6109MAA Automotive Vehicle Dynamics and Aerodynamics

Vehicle Dynamics Coursework (VD) RESIT

Course

Student name

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Introduction

The study of vehicle dynamics examines how a car will respond to driver inputs on a particular road (Plöchl & Edelmann, 2007). The development of vehicle dynamics in relation to automated driving is necessary because vehicle dynamics will play a crucial role in the realization of such automated driving systems. The objective of this work is to examine the automotive vehicle dynamics and aerodynamics system using Simpack simulation software then compare results with basic hand simulation.

Task One: Behaviour analysis of the standard car in Simpack

The handling characteristics of the regular model standard car can be extracted through the first simulation of the constant radius and double Renault Megane lane change cornering events using Simpack, allowing for the evaluation of the vehicle. The analysis was completed based on ISO 3888-2 double lane change (Robert, 2006) as illustrated in Figure 1.

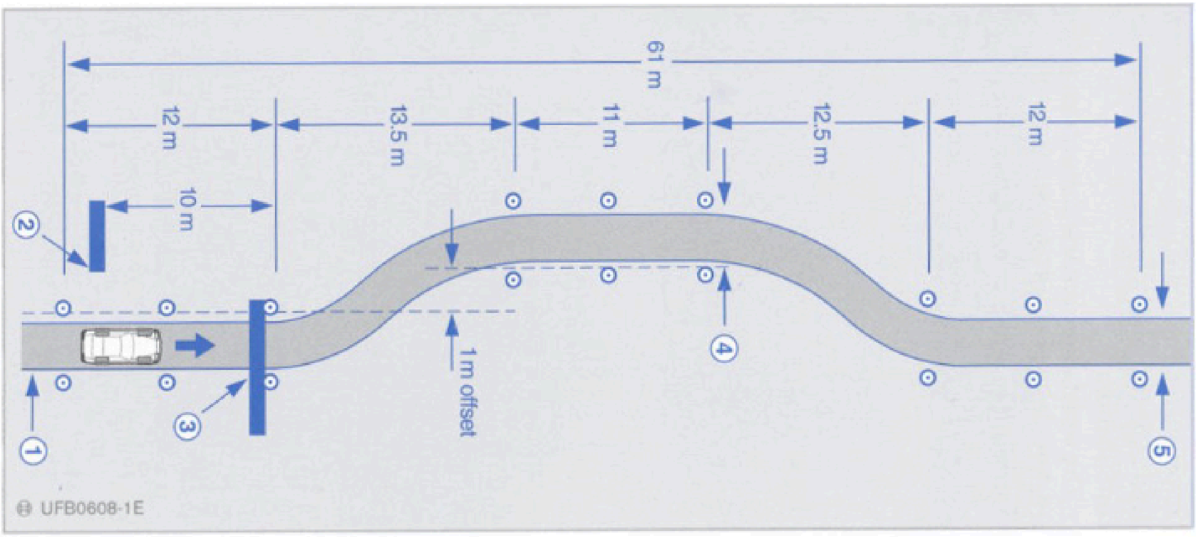


Figure 1: Double line change analysis details (Robert, 2006)

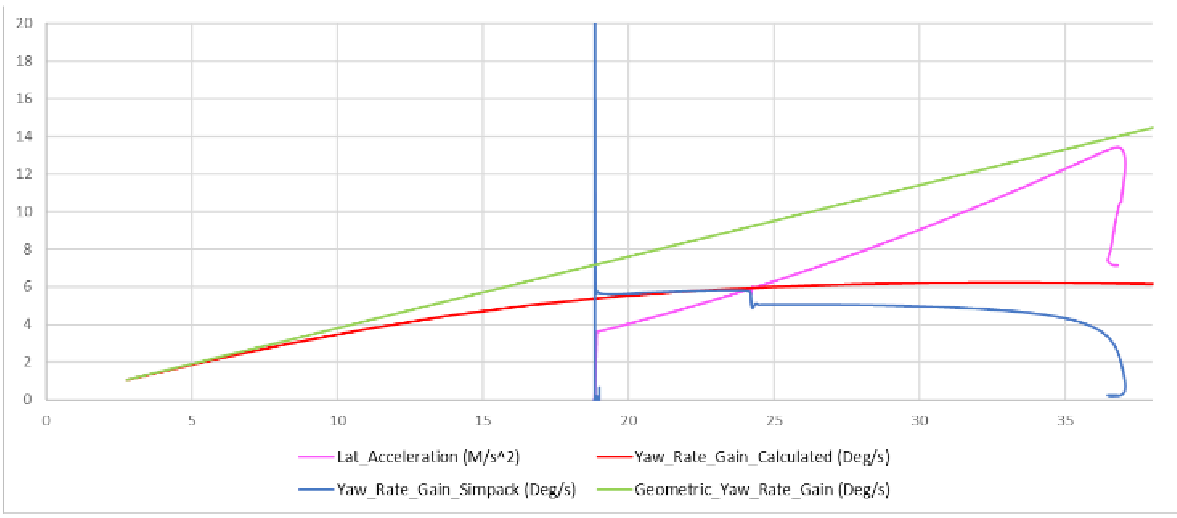


Figure 1: Baseline Standard Car Simpack Data

As the car advanced, the yaw rate gain in the initial CRC simulation in Figure 1 decreased, which implies that the rate at which the vehicle rotated slowed down. To determine how the vehicle reacts dynamically and provide numbers for the yaw rate and the lateral acceleration of the chassis, the double lane change simulation (Figure 2) was completed.

