Fuel Consumption, efficiency and pollution

For both vehicles, rule 13.14 states a minimum fuel cell volume of 110L, allowing the vehicle to lap 12 times the Le Mans circuit (FIA, 2023) (IMSA, 2023).

Table 1. Fuel consumption comparison

	Fuel Consumption					
	Fuel Consumption/Lap (kg)	Fuel Consumption/Lap (L)	CO2 emissions per lap (kgCO2)	Fuel Energy Consumption/Lap (MJ)	Engine Energy Consumption/Lap (MJ)	Powertrain Efficiency (%)
LMH	2.49	3.30	7.62	98.53	55.29	51.08%
LMDh	2.54	3.36	7.77	100.32	59.95	45.52%

As the LMH has a greater MGU-K input, LMDh consumes more fuel per lap, achieving lower powertrain efficiency. This efficiency can be further improved, the topic will be treated later.

Improved efficiency would lead to lower fuel consumption, improving the laps per stint and overall race pace.

Assuming a 110L fuel load, the LMH could do 33 laps per stint, while the LMDh would do 32, due to the higher fuel consumption.

As the LMDh consumes more fuel, its pollution levels will be higher.

Fuel density was assumed to be 0.755g/cc (ELF, 2023), and CO_2 emissions were assumed to be 2.31kgCO_2/L.

Table 2. Lap-time comparison

Laps Comparison					
Time per Lap (S.mm)	Laps per Stint	Estimated pit stops	Laps in 24h	Estimated time difference at completion (S.mm)	Estimated CO2 emissions (kgCO_2eq/L)
246.556	33	11	351		2674.06
246.968	32	11	350	102.36	2719.99

The estimated per vehicle emissions are negligible compared to the emissions created by the event organization, at an average value of 3,363 MTCO_2eq (McCullough, 2023).

Power at the Drive Shafts, Power Deployment

For both vehicles, rule 5.1.2. limits powertrain power to 500kW ±20kW.

For the LMH, rule 5.3.2. states that the MGU-K power must not exceed 200kW and rule 5.3.2.2 indicates that the MGU-K power must be delivered only to the front axle (FIA, 2023).

For the LMDh, rule 5.3.2. indicates that both the engine and MGU-K power must be delivered to the rear axle (IMSA, 2023).

We encounter the following two situations.

Table 3. Maximum engine power output at the drive shafts

	Power at the Shafts (kW)						
	Drive type	Engine Output	MGU-K Output	Front Shafts Power	Rear Shafts Power	Total Output	Mechanical Efficiency (%)
LMH	RWD	528.29	0	0	500.3	500.3	94.70%
LMDh	RWD	528.75	0	-	504.95	504.95	95.50%

- For maximum engine power output, both vehicles behave as RWD, and no MGU-K power is outputted.

Table 4. Maximum MGU-K power output at the drive shafts

	Power at the Shafts (kW)						
	Drive type	Engine Output	MGU-K Output	Front Shafts Power	Rear Shafts Power	Max. Total Output	Mechanical Efficiency (%)
LMH	4WD	339.4	187.87	180.4	317.06	497.46	94.35%
LMDh	RWD	501.59	30.39	-	505.03	505.03	94.93%

- For maximum MGU-K output, injection is cut, reducing the engine output. LMH drive type is now AWD, while LMDh remains RWD.

We can observe that AWD systems lead to lower mechanical efficiency, as the power loss in the gearbox is higher than in RWD or FWD systems.

In both vehicles, powertrain efficiency is improved when the MGU-K is engaged.

This could be further improved, utilizing, in the LMH, the allowed 200kW and, in the LMDh, the 50kW for which the Bosch MGU-K is rated for, reducing the need for engine power in hybrid mode.

