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1) Abstract

The FF 'Ferrari Four', was Ferrari's first AWD vehicle, was debuted in March 2011. The task at hand is to analyse the Ferrari FF vehicle All Wheel Drive Technical data and press announcements are used to get base vehicle information. For analytic calculations, necessary data is entered into Microsoft Excel. To properly appreciate mass distribution to do this a lumped mass model is developed. Thus, doing this one can understand the implications on vehicle dynamics and potential control techniques from the torque vectoring front wheel drive system.

2) Base Vehicle data

The Ferrari FF is a coupe powered by a V12 producing 486kW at 8000rpm. A 6262cc V12 petrol engine is positioned behind the front axle line, where the cylinders have an offset of 65 degrees. The propulsion system is passed through a 4RM which transmits torque to all four wheels of the vehicle. The four-wheel drive system on the Ferrari FF is different to traditional systems. Due to the FF being mid-engine the rear transaxle is connected to the engine by a single driveshaft. The front wheels are powered by a power transfer unit or PTU. The PTU is connected directly to the engine and located over the front axle. Benefits of this setup is the system is 50% lighter therefore, the vehicles power to weight ratio is greater thus improving performance. (Microsoft teams, Ferrari FF info scan)

3) Generic Torque Vectoring Systems

Torque vectoring is a computer-controlled technology that regulates the amount of power sent to each individual wheel by your car's engine or motors. An automobile with torque vectoring will have more grip on slippery surfaces and be able to accelerate more quickly by regulating power more effectively. (Torque vectoring explained, 2022) To increase drive torque the system must increase slip at the contact patch.

Using differentials for torque vectoring

An open differential has no way of controlling which wheel obtains the most torque. When one of the wheels begins to spin due to slippery condition, the engine's power will pursue the path with the least resistance, spinning the slipping wheel instead of the one that always has traction.

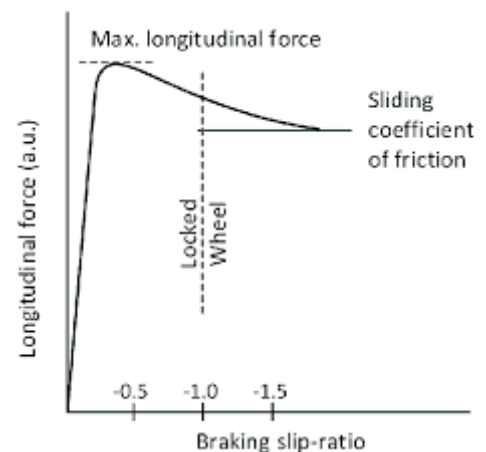


Figure 1-Graph showing longitudinal force vs braking slip ratio (Research Gate 2019)

A torque vectoring system controls how that power is distributed electronically. It accomplishes this by utilising small clutches within the differential that precisely control the amount of torque transmitted to each wheel and, as a result, the amount of wheel slippage allowed. This will depend on the amount of grip the wheels have and what the driver is demanding of them.

A limited-slip differential (LSD) is a mechanically regulated system that performs a similar function. An LSD can restrict power toward a wheel that does not need, but rather an electronic system can proactively transfer this to the wheel with the highest amount of grip.



Torque vectoring using brakes

However, differentials aren't always used in torque vectoring systems. It would be too pricey for its price range and hard to fit into a compact hot hatch like the Volkswagen Polo GTI, for example. Torque vectoring via brakes can be applied in this type of application. The brakes are used to prevent the wheel from slipping. This permits more power to be transferred to the wheels that still have grip, allowing a car to accelerate faster on slick roads or out of tight turns.

Pro and Cons of torque vectoring system

The Advantages of torque vectoring

- It's beneficial in slick situations.
Torque vectoring can assist you in avoid getting stuck in slick circumstances.
- It will help with cornering stability.
You can take corners with more confidence when the vehicle has more grip
- It's beneficial for track days.
Torque vectoring will come in useful if you're striving for lap times around a course. It's no surprise that the technology was born in the world of motorsport.