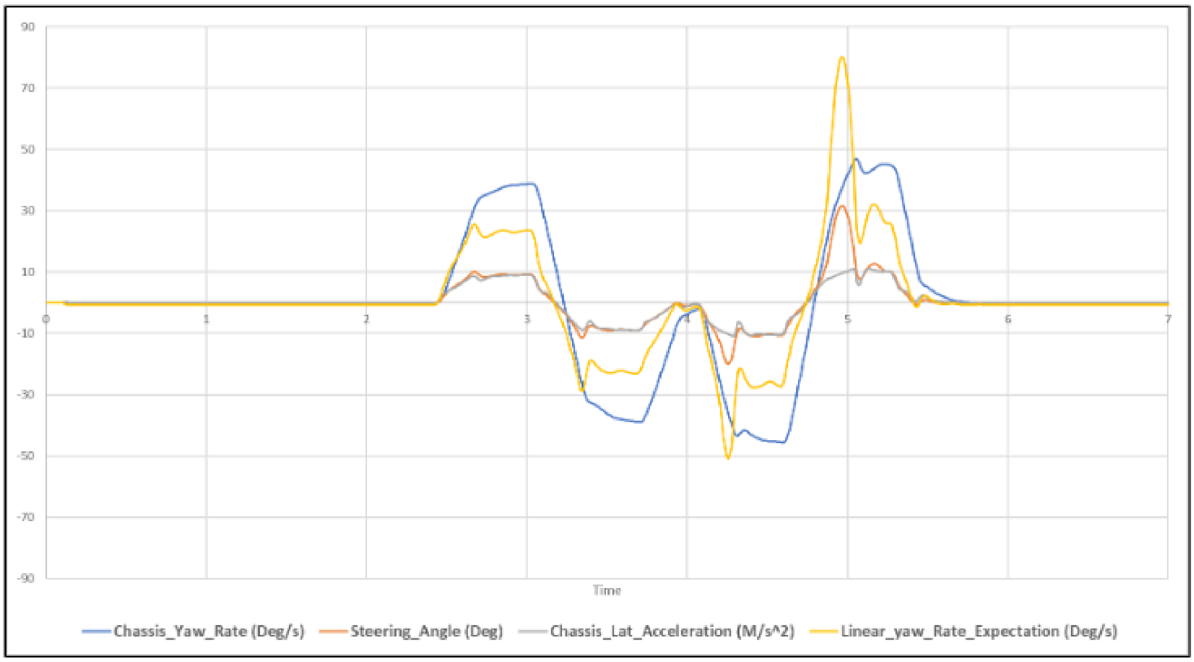


Figure 2: Baseline data for Double lane change model

There were no lateral acceleration spikes during the baseline double lane change manoeuvre (Figure 3). Although lateral acceleration aids in the car's ability to turn when cornering, any spikes could cause a sudden increase in lateral velocity, making the vehicle more difficult for inexperienced drivers to handle and possibly resulting in a total loss of control.

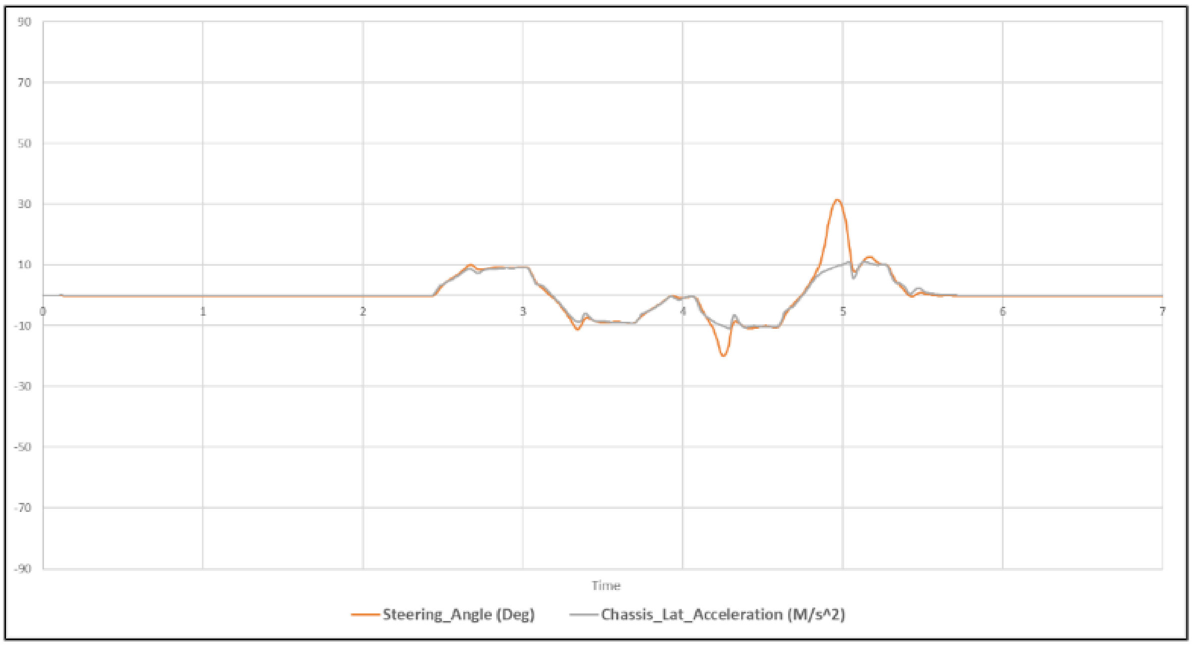


Figure 3: DLC Chassis Lateral Acceleration for Baseline Model

According to the push/spin analysis, the vehicle exhibits more oversteer than understeer. Spin indicates that most of the weight transfer occurs towards the back of the vehicle, increasing the drifting likelihood and reducing the car's capacity to achieve higher cornering speeds (Zhang, 2023). This is preferable for the driver of the vehicle than experiencing more understeer.

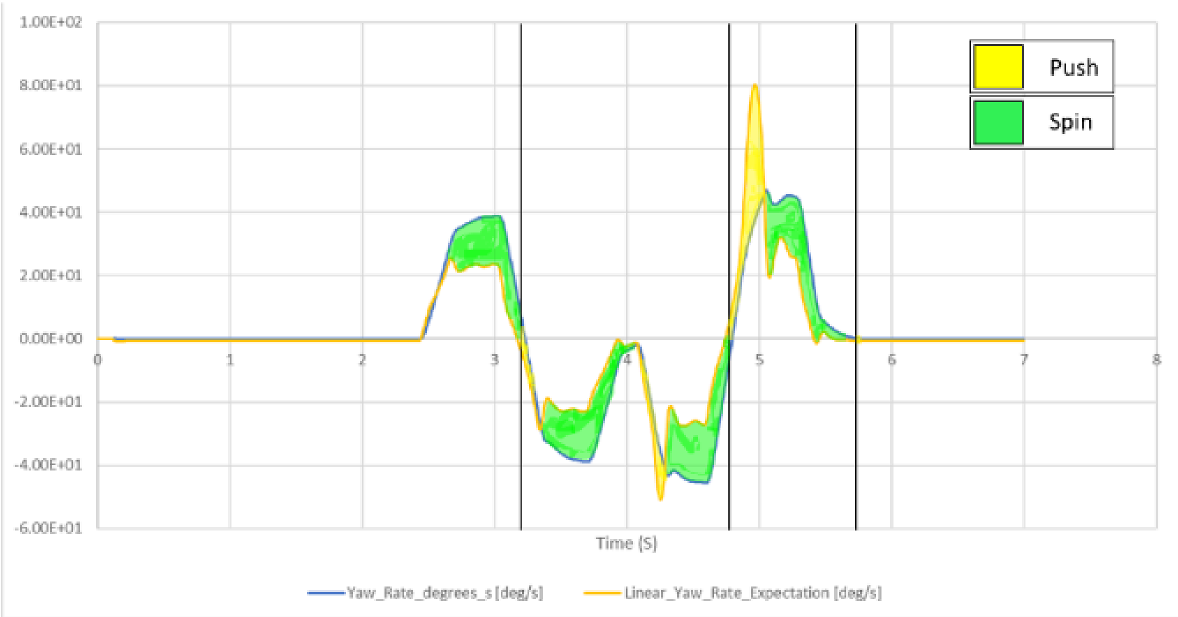


Figure 4: Simulation of the Baseline Model Push and Spin (power and Torque)

The yaw rate gain curve for the simpack model would be made using the yaw rate and steering angle, with velocity serving as the value in the x-axis. The vehicles oversteer, understeer, or neutral steering would be visible on the yaw rate gain curve

