of grip before the rear tyres. This means that the vehicle will naturally understeer. This shows a direct correlation between the weight distribution and the cornering performance of a vehicle, therefore the FF having a weight distribution close to 50-50 gives an ideal handling platform for a sports car such as the FF.

As discussed in section 3.3, the position of the inertial conjugate shows the position at which no reactionary force at the centre of gravity occurs with a load applied. With regards to vehicle dynamics, if a front wheel rides over a bump and the position of the inertial conjugate is towards the rear of the car, there will be no reactionary force acting on the vehicle. Therefore, the bump will not be felt by the vehicle's passengers (RATMIG, 2013). Using this statement with regard to the FF, the same can be

said. The inertial conjugate is positioned 1606.17mm from the centre of gravity and the rear axle is 1584.7mm from the centre of gravity, therefore the RATMIG, 2013 statement can be applied to the FF. This can be further supported by the design of the FF, which is described by Ferrari as a Grand Tourer or GT vehicle (Ferrari, 2011), which is a sports car that is not only designed for performance but also designed for long distance comfortable running (allcarleasing.com, n.d.). Consequently, designing the FF with a dynamic index towards the rear not only provides optimal chassis handling performance, but also ideal passenger comfort.

Section 4 – 4RM Analysis

Section 4.1 – Front Wheel Torque Path

The 4RM uses a radically different design compared to a typical TVD system. Instead of a central differential that varies the torque across the four wheels, the front wheels are driven by a secondary gearbox directly attached to the crankshaft and the rear wheels are driven by a differential and clutch pack setup (Ferrari, 2011), similar to a standard TVD setup. The secondary gearbox is fitted with 2 gears, the first is engaged when the primary gearbox is in first and second gear and then the second gear is engaged when the primary gearbox is in third or fourth. Past fourth gear, no torque is applied to the rear wheels resulting in a totally rear-wheel drive design (Ferrari, 2011). Designing the system this way created a system roughly half the weight of a standard all-wheel drive system, therefore preserving the low weight sports car design the company was looking for.

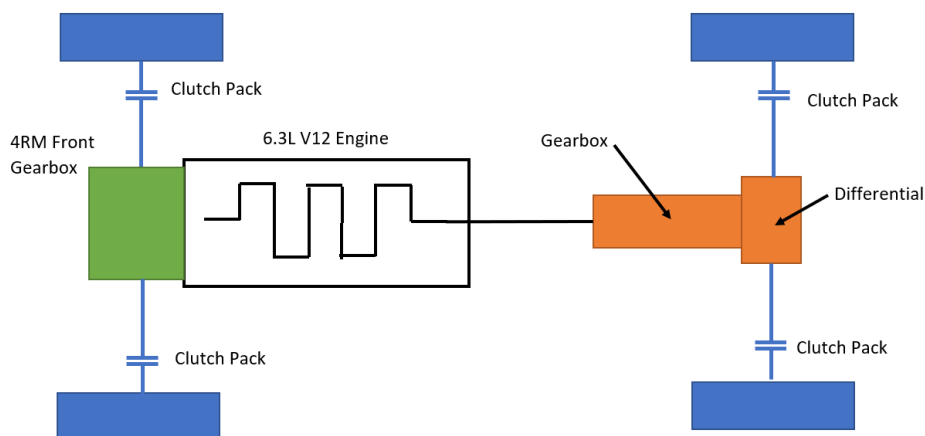


Figure 4.1 – Torque Path diagram of the Ferrari FF showing how the power is applied to all four wheels

The torque to the front wheels is limited to 20% of the overall engine torque. This is due to the driveshafts being designed to the minimum mass possible (Ferrari, 2011). This preserves the roughly equal weight distribution that the FF has, providing even weight transfer across the four wheels and, therefore, an optimal handling performance.

Section 4.2 – Clutch Pack Analysis

As mentioned in section 2.2 and 4.1, the 4RM vectors the torque for each wheel using a clutch pack on each wheel. Therefore, understanding the forces acting on the clutch plates, during wear and from new, can enable a clutch designer to create a clutch capable of withstanding such forces throughout the life cycle of the vehicle.