The disadvantages of torque vectoring

- In most cases, you won't notice the benefits on normal day driving.
You won't notice the benefit of torque vectoring until you're driving on muddy country roads or driving a car aggressively. As a result, buying a car solely for the technology is pointless unless you intend to use it.
- It's complex and costly
Although torque vectoring is standard on many high-performance vehicles, it can be an expensive option. It's also difficult and expensive to repair if something goes wrong.

4) Ferrari FF Investigation

Using data from Ferrari's website, a spreadsheet was developed to acquire a rudimentary concept to anticipate how well the vehicle is at handling and performing. Mathematical simulations will also be used to determine the clutch pack parameters and the vehicle's dynamic index.

4.1) A lumped mass model of the vehicle

A mass distribution model was constructed for the Ferrari FF. the FF has a 47/53 rear bias weight distribution as shown in figure 2 which is shown below, which was created in excel.

lumped mass model		all masses in kg			
Front Right Mass				Rear Right Mass	
441.8				498.2	
M1	883.6	M2	160	M3	996.4
L		G		1.45	
2.99					
Front Left Mass				Rear Left Mass	
441.8				498.2	
Centre of Gravity		1.57	M		
IZZ inertia		4189.4	kg/m ²		
DI		0.92216			

Figure 2- Lumped mass model of Ferrari FF made in Microsoft Excel

5) Calculation of the longitudinal C of G position

Finding the centre of gravity of the FF was the first calculation that need to be calculated. To do so the equation shown below was used:

$$C \text{ of } G = \frac{(m_2 * G) + (m_3 + L)}{m_1 + m_2 + m_3}$$

6) Calculation of the vehicle's moment of inertia (about Z-Z axis)

From the front the FF's centre of gravity is 1.57m. the FF has a rear bias weight distribution because half of the vehicle's wheelbase is 1.45m. The end goal of these calculations is to find the vehicles dynamic index, but firstly after solving the vehicles centre of gravity, they now need to solve for the vehicle's inertia, by using this equation:

$$I = mk^2$$

7) Position of the inertial conjugate

On the other side of the centre of gravity from the ball contact, there is a position where linear acceleration is zero. This is the 'centre of percussion' or inertial conjugate. Mass, moment of inertia, and distance from the centre of gravity to the front and rear axles all influence lateral acceleration and hence lateral force, direction, and magnitude at the rear tyres. (Sandford, 2022).

The car's inertia was calculated at 4189.4kg/m² by adding all the inertias for the three masses. Using the dynamic index formula, the vehicle's dynamic index could now be determined:

b = wheelbase – a

M = mass

I_{zz} = inertia

a = weight bias x wheelbase

$$I_{zz} = \text{inertia. Dynamic Index} = \frac{I_{zz}}{M.a.b}$$

8) 'Dynamic index' of the vehicle

This formula can be used to calculate the vehicle's theoretical dynamic index. The dynamic index takes into consideration the vehicle's centre of gravity, yaw inertia and wheelbase of the vehicle. This delivers a dynamic index figure that would be used to calculate the FF's theoretical driving characteristics. In general, if the dynamic value is higher than one, the vehicle's inertial conjugate would be behind the rear axle, reducing the rear tyre slip angle thus resulting in a sluggish turn in, however it does provide slightly better stability.

If the dynamic index is below one, its inertial conjugate is in front of the rear axle, increasing the inertial force applying on the rear tyre slip angle and resulting in a faster turn. It can result in a far nimble vehicle, but if the value is significantly lower, this can make the vehicle unpredictable. The dynamic indexes of a few various of vehicles are shown below.

Dynamic Index comparisons	mass	weight dist (f/r)	wheelbase (m)	Dynamic Index
Ferrari FF	1880	47/53	2.99	0.922
Honda s2000	1274	50/50	2.4	0.866
Hyundai i30n	1409	63/37	2.65	1.2
1960's VW beetle	840	40/60	2.4	0.48
Nissan GTR	1740	47/53	2.7	0.89