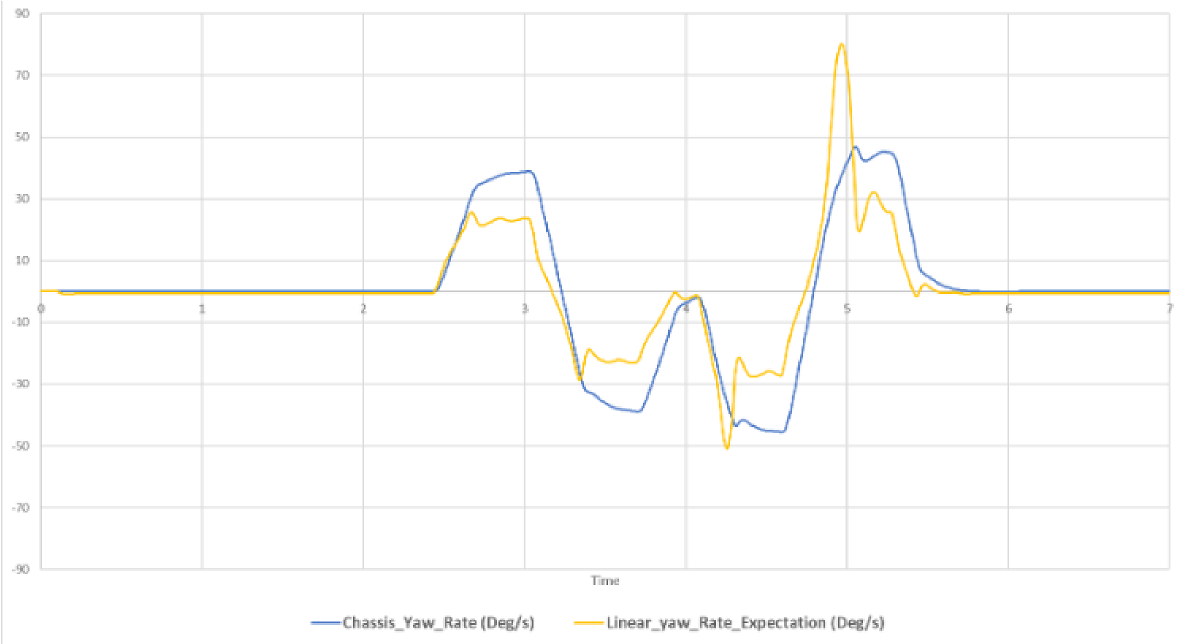


Figure 5: Comparison of the baseline model's yaw rate

A longitudinal acceleration of 1 (M/s2) was achieved in the simulation after the acceleration was stopped after 37 seconds. The metrics were used to evaluate the car's performance and steering.

Task 2: Numerical values extraction based on the behaviour of the standard vehicle

The following are extraction of the Simpack numerical values used for calculations: Finding the "oversteer and understeer allows for the study of the understeer gradient using Yaw rate analysis.

Table 1: Simpack Numerical Extration

Variable	*Unit*	*Renault Megane*
Weight	ib	1700
Front weight	%	40
Yaw moment of inertia	Km^2	865
Wheelbase	ft	9.2
Height (Cg to front axle)	ft	5.7
Total front tire cornering stiffness	Ib/rd	62208
Total front tire cornering stiffness	Ib/rd	96600
Centre of gravity/pressure height	inches	89

i. Weight distribution

$$Wr = \frac{W \, x \, CGf}{WB}$$

$$Wf = W - Wr$$

Where: WB=Wheelbase; wf=Front weight; wr=weight on rare axle; Centre gravity/pressure.

$$Wr = \frac{1700 \text{ x } 89}{9.2}$$

Wr = 2.07

= *1700* - 2.07

= 1697 *lb*

Thus, weight distribution is **1697 *lb***

ii. Natural frequencies

The natural or undamped frequency for the standard car Renault Megane is, Undamped natural frequency is given as,

$$\omega_n = \frac{Y_\beta N_r + N_\beta M u - Y_r N_\beta}{M u I_{zz}}$$

Where,

Damping in side slip derivative, $Y_\beta = C_f + C_r$

$$= 13752 + 11460$$

$$= \mathbf{25212}$$

Lateral force/yaw coupling derivative, $Y_r = \frac{aC_f - bC_r}{u}$

$$= \frac{2.92 * 13752 - 5.41 * 11460}{117.36}$$

$$= \mathbf{-186.12}$$

Yaw damping derivative, $N_r = \frac{a^2 C_f + b^2 C_r}{u}$

$$= \frac{2.92^2 * 13752 + 5.41^2 * 11460}{117.36}$$

$$= \mathbf{3857.1}$$

Static directional stability derivative, $N_\beta = aC_f - bC_r$

$$= (2.92 * 13752) - (5.41 * 11460)$$

$$= \mathbf{-21843}$$

Therefore,

$$\omega_n = \frac{25212 * 3857.1 + (-21843 * 2000 * 117.36) - (-186.12 * -21843)}{2000 * 117.36 * 26734}$$

$$= \mathbf{-0.8022\ rad/s}.$$

The undamped natural frequency for the Renault Megane is, Undamped natural frequency is given as,

$$\omega_n = \frac{Y_\beta N_r + N_\beta Mu - Y_r N_\beta}{MuI_{zz}}$$

Where,

Damping in side slip derivative, $Y_\beta = C_f + C_r$

$= 62228 + 96608$

$= \mathbf{158836}$

Lateral force/yaw coupling derivative, $Y_r = \frac{aC_f - bC_r}{u}$

$= \frac{5.71*62228 - 3.81*96608}{117.36}$

$= \mathbf{-108.68}$

Yaw damping derivative, $N_r = \frac{a^2C_f + b^2C_r}{u}$

$= \frac{5.71^2*62228 + 3.81^2*96608}{117.36}$

$= \mathbf{29237}$

Static directional stability derivative, $N_\beta = aC_f - bC_r$

$= (5.71 * 62228) - (3.81 * 96608)$

$= \mathbf{-12755}$

Therefore,

$$\omega_n = \frac{158836*29237 + (-12755*1719*117.36) - (-108.68*-12755)}{1719*117.36*20500}$$

$= \mathbf{0.5004\ rad/s}.$

b) Critical damping ratio

The damping ratio for the Renault Megane is,

Damping ratio is given as,

$$\zeta = -\left[\frac{N_r + Y_\beta}{2\omega_n I_{zz} Mu}\right]$$

$= -\left[\frac{3857.1 + 25212}{2*(-0.8022)*26734*2000*117.36}\right]$

$= \mathbf{0.0000028}$

The damping ratio for the Renault Megane car is, Damping ratio is given as,

$$\zeta = -\left[\frac{N_r + Y_\beta}{2\omega_n I_{zz} M u}\right]$$

$$= -\left[\frac{29237+158836}{2*0.5004*20500*1719*117.36}\right]$$

$$= \mathbf{-0.000045}$$

iii. Understeer gradient

$$K_{strg} = W_f \frac{r\nu + p}{K_{ss}}$$

Where r - wheel radius = 0.373 m^2; caster angle = 0.129 radp; pneumatic trail = 0.048 mssK; steering stiffness = 3690 N-m/deg.
Thus, Kstrg = 0.34deg/g

Torque:

$$K_{at} = W \frac{p}{L} \frac{C_{\alpha f} + C_{\alpha r}}{C_{\alpha f} C_{\alpha r}}$$

$$K_{at} = 0.28 \deg / g$$

Together with all the elements, total understeer gradient:

K = .28+0.01+0.26+1.02+-2.37e-04+.034+0.28=2.19 deg/g

Understeer gradient for Renault Megane is, **2.19 deg/g**

iv. Stability factor

Stability Factor = T/2H,

where T= “track width”; H =“ vehicles centre of gravity/pressure height”

For Renault Megane is Height = 5.7ft
Centre of gravity/pressure 89inches
Stability Factor = T/2H,

$$\text{Stability Factor} = \frac{2(5.7)}{89}$$

Stability Factor = 0.128

Task 3: Changes to car to improve handling the car in Simpack

Calculations were completed to obtain change in the car to enhance the handling. The desired yaw rate ((r)) can be derived by taking the longitudinal velocity (V), steering response (), wheelbase (L), and stability factor (K) of the vehicle 0.0056 in this case as well as applying it to the CRC event.

$$\omega (r) = \frac{V,\delta}{L (1+K .V 2)}$$

<u>CRC Test Conditions</u>

Yaw rate, steering angle, longitudinal velocity, lateral acceleration, yaw rate gain, and stability factor are all being measured. Final prerequisites:

- 100 meter radius with a start speed of 19 m/s
- end velocity 50 m/s
- Acceleration began at 6 seconds and ended at 37 seconds.
- 26 seconds remain.

<u>DLC TEST Conditions</u>

Yaw rate over time, lateral acceleration, and velocity are all being measured, Requested yaw rate, Angle of Ackerman steering, Final prerequisites: Velocity of 49 km/h (49/3.6 in the simpack file); zero accelerating; Stability factor = 0.128.

A table containing values for the minimum radius and maximum radius for a vehicle traveling at a lateral acceleration of 1-3 (m/s2) from a speed of 10-180 m/s was initially developed to complete the CRC testing. The stability factor of the simpack model data would then be calculated using this to create a yaw rate gain curve. A 100m radius was selected for the test in the CRC test for the simpack model in accordance with the BS ISO protocol. The theoretical chart indicated that 20 m/s was the lowest speed.

The stability factor of the simpack data was estimated for the first portion of the curve that spans from 19 m/s to 24 m/s since the lateral acceleration was utilized to test the tyre linearity model's limit, which is at 5 (M/s2). Therefore, to eliminate the anomaly that appeared at the initial speed in the yaw rate gain curve, the simpack model's initial speed was set to 19 m/s (Figure 1). At the six-second point, the car began to accelerate, with the end speed set to 50 m/s as in the theoretical table.

The CRC simulation demonstrates how the rear of the car is the first to step out and veer off the track. The driver immediately regains control and understeers the vehicle until the simulation is complete. The front and rear anti-roll bars can be adjusted to give the car greater understeer, which would be beneficial in the DLC test. Furthermore, modifying the roll bars would be the most advantageous for a prolonged continuous load (Huang et al., 2023).

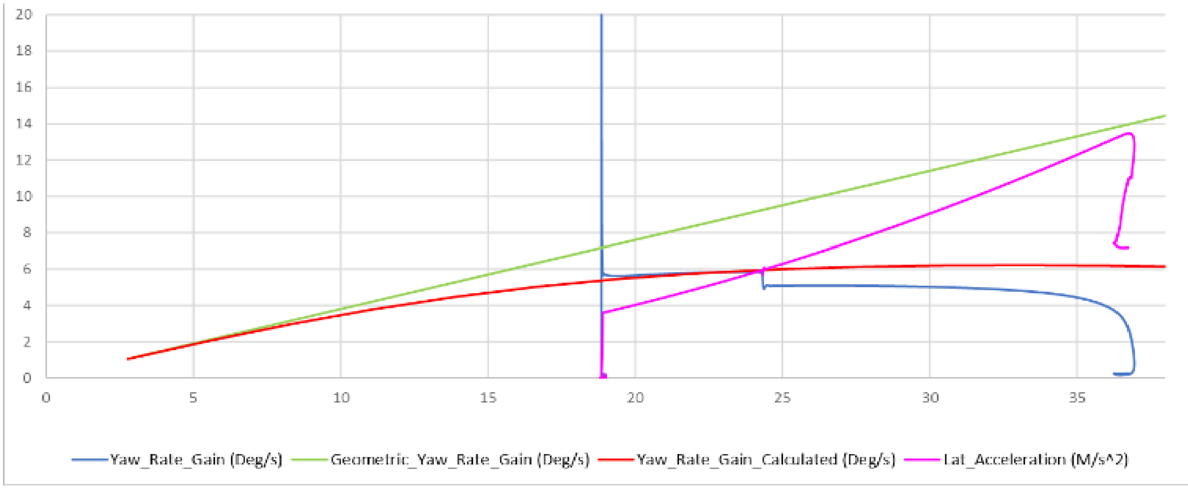


Figure 6: Improved Model CRC Data

Due to (Setup Tips, n.d.), the front roll bar was softened to increase car stability, but it didn't perform as desired so it was stiffened. Since there is nothing to unsteady the car in a simulation, it proved to benefit the performance. The rear roll bar was stiffened to support the rear when under acceleration like on the CRC test.

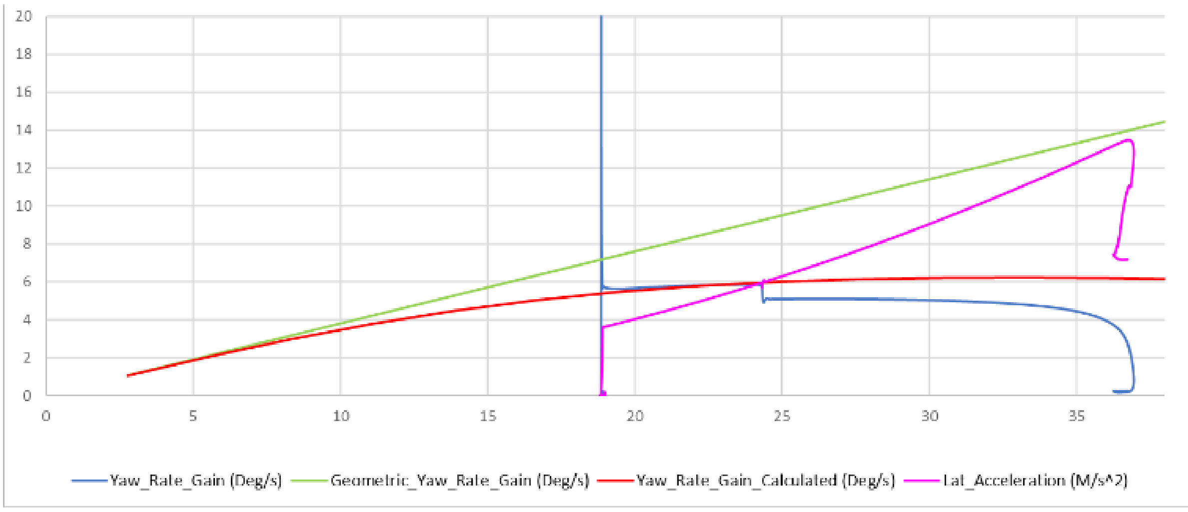


Figure 7: Enhanced model CRC data

The front spring rate was lowered while the rear spring rate was raised for the springs. Stiffening the rear spring rate can lessen oversteer mid-corner, which can assist lessen the understeer gradient, as shown in (Figure 7). To lessen understeer from mid-corner until corner exit, the front spring rate was lowered. As a result of less understeer and more corner entrance stability, the automobile can better navigate the next turn and get back on course.