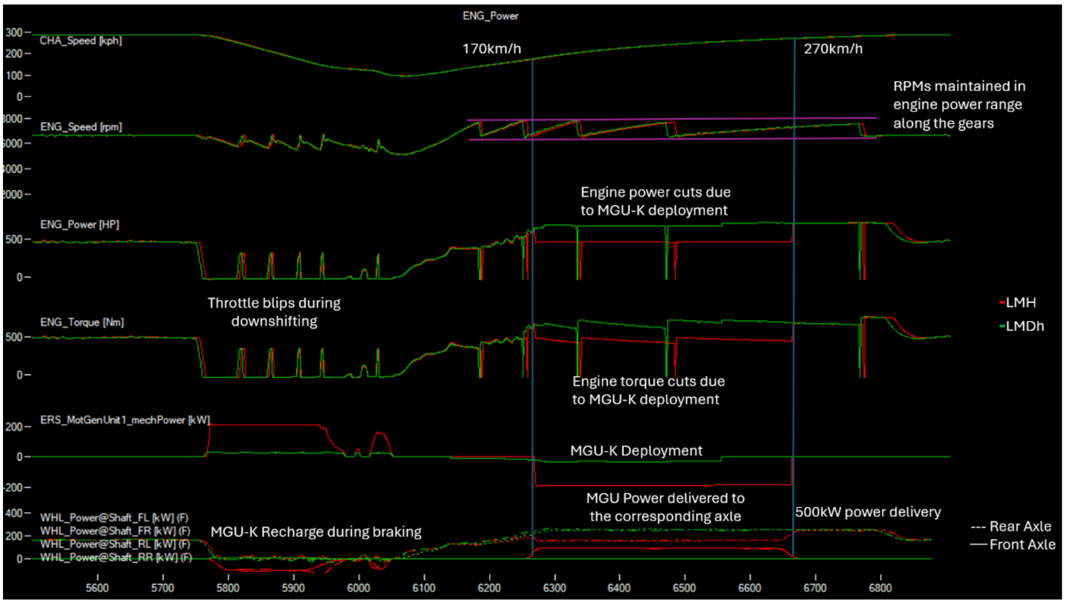

Figure 1. Engine and MGU-K power output at the drive shafts

Determined by the BoP, the activation of the MGU-K is limited to the range of 170-270km/h for both vehicles.

The geometric progression between gears, seen on the engine RPMs, prioritizes the torque output. For both vehicles, assuming that 4th gear is a direct gear, gear ratios are the following:

Table 5. LMH & LMDh transmission gear ratios

Transmission							
Gear 1	Gear 2	Gear 3	Gear 4	Gear 5	Gear 6	Gear 7	Final Drive
	1.415	1.205	1	0.839	0.711	0.614	4.77

Aero Balance and Mechanical Balance

Aero balance matters most on high-speed cornering stability, inducing understeer when rear-biased and oversteer when front-biased, and in braking events, inducing understeer when front-biased and oversteer when rear-biased.

A forward-biased aero balance can help with drivability, but make steering harder due to the incremented front wheel loads.

A rear-biased aero balance can help the car rotate in corner entry, but make its behaviour unstable (Segers, 2014).

Comparing the Porsche curves with Mulsanne, as examples of high and low speed corners, we can also see how, as speed is reduced, downforce is reduced, which in turn increases the ride height, further reducing the aerodynamic efficiency of the vehicle.

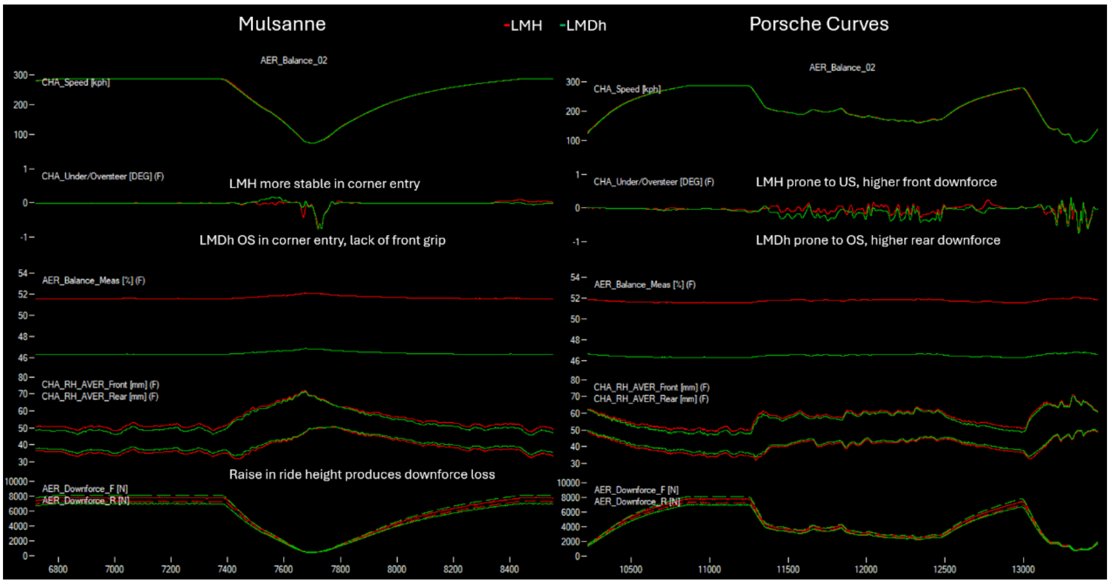

Figure 2. High and low speed aero balance corner comparison

On Mulssane, the LMH does not experience understeer or oversteer on corner entry due to the balanced aerodynamic loads, whilst the LMDh experiences some US due to the lower front wheel load. Mid and corner exit behaviour are dictated by mechanical balance and driving style.

On the Porsche curves, behaviour is dictated by the aerodynamic balance. The LMH is prone to understeer due to the higher front-biased aero, whilst the LMDh is prone to oversteer due to the rear-biased aero.

BoP regulations limit Cl/Cd to 4.1 (Walravens L., 2025), both vehicles are under this limit.