Figure 3-Comparison of different vehicles dynamic index, made in Microsoft Excel

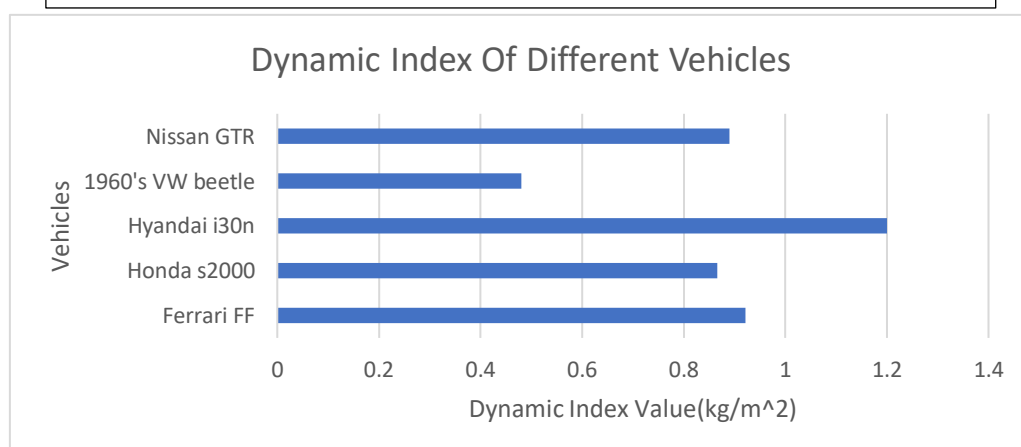


Figure 4-Graph comparing different vehicles dynamic index, made in Microsoft Excel

The different dynamic indexes from a few different vehicles are shown in the comparison chart above. High performance automobiles tend to have a dynamic index between 0.9 and 0.92. (Sandford, 2022). The Honda and Nissan have a good weight distribution and lengthy wheelbases gives the cars a high dynamic index. The i30n's weight distribution is strongly front-biased, which implies the front tyres will work a lot harder than the rears, leading them to overheat and cause understeer throughout sharp corners.

Because the car's weight is already over the front axle, this limits the work done by the rear brakes, resulting in even less grip in the back. The old beetle has a rather low dynamic index of only 0.48, that might also result in a twitchy and nimble vehicle. However, because the beetle only produces 57 horsepower, that's not a problem, however, occasionally it might become unstable at higher motorway speeds because to its poor dynamic index.

9) Comment on the base vehicle specification

- Front weight distribution 47%=883.6kg
- Rear weight distribution 53%=996.4kg

Ferrari FF		
Dynamic index	0.92	kg/m ²
Inertial conjugate	1.46	m
longitudinal Cog	1.57	m

The Ferrari features a 53 percent rear weight bias, which has a few advantages. The greater pressure on the rear tyres, for example, allows for more braking in the back while preventing the fronts from overheating. This improves grip while accelerating, therefore helps to prevent wheelspin and enables for power to be applied sooner in the turn, allowing the car to accelerate faster out of the bends. The Ferrari's dynamic index indicates that the inertial conjugate is ahead of the rear axle, implying that the car will feel more responsive and enjoyable to drive.

Figure 5-Table showing Ferrari FF data, made in Microsoft Excel

10) Identify the mechanical torque path to the front wheels and comment on your findings

4RM (4 Ruote Motrici) Torque path

Normally, all four-wheel drive vehicles have a single gearbox attached to a transfer box that transfers power to the front and rear wheels. The FF uses two transmissions to transfer power from the V12 engine to the wheels. The Ferrari 4RM system features two transmissions, one being a transaxle F1 dual clutch 7-speed transmission that does the bulk of the work. The second box, which is attached towards the front of the engine, and can send 20% of the Ferrari's power to the front wheels. (Ferrari 4RM or 4 Ruote Motrici explained - Why High End, 2022)

In a helical structure comparable to a manual transmission, this box has three gears: one reverse and two forward. For reverse, the gear ratios are the same, with the first gear covering 1st and 2nd in the front and the second gear covering 3rd and 4th in the rear. Due to the enormous rear tyres, the system itself is not required after 4th gear. (Houston, 2012) The power is now transmitted to an electronic differential that can vector torque towards the front axles through two carbon fibre wet clutches connected to a tilt sensor to anticipate when the back wheels lose grip. (Ferrari 4RM or 4 Ruote Motrici explained - Why High End, 2022)

Advantage of the 4RM system that delivers power to the front wheels weighs 90 pounds lighter, which is less than half of the weight of the extra pieces that make up a traditional four-wheel drive system. (Ferrari 4RM or 4 Ruote Motrici explained - Why High End, 2022)

For a transaxle gearbox, the back of the crank is linked as usual. Due to the Ferrari having 'part time' system AWD system. The goal of the FF has been to create a car capable of travelling throughout Europe in a 'supercar' at any time of year, and by sending only 20% of power towards the front, the car nevertheless, still drives like a rwd car, but performs like an awd car.