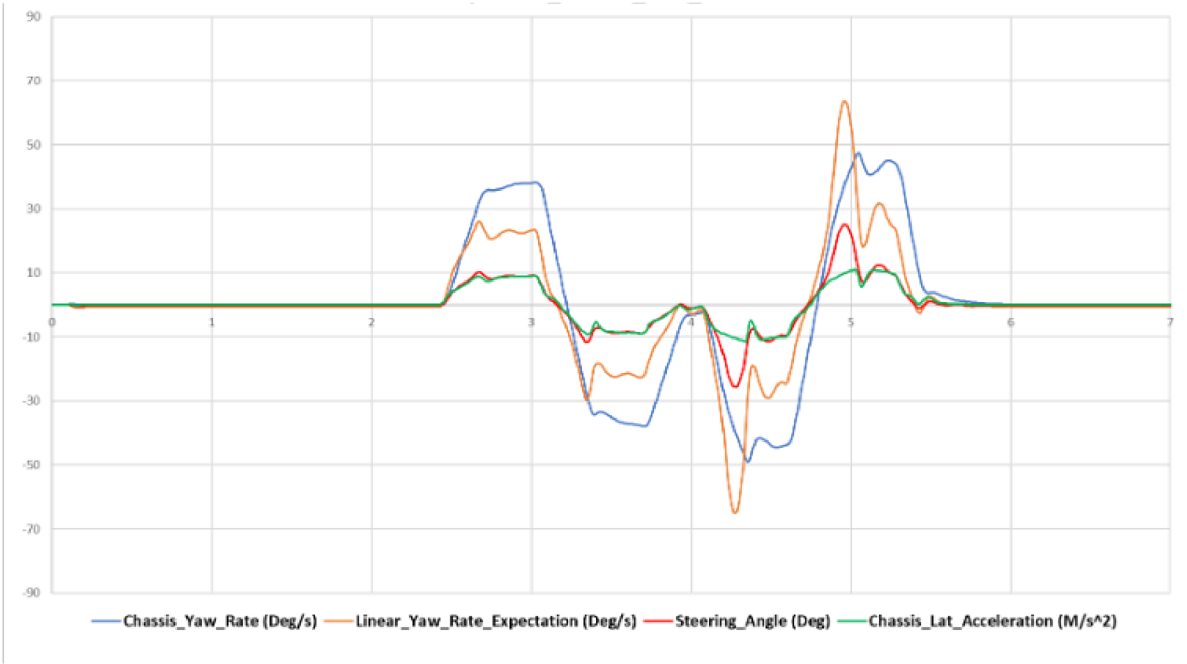


Figure 8: Enhanced Model DLC Data

To manage the behaviour of the automobile mid- to late-corner, slow down the weight transfer, and boost stability, the front damper coefficient was finally increased while the rear damper coefficient was decreased. This allowed the rear mass to travel further and experience a lesser deceleration. To improve the car's responsiveness and reduce frontal body roll, the front was extended.

Table 1: Baseline model parameters changed to generate an enhanced model

Parameter	Hand calculation	Simpack calculation
Front Spring Rate	85,000	78,000
Rear Spring Rate	89,000	100,000
Front Anti-roll bar	25,000	27,250
Rear Anti-roll bar	50,000	57,500
Front Damping Coefficient	6,300	6,900
Rear Damping Coefficient	7,300	6,600

The components of many models that were tested but not implement in the final enhancement have been attached in the appendix A and B.

Baseline and improved models

With the exception of turns 3 and 4, where the expected yaw rate peaks at lower values for the improved vehicles in both turns and the improved vehicles' yaw rate peaks at turn 3, giving it slightly more turning ability than the baseline in that particular turn, the improved yaw rate and the baseline yaw rate are similar. This is evident in the tracking error calculation at turn 4, which was selected because of the challenge it presented to the automobile as shown in Fig 9.

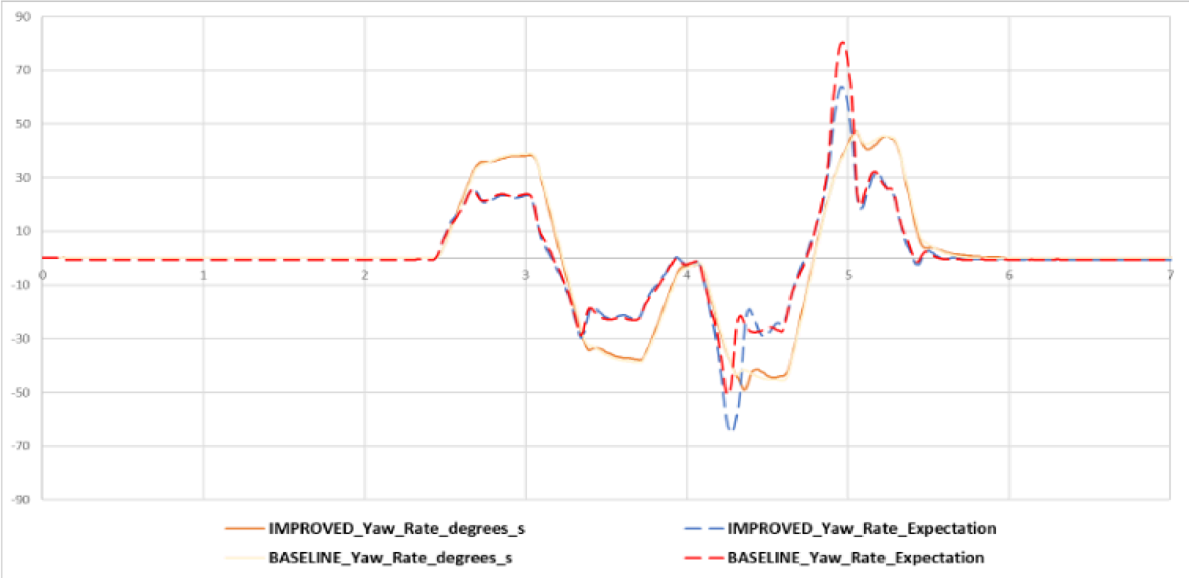


Figure 9: The yaw rate of the baseline and modified models

Tracking error =

$$\frac{\left\| \omega(a) \right| - \left| \omega(r) \right\|}{t(avg)}$$

The tracking error for both the baseline data and the upgraded DLC data was calculated using this equation. The baseline's tracking error was 1.998, whereas the improved baseline's tracking error is 1.598. This demonstrates that there is a difference in how both cars perform on turn 4, as seen in Figure 9.