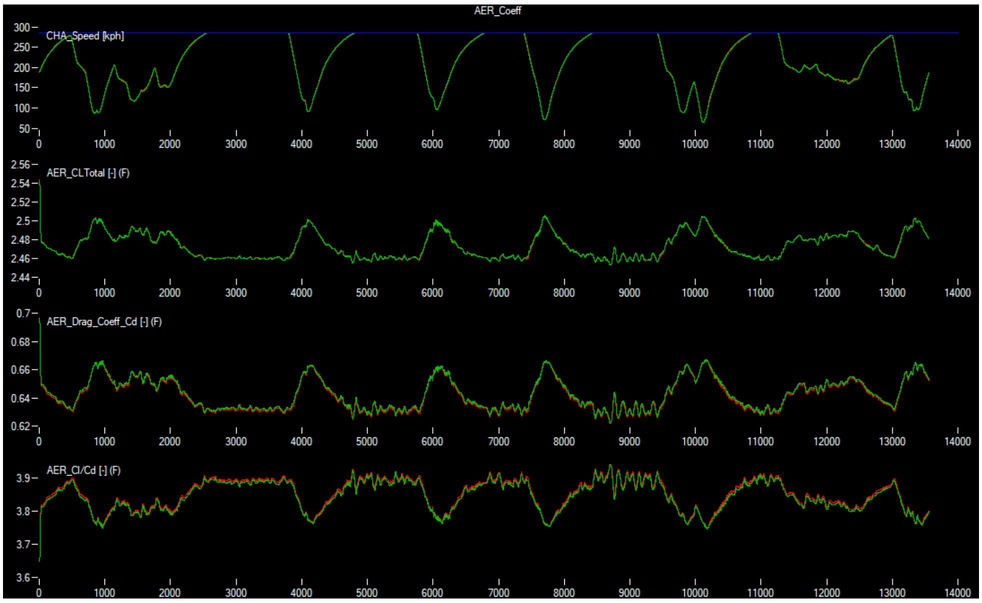

Figure 3. Lift-to-drag ratio along the circuit

For both vehicles, rule 4.1. states that the vehicles must achieve a dry weight no less than 1030kg, adjusted by BoP, while rule 4.3. indicates that cars must allow up to 50kg extra in ballast for BoP adjustment (FIA, 2023) (IMSA, 2023).

The weight of the vehicle has an effect on the load transfers, changing the mechanical balance. Both vehicles weigh around 1150 kg.

Mechanical balance refers to the distribution of grip along the vehicle, from suspension settings, weight distribution and tyre selection, disregarding the effects of aerodynamics over the tyre loads (Segers, 2014).

It is expressed as Lateral Load Transfer on cornering and Longitudinal Load Transfer on braking and acceleration.

Table 6. LMH and LMDh suspension settings

Suspension set-up			
		LMH	LMDh
Ride Height (mm)	Front	67.6	97.21
	Rear	70.26	92.61
Spring Rate (N/mm)	Front	478.52	524.13
	Rear	559.54	505.87
Damper Rate (Ns/mm)	Front	~14,000	~14,000
	Rear	~15,000	~15,000
ARB Stiffness (Nmm/deg)	Front	8,253.64	8,345.37
	Rear	4,678.73	4,170.79

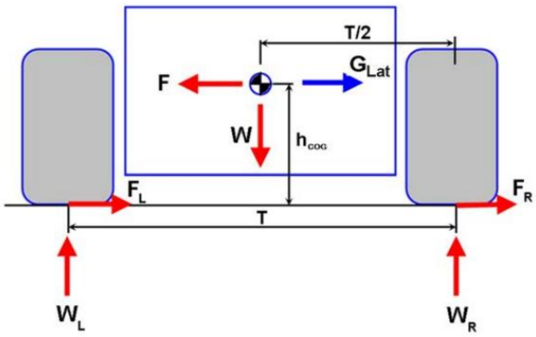

Figure 4. Lateral weight transfer for a right-hand turn (Segers, 2014)

Lateral and longitudinal Load Transfer are calculated to characterize the mechanical balance.

Load transfer differs between the front and rear axle, but the value is calculated as average for the vehicle.

Table 7. Mechanical balance

	Mechanical Balance (%Front)			
	Static	Under Braking	High-Speed Cornering	Low-Speed Cornering
LMH	50.25%	62.44%	68.92%	54.90%
LMDh	50.31%	60.35%	68.50%	51.90%

Aerodynamically induced forces are not considered. We examine the effects of mechanical balance on load transfer. We can also conclude that the roll stiffness is greater at lower speeds, as load transfer in high-speed cornering is higher.

The Centre of Pressure should not be in front of the Centre of Gravity. This would cause rear instability. Both vehicles maintain their Cp behind the CoG during braking.