11) Calculated clutch pack(s) torque capacity, approximate sizes, axial force application values

As previously established, the FF can transmit 20% of its power towards the front wheels, implying that the Ferrari will deliver up to 136n/m towards the front axles through two clutch packs, each with four plates, as shown in the picture of the Ferrari's simulation.



Figure 6- Torque vectoring clutch packs (Ferrari, 2011)

A rudimentary spreadsheet was created in Excel to calculate the approximate sizings as well as the clutch packs torque capabilities. The Ferrari, as previously noted, uses carbon fibre wet clutches to transmit and distribute torque to the wheels. These have a coefficient of friction of 0.11/0.14 on average (professional technology friction, 2022).

There are four clutch plates, with every two contact faces, and by plugging this information into the formulae below, somebody can make a logical approximation regarding clutch plate sizing. Because the PTU has a diameter of 170mm, something larger beyond 160mm would be unlikely. They can save time by dropping down different factors that are also assessable to immediately see the consequences of changing the clutch plates' inner and outer diameters. The dimensions chosen were 105mm inner diameter and 155mm outside radius. At a maximum torque of 136.6N/m, this required 1,297.47N of axial force per plate.

These clutches which power the front axles are engineered to be continuously slipping, ensure that the two front gear ratios to easily transition to the four rear gear ratios. In addition, only 20% of the torque is sent to the front wheels. (Ferrari 4RM or 4 Ruote Motrici explained - Why High End, 2022)

Engine speed		6000	rpm	Equations	
Max Power @ 8000rpm		486	kw	Uniform pressure theory	$W = \frac{2T}{\mu(r_2 + r_1)}$
Max Torque		683	n/m		
Torque split front		136.6	n/m		
Number of clutch packs		2		Uniform wear theory	$W = \frac{3T(r_2^2 - r_1^2)}{2\mu(r_2^3 - r_1^3)}$
Plates per pack		4			
Faces per pack		8			
Total faces		16			
Inner plate diameter	r1	0.105	m		
Outer plate diameter	r2	0.155	m		
Axial force	w	?			
mu carbon cutch	mu	0.1			
Uniform wear theory	w	10379.74	n		
Per plate	w	1297.47	n		
Unifrom pressure theory	w	10507.69231	n		
Axial load per plate	w	1313.461538	n		

Figure 7- table of Ferrari FF data made in Microsoft excel

12) Calculated potential longitudinal acceleration improvements on a variety of surfaces

With sets of data from the car, calculating the greatest starting acceleration (forgetting about weight transfer) is simple. After constructing an excel model, parameters can be modified to mimic the car launching on various surfaces.

The weight distribution of the Ferrari FF is 47 percent in front and 53 percent in back. This ratio becomes much more rear-biased during heavy acceleration. Furthermore, the weight is not transferred as evenly here. The engine is further back and heavier, and the gearbox is behind the rear axle. As a result, the FF has a significantly more rear-biased weight distribution, and the rear wheels provide more traction than the front wheels. (The four-wheel drive Ferrari FF | FF vs Nissan GT-R, power and weight distribution, transaxle 4WD | robotpig.net, 2022)

13) How the yaw rate is increased, relate to handwheel position

The yaw rate increases caused by the system can be determined using the difference between calculated loads and tractive forces. The yaw moment of each axle is calculated by multiplying the difference between left and right wheel forces per individual axle by half the vehicle track.

$$Yaw_f = \Delta F_f \times \left(\frac{Track\ width}{2} \right)$$

$$Yaw_r = \Delta F_r \times \left(\frac{Track\ width}{2} \right)$$

1510.73Nm and 1688.35Nm were estimated as the front and rear net yaw values, accordingly. The following equation can be used to combine the values to get an overall vehicle yaw moment. Because the front and rear tracks are unequal, the overall yaw value is calculated using the mean of the two, resulting in 2669.83Nm.