Task4: Straight line braking test

Pressure wave analysis

The stability factors of the vehicle are significantly influenced by the tires. The characteristics of a tire are essential to the dynamic properties of a vehicle. The most popular models used to analyze tire characteristics are the magic formula, LuGre, and Dugoff's tyre model. The tyres' performance when cornering depends on the vertical force of the vehicle operating on each tire as well as the size of the lateral force. Around a 0.7g lateral acceleration, the vehicle frequently lost control. A larger lateral acceleration, on the other hand, suggests superior handling performance during the corner below the 0.7g threshold.

$$y(x) = D \sin(C \arctan(B x - E(B x - \arctan(B x))))$$

The "D" from the formula is impacted by the normal or vertical force applied to each tire. To maximise the lateral acceleration, the "D" values must be increased. To achieve that, the rate of load transmission between the tyres must be increased.

The simpack model has more lateral acceleration when approaching the corner than the simulator model. The two trend lines are correlated linearly. Simpack assumes that no external influences exist, which results in a smooth curve along the specified speed as shown in Figure 10. When conducting the test, the simulator might have a CRC track with a bigger radius, which would result in a different steering angle input that would directly affect the lateral acceleration. The stability factors of in Fig 1 and Fig13 are, correspondingly, 0.0056 and 0.00084, which are influenced by the following:

i. The vehicle's tilt angle before it rolls over:

$$SSF = \frac{T}{2H} = \tan(\phi),$$

ii. The vertical weight transferred in the front axle on each tire:

$$SSF = \frac{T}{2H} = \frac{v^2}{rg},$$

iii. The angular velocity that the vehicle travels around the curves of radius:

$$F_{LT} = \frac{m a_y h}{T}$$

iv. Around a turn, the impact of surface slope:

$$SSF = \frac{\frac{T}{2H} - \tan(\phi)}{\frac{T}{2H}\tan(\phi) + 1} = \frac{v^2}{rg},$$

As was previously mentioned, the initial configuration of the simulator may have involved a different sort of tyre setting, a higher or lower centre of gravity, or a different track width. Since the SSF depends on the track width and height, adjustments would be needed. The yaw rate, steering angle, lateral acceleration, and raw rate expectation were all displayed in the data representation from the DLC simpack event (Figure 2). Simpack's yaw rate does not correspond to the model's predicted yaw rate for 11 less than 5 seconds, with a similar quantity of variation and a lower degree of yaw rate magnitude than anticipated. The vehicle exhibits greater oversteer than understeer, as shown in (Figure 4).

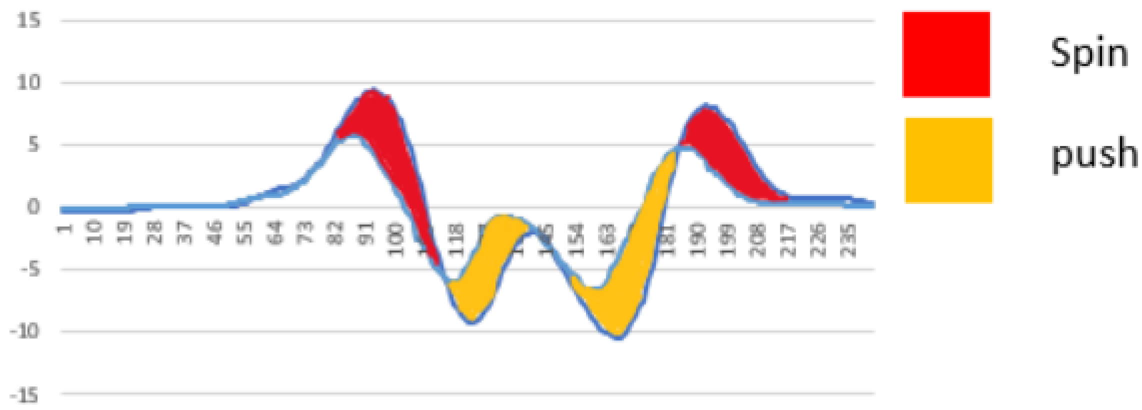


Figure 10: Hand calculation-derived Push and Spin test

The simulated model has less pressure and wave than the simpack DLC data from Figure 10, which indicates that the vehicle responds to demands more effectively and predictably than the simpack model.

Table 2 shows the calculation results of the pressure wave for the rare toe of Renault Megane at 120km/h on an open line with a line spacing of 5.1m. Although the rule of pressure variation is the same at each place on the car's side throughout the crossing, the magnitudes of the pressure waves vary. Table 2 provides the magnitude of the pressure wave at five distinct positions on the side of the road to fulfil various calculating demands.

Table 2. The pressure wave hand calculation test for rare toe open line at 120 km/h

Point	P1	P2	P3	P4	P5
Δp (Pa)	205	350	220	310	290

Because the pressure wave forms at each measuring site have a similar shape, only the pressure change process at point P3 in the intersection process is analyzed, as seen in Figure 13. All spots on the car surface on the intersection side experience a positive and negative alternating pressure shift that sweeps across the whole train surface in the longitudinal direction during the entire process of passing through the head of the car. Because of the short duration and significant amplitude of the train pressure change.

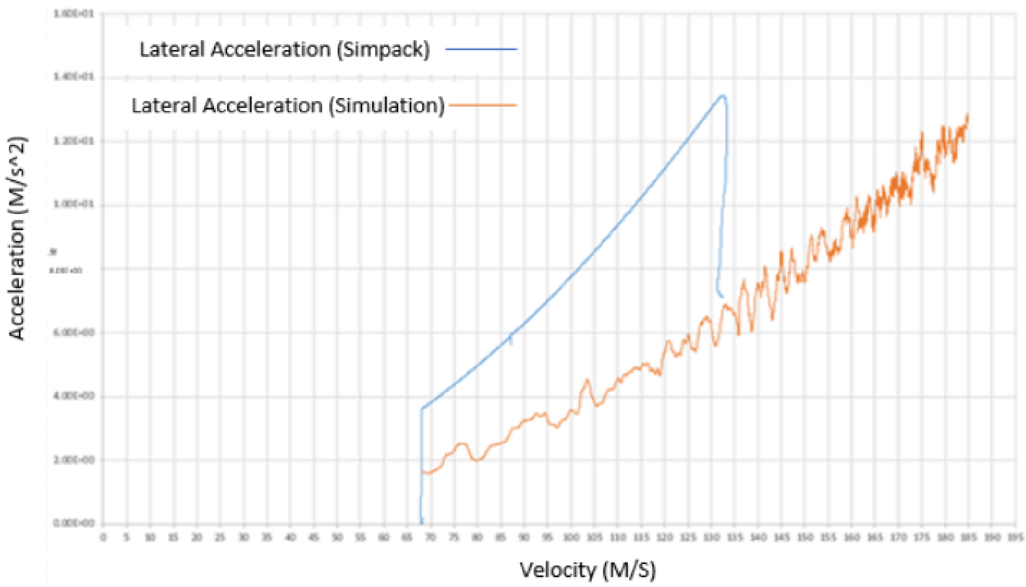


Figure 13: Pressure change process calculation results for P3

The ability of a vehicle to handle is affected by steering angles, and lateral acceleration limits a vehicle when there is a significant lateral weight shift. At a standstill, a vehicle's weight distribution will have an impact on how it handles; if the center of gravity is closer to the front axle, the vehicle will understeer as a result of the tire friction coefficient. In other words, the data indicate that more pressure wave is concentrated greater at the rear toe of the vehicle. It can make the car oversteer. For the vehicle's friction restrictions to be used to their best ability, a maximum entry speed is necessary (Huang, Liang, & Zou, 2022). When the vehicle is attempting to return to the original track, there is a noticeable pressure push under five seconds. Due of the driver's difficulty in maintaining a consistent step steer at 180 degrees.