Table 8. CoG and Cp positioning on vehicle length

	CoP (%Front)		Cp (%Front)	
	Static	Under Braking	Static	Under Braking
LMH	50.25%	62.44%	51.57%	52.58%
LMDh	50.31%	60.35%	46.30%	47.30%

Chassis Handling (Understeer/Oversteer)

Rule 10.2.1 states that any adjustment of suspension settings other than ARB stiffness is prohibited. ARB stiffness is not modified during the lap.

To categorize the roll stiffness, we compare roll angle with lateral acceleration (Segers, 2014). The slope of the trendline indicates the roll gradient.

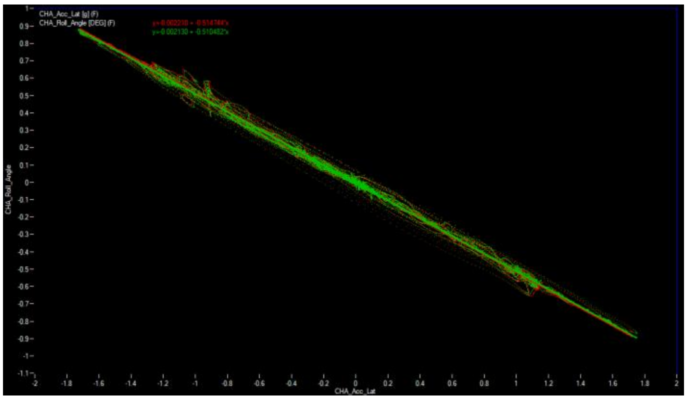

Figure 5. LMH and LMDh Roll Gradient

We can conclude that the roll is 0.51 degrees per G of lateral acceleration in both vehicles.

Account for suspension settings, we plot both axles independently.

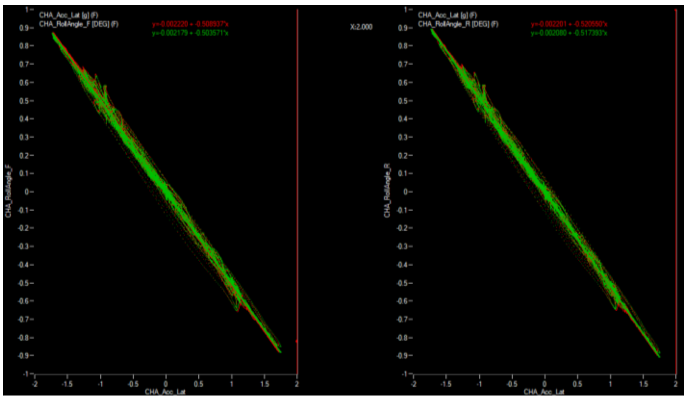

Figure 6. Front and rear roll gradients

In this case, both vehicles have a stiffer rear axle, confirming the similarities in suspension settings. The LMH roll gradient is slightly higher.

Table 9. Chassis roll characteristics comparison

Chassis Handling			
		LMH	LMDh
Vehicle Roll Gradient	deg/G	0.5147	0.5104
Roll Ratio		1.024	1.028

To analyse the response to steering inputs, we compare the steering inputs to the yaw rate.

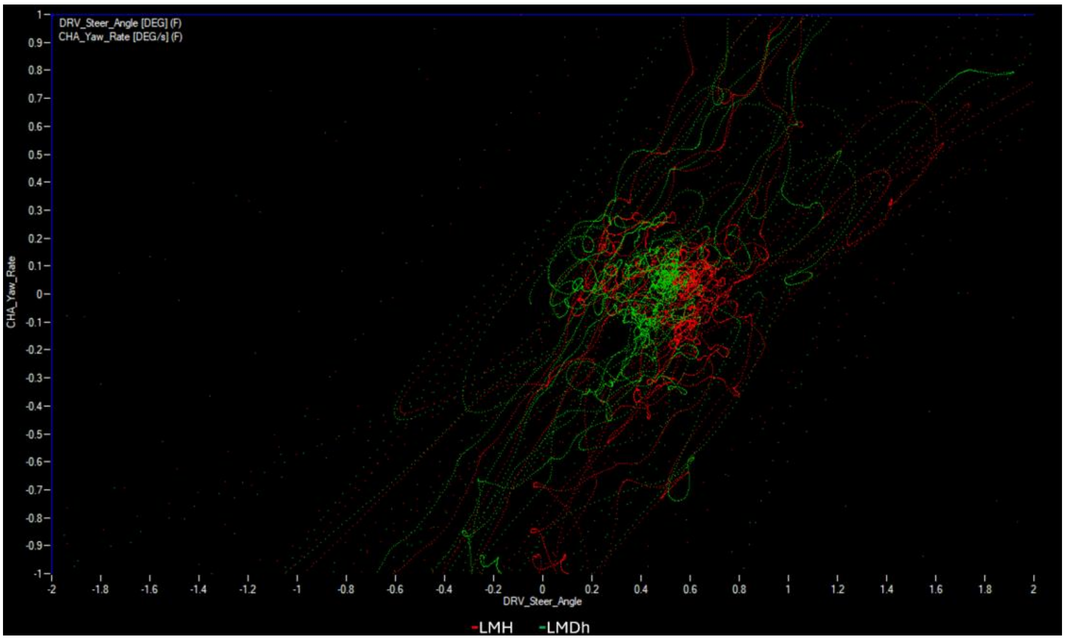

Figure 7. Vehicle response to steering inputs

As we see a small variation in yaw rate compared to the steering input, we can confirm a well-balanced vehicle.