$$Yaw_t = (Yaw_f + Yaw_r) \times \left(\frac{Track\ width}{2} \right)$$

Yaw Rate			
FRONT	front left force	2929.524 N	
	front right force	2704.176 N	
	difference between sides	225.348 N	
	yaw moment	188.8416 Nm	$Yaw_f = \Delta Force \times \left(\frac{Track\ Width}{2} \right)$
REAR	rear left force	5082.316 N	
	rear right force	3049.389 N	
	difference between sides	2032.926 N	
	yaw moment	1688.345 Nm	$Yaw_R = \Delta Force \times \left(\frac{Track\ Width}{2} \right)$
COMBINED YAW MOMENT		1566.043159 Nm	$Yaw_t = (Yaw_f + Yaw_R) \times \frac{Average\ Track\ Width}{2}$
		angular acceleration	0.373768 rad/s ²
		angular acceleration	21.41533 deg/s ²
		force	1060.033 N
			$F = \frac{T}{r}$
steering angle	L	563.55 N/deg	
	R	520.2 N/deg	
	L+R	1083.75 N/deg	
	steer wheel angle	0.978116 deg	
	hand wheel angle	11.24833 deg	

Figure 8- Yaw Rate calculations made in Microsoft excel

According to research, the typical cornering stiffness is 867N/degree. The overall stiffness of the steering wheel angle is computed by multiplying the cited value by the matching road surface μ value, producing 1387.2N/degree. The wheel angle is roughly 0.764 degrees once the computed lateral force is divided by that of the overall cornering stiffness. The necessary handwheel angle is 8.788 degrees to the left may be calculated using the FF's road/hand wheel ratio, because as car will prefer to steer further toward the low μ route.

14) How the AWD system will inter-react with other vehicle dynamic control systems

Electrical control systems are extensively used in cars to observe the cars behaviour thus potentially improve the safety of the driver and the cars dynamics. Numerous sensors collect data and communicate with the car's ECU in order to control and optimise performance of the vehicle. This system can improve anything from steering angle to desired torque delivery to accelerator pedal, all the driver's action are monitored, and this system improve the vehicles performance.

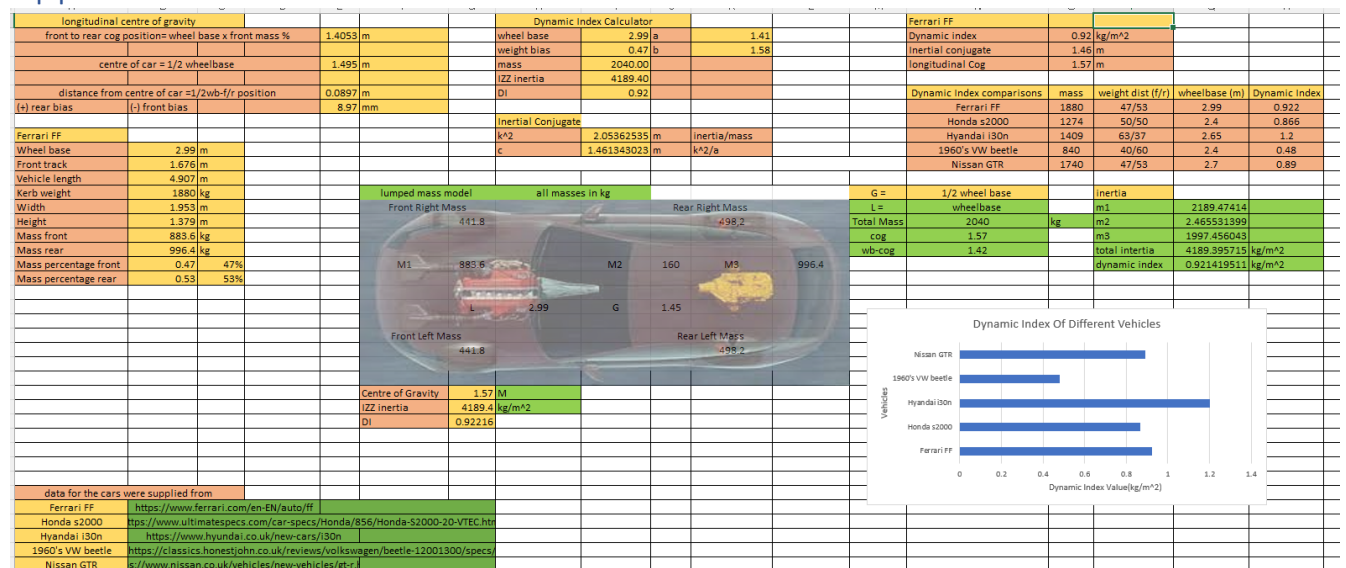
Anti-lock brakes (ABS/EBD) are included on the FF and work independently for each wheel. Because of the analogue ABS ring detecting methods, the ABS as well as wheel speed sensor are frequently matched. Wheel velocities are generally determined by the pace at which the ABS ring passes the sensor. When the ABS sensors detect that the wheels have stopped rotating under hard braking, they begin to reduce the braking force provided until the car slows down without wheel lock.