Conclusion

An improved model could be produced by simulating the standard car handling characteristics during double lane change and constant radius cornering events using simpack modeling software (Nurprasetio et al., 2022). After conducting an initial baseline analysis using the Simpack data available, a development strategy was created through the research of sources to learn what traits to look for and how to manipulate these to create improvements before each model was tested and an optimized model was selected. With the help of this technology, the handling performance of the vehicle increased, enabling it to complete the CRC and DLC events more quickly. The optimized model displayed a reduced tracking error, enabling the car to better attain the anticipated yaw rate and provide greater control during turns.

Lack of real-world variables will, nonetheless, compromise the model's validity because of the simulation's design. Simpack mimics ideal settings based on assumptions and ignores outside influences that might have an impact on a vehicle's handling qualities in typical real-world driving situations. These might incorporated; there can be vibrations, which might cause resonance and instability. The necessary path for a vehicle may be adversely affected by external influences like side winds. Variations in the state of the road may cause changes in friction because of the weather and the contact area because of the kind and condition of the road (Tang et al., 2019). Simpack will replicate a brand-new, flawless spring, therefore suspension wear is not included in the simulation.

References

Huang, W., Ahmadian, M., Rahimi, A., & Steiginga, L. (2023). Dynamics performance of long combination vehicles with active control systems. *Vehicle System Dynamics*, 1-50.

Huang, Z., Liang, Z., & Zou, J. (2022, July). Optimization of Vehicle Suspension Parameters Based on SIMPACK/Isight Simulation of Wheel Eccentric Out-of-roundness. In *2022 International Conference on Computer Engineering and Artificial Intelligence (ICCEAI)* (pp. 270-274). IEEE.

Nurprasetio, I. P., Widyantara, R. D., Budiman, B. A., Lestaluhu, R., Djamari, D. W., Triawan, F., & Aziz, M. (2022). Electric Delta Trike Stability Characteristic and Maneuverability Analysis: Experiment and Multi-Body Dynamic Simulation. *Automotive Experiences*, *5*(3), 389-401.

Plöchl, M., & Edelmann, J. (2007). Driver models in automobile dynamics application. *Vehicle System Dynamics*, *45*(7-8), 699-741.

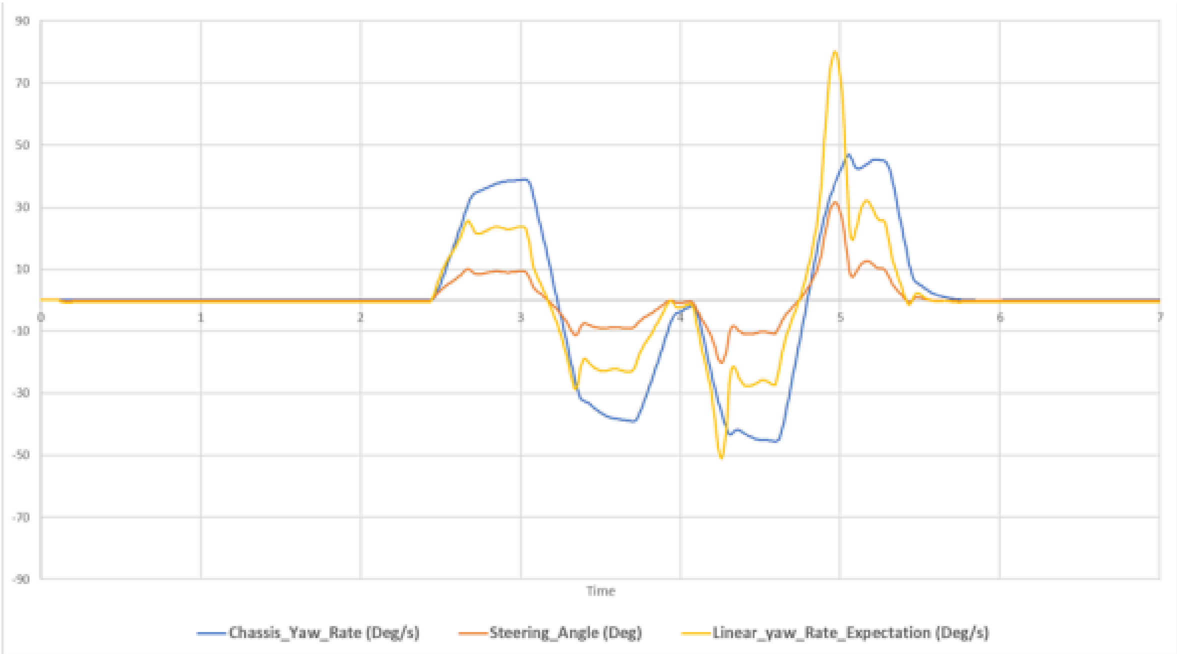
Robert Bosch GmbH. (2006). *Safety, Comfort and Convenience Systems*. John Wiley & Sons Ltd,

Tang, Z., Yuan, X., Xie, X., Jiang, J., & Zhang, J. (2019). Implementing railway vehicle dynamics simulation in general-purpose multibody simulation software packages. *Advances in Engineering Software*, *131*, 153-165.

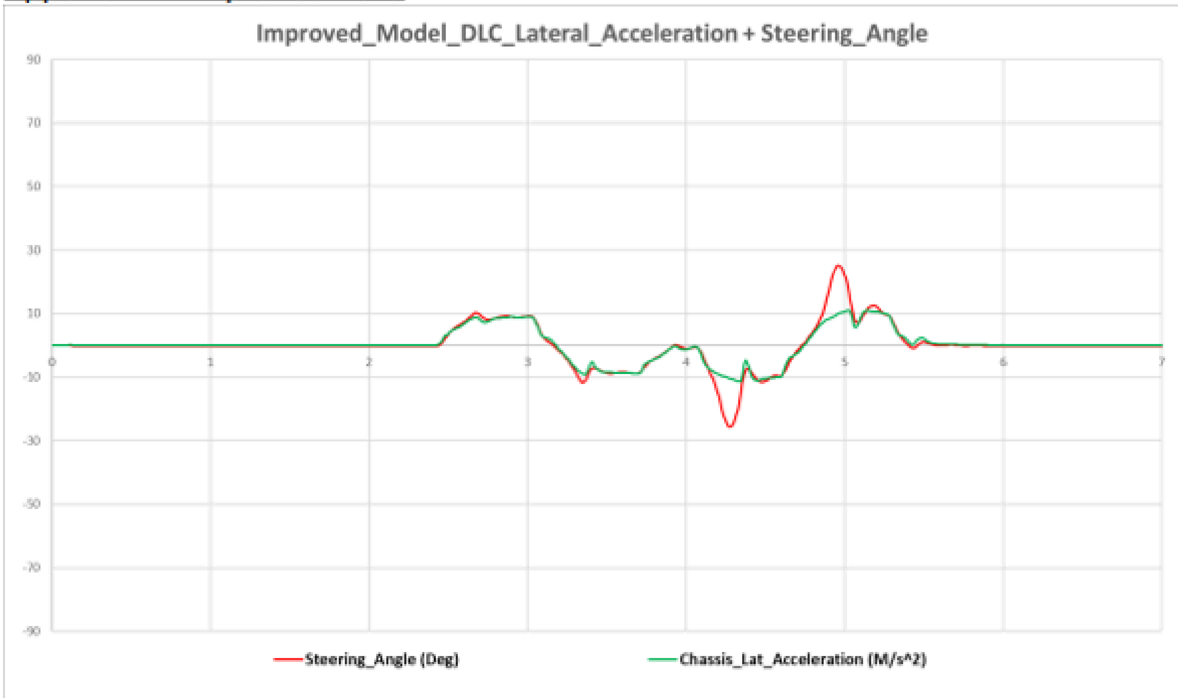
Zhang, C. (2023, May). Vehicle turning simulation with analysis and resolution of understeer and oversteer. In *International Conference on Computer Graphics, Artificial Intelligence, and Data Processing (ICCAID 2022)* (Vol. 12604, pp. 729-739). SPIE.