With this in mind, the constant pressure and wear theory, the equations of which are shown below, have been applied to the FF to find the forces acting on the clutch packs.

$$\text{Constant Wear } (W_{\text{wear}}) = \frac{T_{\text{max}}}{n\mu(r_2+r_1)} \quad (5)$$

$$\text{Constant Pressure } (W_{\text{press}}) = \frac{3T_{\text{max}}(r_2^2-r_1^2)}{2n\mu(r_2^3-r_1^3)} \quad (6)$$

Where T_{max} is the peak torque of the engine, n is the number of clutch plates, μ is the coefficient of friction between the clutches, which is taken to be an oily carbon on carbon contact (Engineering Toolbox, 2004), r_2 is the outer radius of the clutch plate and r_1 is the inner radius of the clutch plate. The values associated with the FF required for the equations above are shown in the table below. However, due to a lack of available information, the clutch diameters needed have been assumed to a similar Ferrari (FerrariChat, n.d.) to keep the W values as accurate as information allows.

Name (Units)	Value
Peak Torque (Nm)	683
Number of Clutch Plates	12
Coefficient of Friction	0.13
Outer Diameter (mm)	215
Inner Diameter (mm)	148

Table 4.1 – Table showing the values required for the clutch plate analysis

Combining table 4.1 and equations 5 and 6, the W_{wear} value for the FF is 2412.23N and the W_{press} value for the FF is 4770.3N.

Section 4.3 – Improvements to Longitudinal Acceleration

As mentioned in Section 4.1, the FF utilises the 4RM system between the first and fourth gears of the primary gearbox. From a longitudinal perspective, the addition of the 4RM system will give improved peak longitudinal acceleration across a variety of surfaces. Consequently, this statement will be proved by calculating the maximum acceleration with and without the 4RM fitted.

To do this, first the weight transfer from front to rear must be calculated. This can be done using the equation:

$$\Delta W_x = \frac{ham}{WB} \quad (7)$$

Where ΔW_x is the weight transfer from front to rear, h is the centre of gravity height, which for a sports car like the FF has been assumed as 0.5m, a is the maximum acceleration, which was calculated from the FF's 0-200km/h time for a value of 5.05m/s², m is the mass of the vehicle and WB is the vehicle's wheelbase. Consequently, the weight transfer from front to rear of the FF was calculated to be 1680.52N. Adding the static load acting on the rear axle, calculated using $F=mg$, where m is 53% of the total mass, the total load acting on the rear wheels of the FF during acceleration is 12027.13N. Rearranging Newton's 2nd Law, $F=ma$, for acceleration gives the equation

$$a = \frac{F}{m} \quad (8)$$

Therefore, the maximum acceleration of a vehicle with a coefficient of friction (μ) of 1, which is a tyre on dry tarmac (Engineering Toolbox, 2004), is 6.04m/s². To incorporate varying surfaces, the equation below can be used.

$$a = \frac{(F \times \mu)}{m} \quad (9)$$

With this in mind, two different surfaces have been chosen to reflect different driving conditions that the FF will operate in, wet tarmac, with a μ value of 0.2 (Engineering Toolbox, 2004), and ice, which has a μ value of 0.08 (hpwizard.com, n.d.). Combining equation 9 with these μ values gives an acceleration of 1.21m/s² on wet tarmac and 0.48m/s² on ice.

The addition of the 4RM system produces an extra accelerating axle at the front of the car. Therefore, when finding the total load acting on the vehicle during acceleration, the front must also be considered. This can be done by subtracting the ΔW_x value from the static load on the front axle, which is 6713.90N. This value can then be added to the total rear axle load to give a total vehicle load when accelerating, which for the FF was 18741.03N. Then, using the newly calculated force in equation 9

will produce the new acceleration value for a 4WD system. In the case of the FF, the new accelerations are shown in the table below.

Name	Acceleration (m/s ²)
Dry Tarmac	9.42
Wet Tarmac	1.88
Ice	0.75

Table 4.2 – Table of calculated longitudinal acceleration for the 4WD FF

Using the method shown, it is clear that the addition of the 4RM system produces improved longitudinal acceleration on a variety of different road surfaces.