It's also noticeable how the data points on the LMH are more present on the right side of the graph, indicating a higher steering input than the LMDh.

The chassis handling balance can be further analysed by comparing the tyres slip angles with their under/oversteering response.

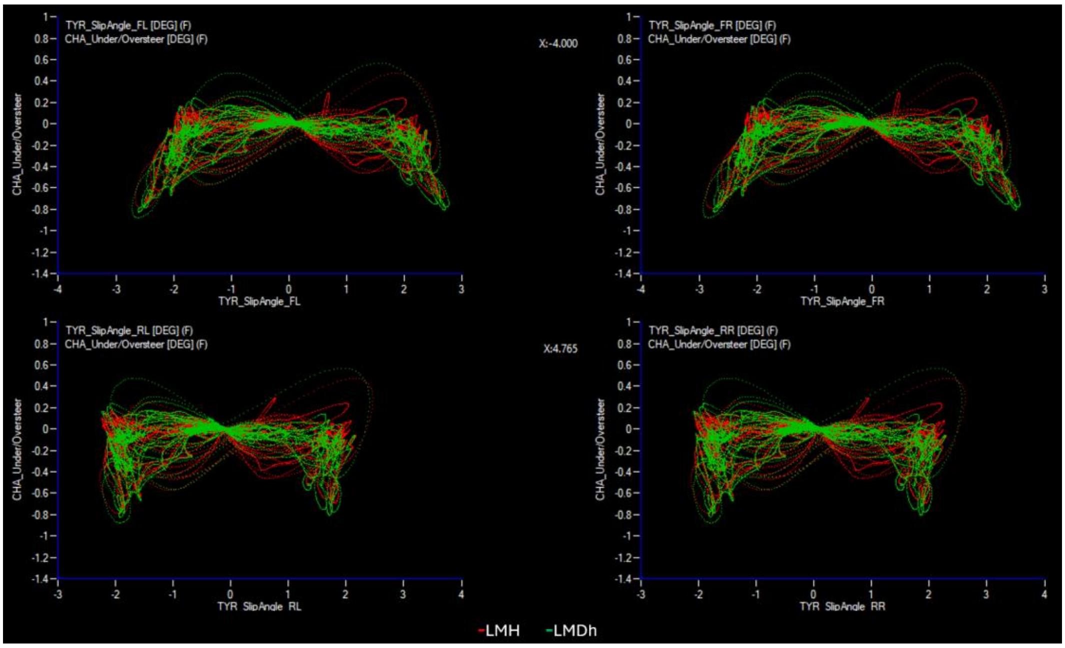

Figure 8. Under/Oversteering response to slip angle

Both vehicles are more prone to oversteer, specially the LMDh on higher slip angles. This tendency indicates a lack of rear-end grip during cornering, as well as an aggressive driving style, covered later on the document.

The tendency of the rear wheel data points towards negative slip angle values indicates a greater presence of right-hand corners on the circuit.

Comparing high-speed with low-speed corners, such as Mulsanne and Porsche, we discuss the effects of lateral acceleration and body roll on chassis handling.