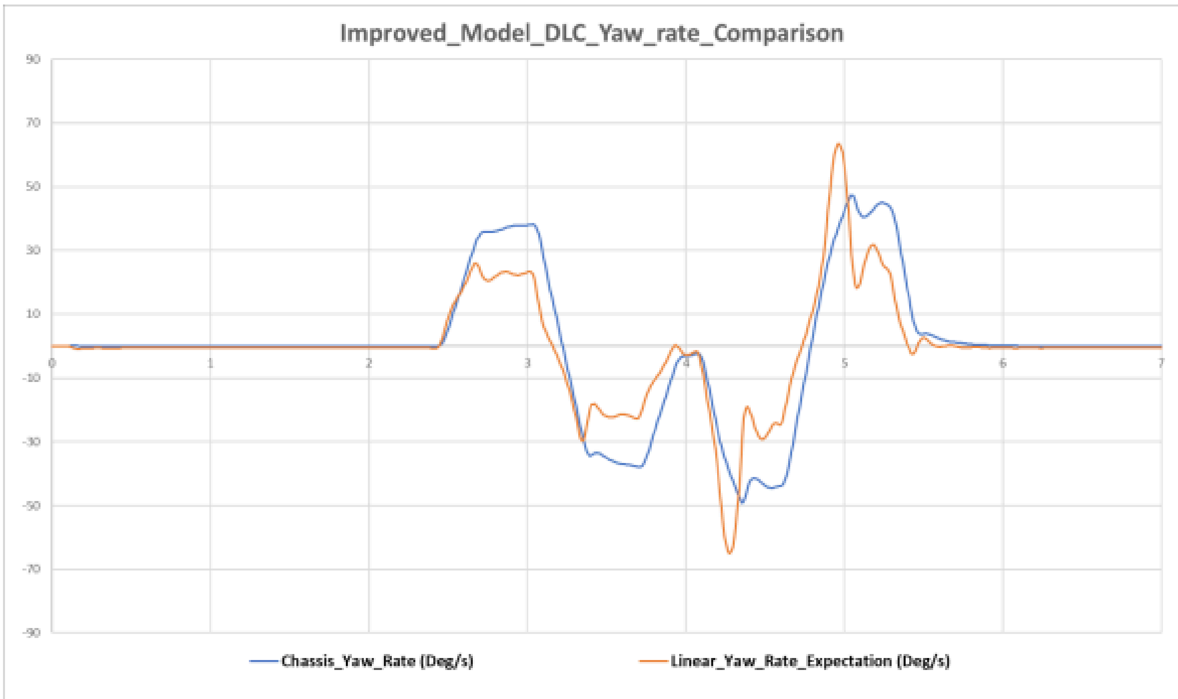
Appendices

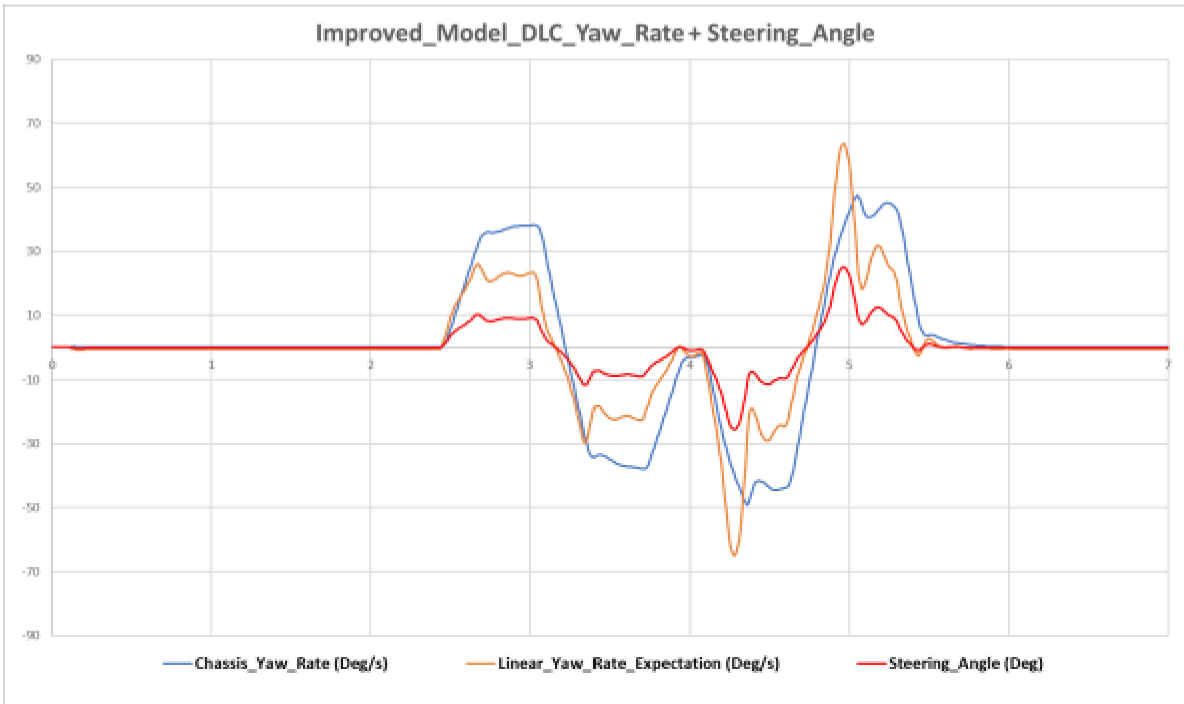
Appendix A: Baseline Data



Appendix B: Improved Data






Improved_Model_DLC_Yaw_Rate + Steering_Angle
90
70
50
30
10
-10
-30
-50
-70
-90
0
1
2
3
4
5
6
7
Chassis_Yaw_Rate (Deg/s)
Linear_Yaw_Rate_Expectation (Deg/s)
Steering_Angle (Deg)