Section 4.4 – Yaw Rate Improvements

The 4RM not only improves the longitudinal acceleration performance but also the yaw rate. In a typical rear-wheel drive vehicle during cornering, the level of slip on the inside wheel increases. This increased slip causes a vehicle to understeer, reducing the overall yaw rate of the vehicle. The addition of the 4RM system decreases the slip on the inside wheel by reducing the torque at this wheel and in turn raising the torque of the corresponding outside wheel. Increasing the torque on the outside, heavier loaded, wheel will increase the yaw rate of the vehicle. This is because the heavier loaded outside wheel will have a higher amount of available grip and therefore more power can be applied to the wheel without sacrificing tyre slip (pistonhead.com, n.d.).

Section 5 – 4RM Package Analysis

As shown in section 4.3, the addition of the 4RM vectoring system improves the longitudinal acceleration performance of the FF. Using 4RM system from first to fourth gear allows for a better straight line acceleration value from a dead stop regardless of the surface.

As well as this, the addition of the 4RM also improves cornering performance. As mentioned in section 4.4, lowering the yaw rate will reduce vehicle understeer through a corner. Reducing the understeer of a vehicle results in better turn in and as a result, a more responsive vehicle handling package. However, larger yaw rates also result in larger loading on the outside tyres. This increased load can create an uneven tyre wear pattern across the four tyres, meaning that tyre replacements will be more common during the life cycle of the vehicle.

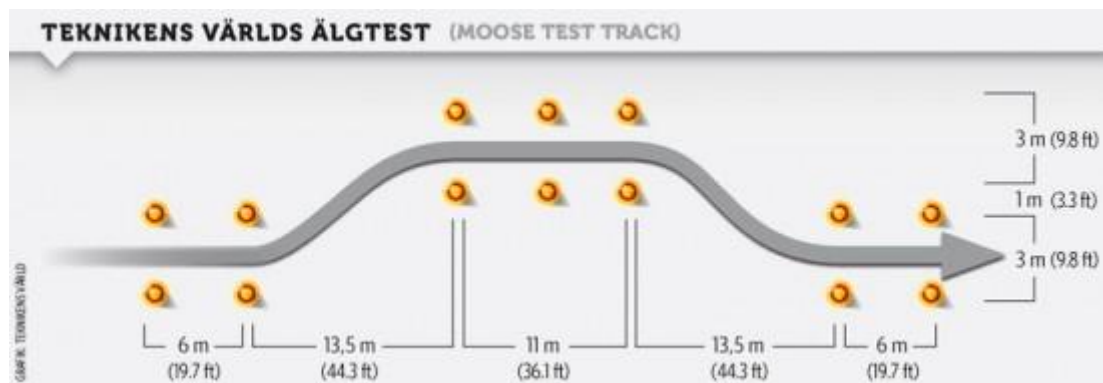


Figure 5.1 – A diagram showing a Moose Testing Track (wapcar.my, n.d.)

From a city driving perspective, as opposed to performance, the addition of the 4RM can benefit the driver when needing instant change in direction, for example during a moose test scenario. The purpose of the moose test is to assess a vehicle's capability to change direction at speed in order to avoid an obstacle on a country road (International Driving Authority, n.d.). Consequently, improving the directional change capabilities of the vehicle, via the 4RM system, can benefit not only performance but also driver and pedestrian safety.

As stated by Ferrari, the 4RM system is fully integrated within the ECU (Ferrari, 2011). This gives the system access to real time data from sensors around the car, for example slip sensors on the wheels will enable the 4RM system to assess the current tyre situation at each tyre at any given point. From this assessment, the torque across the four wheels can be vectored to match the current situation. As well as this, the vehicles yaw sensors can be observed by the system in order to match the torque vectoring to the level of turning required. For example, if the yaw rate is too high and the vehicle moves into a state of oversteer, as observed by the slip on the outside wheels, the torque vectoring can be relaxed to return to a level cornering state.

Section 6 – Conclusion

In conclusion, it is clear that the addition of the 4RM system to the Ferrari FF not only benefits the straight-line performance but also the handling of the vehicle, as proved in section 4.3, where the addition of the 4RM torque vectoring system improved the acceleration over a range of different road surfaces.

Despite this, the results of this report should be taken with a large caveat. A large amount of the measurements used in the calculations have been assumed from similar vehicles and, therefore, the true values for the Ferrari FF will be different. In future, measurements of the real vehicle should be taken to get an accurate insight into the vehicle dynamics detailed in this report.

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