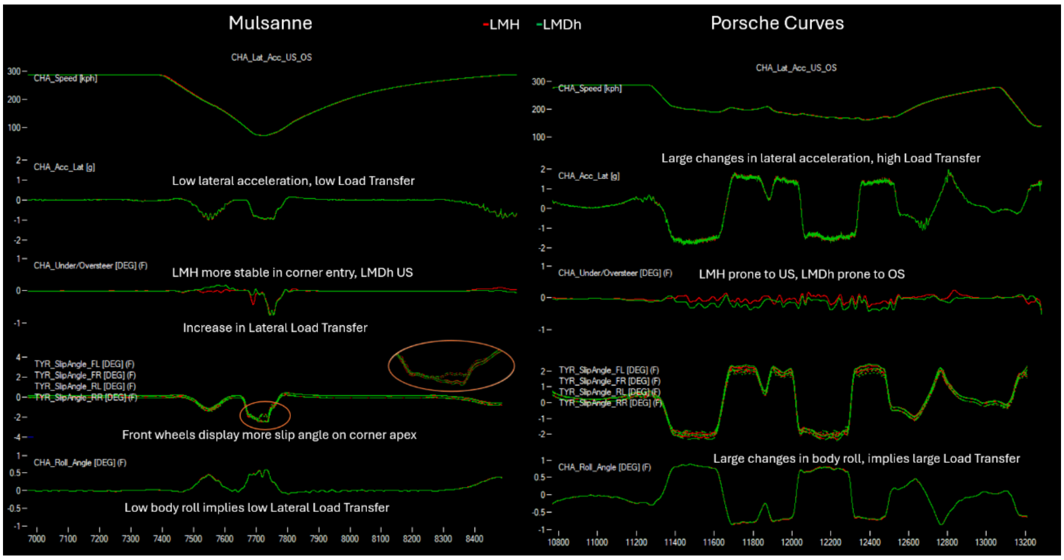

Figure 9. Effects of body roll and lateral acceleration on chassis handling

We can see that chassis handling on high-speed corners is more dependent on aerodynamics, as larger lateral accelerations and body-roll on Porsche have less effect on under/oversteering than in Mulsanne, confirming what was previously mentioned on the "Aero-balance" section.

On Mulsanne, LMDh displays some corner entry understeer, induced by the lack of front axle load. Corner exit oversteer will be touched upon on the driving style.

Tyre Saturation and Tyre Energy

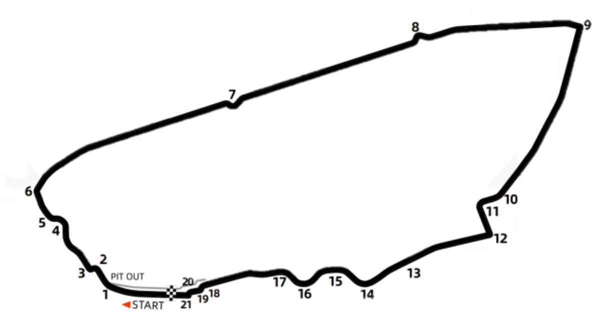

Figure 10. Circuit de La Sarthe

To discuss tyre behaviour, we need to understand the track. Le Mans is a track where most of the turns are right-handed, this will indicate which side will consume more energy and wear out sooner.

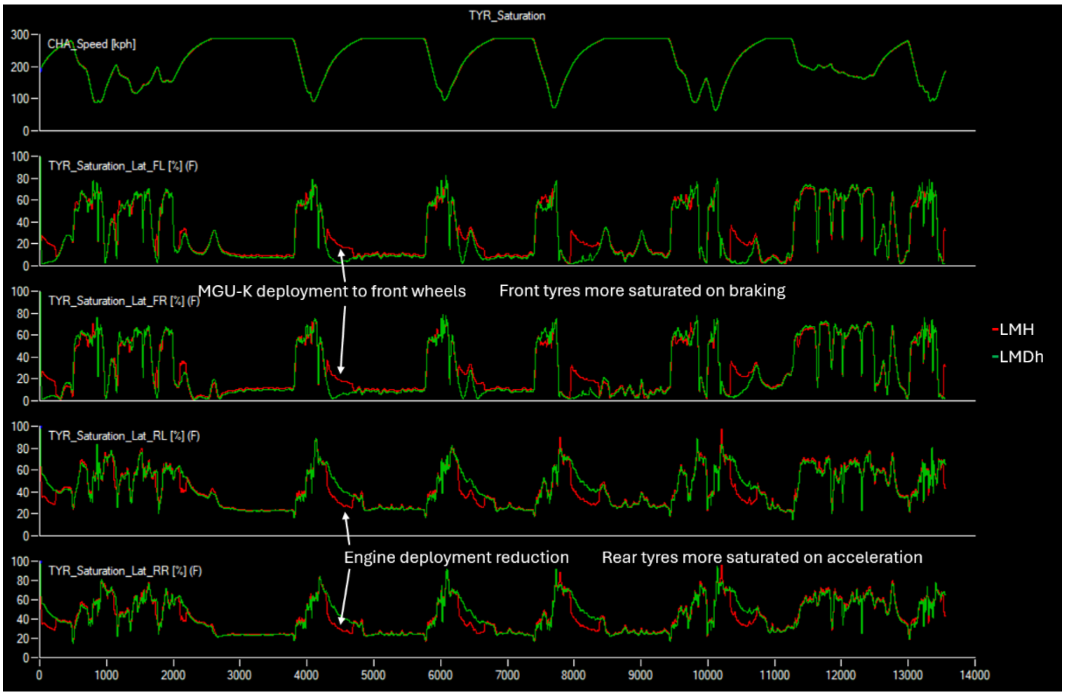

Figure 11. Lateral tyre saturation for LMH and LMDh

Looking at tyre saturation, we can see that the rear axle is more saturated over the lap, as the engine is always providing torque to the rear axle.

As saturation on the LMH front tyres increases and saturation on the rear tyres decreases, MGU-K deployment on the LMH is noticeable, improving stability on corner exit.

Due to longitudinal load transfer, front tyres are more saturated on braking while rear tyres are more saturated on acceleration.