F1-Trac traction control, regulates torque and directs power to the rear wheels via E-Diff. Roll and yaw sensors assist the ECU in determining the position of the vehicle throughout manoeuvres, allowing it to recognise if overrun develops in low frictional turning. Electronic stability control (ESC) is a mechanism that monitors stability and traction. There different settings on the steering wheel to adjust the amount of wheel slip the system allows for different driving condition these setting are;

- Comfort
- Sport
- Wet
- Ice and Snow
- ESC off

16) Conclusion

To conclude, the clever 4RM system was tested based on a variety of car estimations and calculations. The part-time all-wheel drive technology is clever in that it gives the driver the exciting sense of a rear wheel drive yet maintaining the safety features of an all-wheel drive via varying road conditions. The PTU measures a maximum starting acceleration of 9.81m/s^2 including all tires on dry asphalt. Ferrari's design and vehicle structure allow for a balanced mass distribution, resulting in improved performance, driving quality and handling.





Appendix B

		torque vectoring AWD			RWD open differential		
Wheel base	2.99	initial acceleration			initial acceleration		
track rear	1.66	rear axle mass	996.40	kg	rear axle mass	996.40	kg
track front	1.68	per corner	498.20	kg	per corner	498.20	kg
mass	1880.00	forces acting on each wheel	4887.34	N	forces acting on each wheel	4887.34	N
weight front	0.47	traction force right (rear)	4887.34	N	traction force right (rear)	4887.34	N
weight rear	0.53	traction force left (rear)	1221.84	N	traction force left (rear)	1221.84	N
inertia	4189.40	total possible traction (rear)	6109.18	N	total possible traction (rear)	2443.67	N
tyre stiffness mu	1.00						
road wheel / steering wheel ratio	0.05	front axle mass	883.60	kg	max initial acceleration	1.30	m/s²
road surface mu left	0.25	per corner	441.80	kg			
road surface mu right	1.00	forces acting on each wheel	4334.06	N	RWD E-diff		
		traction force right (front)	4334.06	N	initial acceleration		
		traction force left (front)	1083.51	N	rear axle mass	996.40	kg
		total possible traction (front)	5417.57	N	per corner	498.20	kg
					forces acting on each wheel	4887.34	N
		total combined tractive force	11526.75		traction force right (rear)	4887.34	N
					traction force left (rear)	1221.84	N
		max initial acceleration AWD-TV	6.13	m/s²	total possible traction (rear)	6109.18	N
		hand wheel angle required			max initial acceleration	3.25	m/s²
		asymmetric drive force	3250.54	N			
		Moment	4859.56				
		cog	1.58	m			
		lateral force on axle	2051.20	N	surface	max accel 4RM	RWD open differential
		low mu lateral force	410.24		asphalt road	9.81	5.19 (m/s²)
		high mu lateral force	1640.96		wet asphalt	5.69	3.01 (m/s²)
		lateral tyre stiffness	1500.00	N	loose gravel	2.90	1.55 (m/s²)
		slip angle required assuming ratio of 1:10	10.94	degrees	compact snow	1.69	1.03 (m/s²)

Appendix C

Engine speed		6000	rpm	Equations		
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Inner plate diameter	r1	0.105	m			
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