Table 10. Tyre energy consumption distribution over the lap

	Tyres cumulative energy (kJ)			
	FL	FR	RL	RR
LMH	571.39	500.33	821.47	771.41
LMDh	542.55	488.27	884.86	836.89

LMH Tyre energy distribution	
21.44%	18.78%
30.83%	28.95%

LMDh Tyre energy distribution	
19.71%	17.74%
32.15%	30.40%

Looking at the tyre's energy consumption, most of the energy goes to the rear axle, indicating that the rear tyres will wear out sooner, especially the rear left.

We can notice how the power distribution in the LMH is less rearward biased, due to the deployment of the MGU-K on the front axle, this will mean more even tyre wear, allowing for a longer stint than the LMDh.

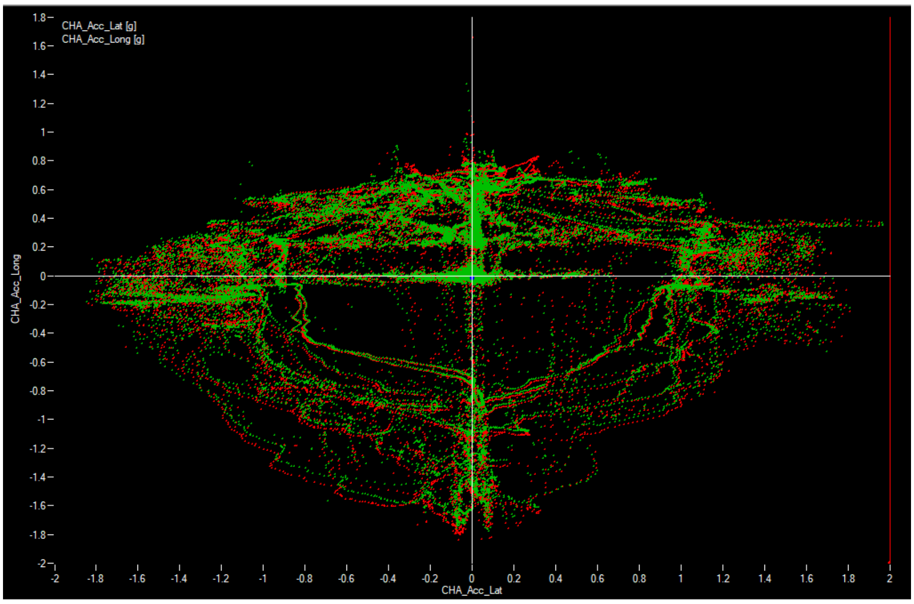

Figure 12. G-G Diagram

The G-G diagram indicates the grip limits of the tyres.

The LMH shows more longitudinal acceleration than the LMDh, indicating that the LMH has a better deployment of power and braking force.

The LMDh shows less lateral acceleration under acceleration and braking conditions, suggesting greater stability than the LMH.

As the data points are concentrated on the positive longitudinal G and negative lateral G, it suggests that the car's set-up should focus on maximizing acceleration on right-hand corner entries (Segers, 2014).

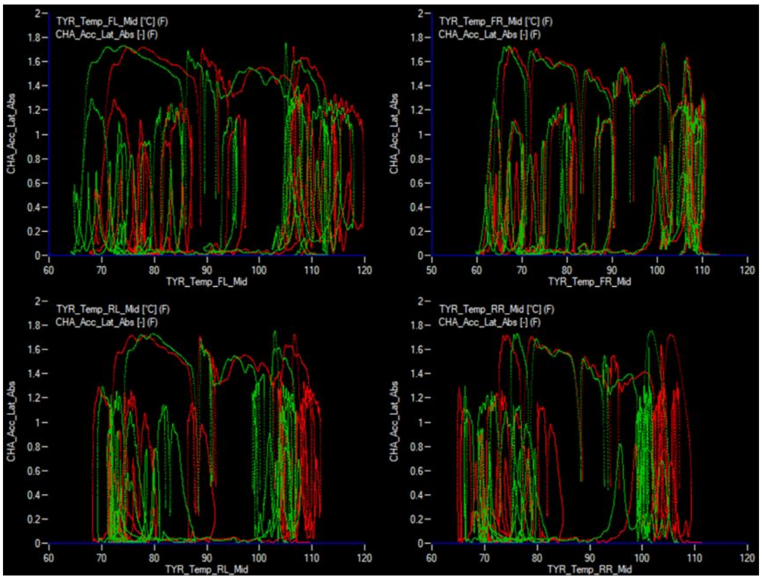

Figure 13. Optimal tyre temperature range

We can determine the optimal tyre temperature by comparing the temperature with the absolute lateral acceleration (Segers, 2014).
In this case, the data points are too concentrated at low and high temperatures to draw any conclusions.

Driving Style

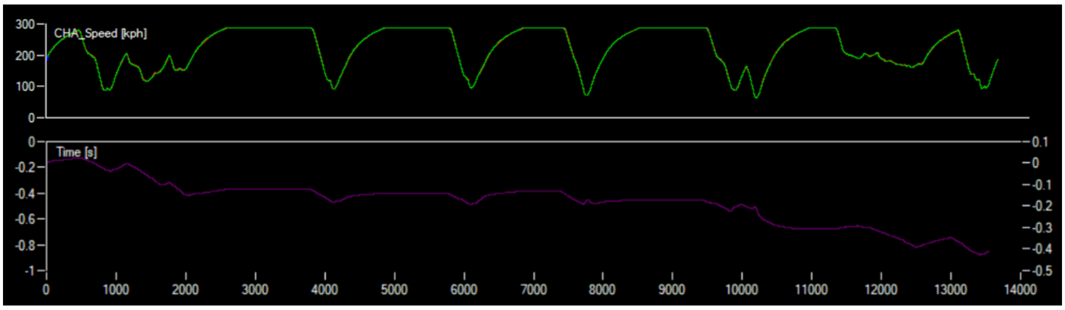

Figure 14. Time difference between the cars

Looking at the speed graph, both drivers have been instructed not to go faster than 286km/h.

Comparing the time difference between the cars with the speed, the LMDh loses time consistently in the corners, while maintaining the delta on the straights. This indicates a sub-optimal use of the brake and accelerator pedals.

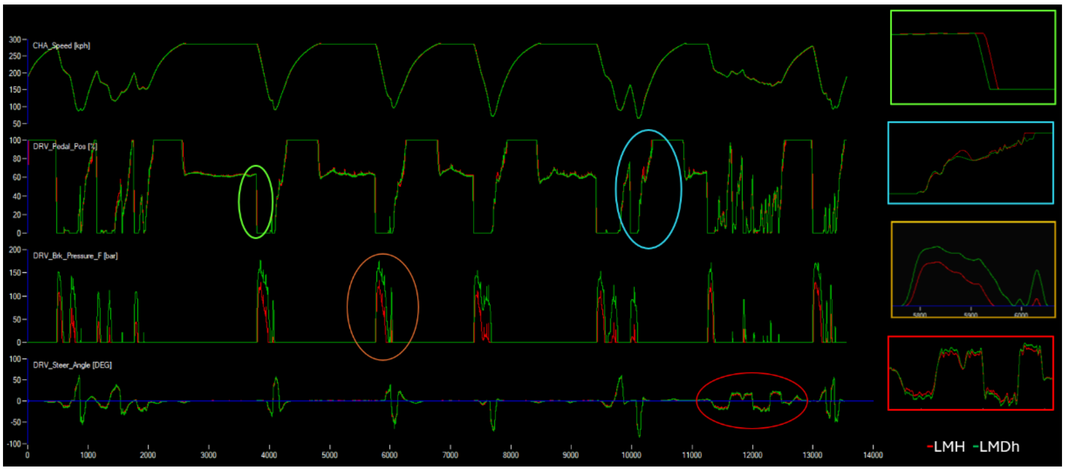

Figure 15. Driver input telemetry

- Accelerator pedal: The LMH driver applies a more aggressive approach with the throttle application, achieving 100% throttle application faster and releasing the throttle closer to the corner, while the LMDh driver is more progressive with throttle application.
- Brake pedal, the LMH driver brakes later, shows a more gradual braking application and slows down the vehicle for a shorter period of time. Although more decisive with the braking, LMH is not using ideal braking.

Ideal braking applies peak pressure at the beginning, maximizing the tyre's grip, and be releases it progressively, avoiding overloading the tyres and a better turn-in into the corner.

- Steering input, the LMH driver applies smoother corrections to their steering input and reduces steering input in high-speed corners, indicating a better use of the tyre's available grip, by managing effectively the tyre's slip angle.

Overall, the LMH driving style is more aggressive, utilizing better the vehicle's characteristics, while the LMDh driver shows a more conservative driving style, probably due to the rear-biased aero-balance generating instability on the vehicle.

Individual reflection

Throught this assignment, a deeper understanding of both vehicle dynamics and vehicle telemetry data analysis was gained.

Analysing the vehicle’s fuel consumption, the impact of energy efficiency in creating a viable race strategy and reducing the environmental impact was made clear.

Assessing the power deployment differences between both vehicles, I was able to identify the powertrain components and how the difference in drive types affects vehicle behaviour, allowing me to determine an advantage in the powertrain of the LMH vehicle.

Analysing the aerodynamic balance, mechanical balance and chassis handling, gave me insights into properly thought-out aerodynamics and suspension set-ups and their effects on grip and wheel loads.

Tyre analysis allowed me to discuss their importance on race pace and strategy, as well as giving me an insight into calculating tyre wear and optimal temperature ranges.

The driving style assessment allowed me to identify proper driving techniques and how to apply them.

Further work should include a complete stint, allowing the visualization of wheel load change effects on race pace, tyre wear and chassis handling, and the possibility to realize set-up changes, in terms of energy deployment, aerodynamics and suspension settings, to further analyse the differences between each vehicle.

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