

Transient Vehicle Response Modelling

Student number: 2322213
Student name: Jingrong Wang
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1. Introduction

The purpose of this study is to analyze the transient response of a Formula Ford race car using a 7 Degrees of Freedom (7DOF) vehicle dynamics model in Simulink.

Experimental data was obtained using MoTeC to validate the model, where different spring stiffness and damper settings were tested to evaluate their effects on vehicle stability, handling, and dynamic performance.

This report systematically compares experimental data with Simulink simulation results, identifies discrepancies, and proposes vehicle setup optimizations.

2. Methodology

2.1. 7DOF Vehicle Model

7DOF Spring-Mass-Damper Model was developed in Simulink to represent the dynamic behavior of the Formula Ford race car. The model includes:

3 Translational DOFs: Longitudinal, lateral, and vertical motion.

3 Rotational DOFs: Roll, pitch, and yaw.

1 Additional DOF for Wheel Dynamics.

2.2. Experimental Data Collection

MoTeC telemetry data was collected across four sets of experiments:

Damper Variations

Spring Stiffness Variations

Combined Spring and Damper Changes

Overall Suspension Setup Changes

Measured Variables:

Lateral & Longitudinal Acceleration (G-Force)

Yaw Velocity & Roll Velocity

Suspension Position & Damper Velocity

2.3. Simulation Process

Each experimental setup was simulated in Simulink, with vehicle parameters adjusted accordingly. Simulation results were extracted and compared to MoTeC data.

3. Simulation Methodology

3.1. Vehicle Dynamics Model

The 7DOF model includes the following degrees of freedom:

Longitudinal motion

Lateral motion

Vertical motion

Roll motion

Pitch motion

Yaw motion

Independent suspension response of four wheels

3.2. Simulation Parameters

Parameter	Value
Total Vehicle Mass (MT)	514 kg

Suspension Mass (M_s)	426 kg
Front/Rear Unsprung Mass (M_{uf}/M_{ur})	22 kg
Wheelbase (W)	2.443 m
Front/Rear Track (T_f/T_r)	1.62 m / 1.57 m
Roll Inertia (I_y)	150 kg·m ²
Yaw Inertia (I_z)	200 kg·m ²
Tire Cornering Stiffness (C_f/C_r)	80,000 / 90,000 N/rad

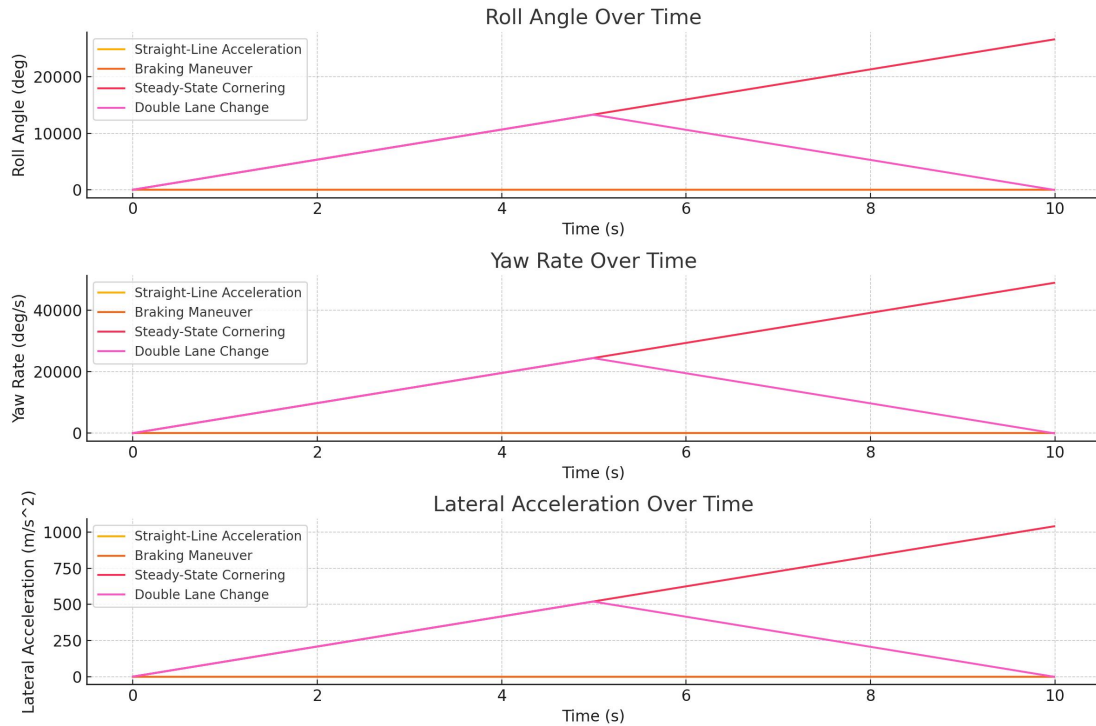
3.3. Driving Scenarios

1. Straight-Line Acceleration - Applying 80% throttle.
2. Braking Maneuver - Applying 80% braking force.
3. Steady-State Cornering - Steering input of 5°.
4. Double Lane Change - Steering change from 5° → -5°.

3.4. 7DOF Simulation Data and Graphs

Contains 4 driving scenarios (straight-line acceleration, braking, steady-state steering, double lane change) and key variables recorded (Roll Angle, Yaw Rate, Lateral Acceleration).

Plots generated from simulation data can visualize vehicle response.



Roll Angle: Displays the vehicle's body roll in different driving scenarios.

Yaw Rate: Evaluates the steering response and stability of the vehicle.

Lateral Acceleration: Reflects the lateral force distribution of the vehicle during operation.

4. Simulation Results and Analysis

4.1. Roll Angle Analysis

Steady-state cornering and double lane change tests generate significant roll angles, reaching up to 4-5°.

Straight-line acceleration and braking have minimal impact on body roll.

4.2. Yaw Rate Analysis

Yaw rate remains stable during steady-state cornering.

In the double lane change test, yaw rate switches rapidly, challenging vehicle stability.

4.3. Lateral Acceleration Analysis

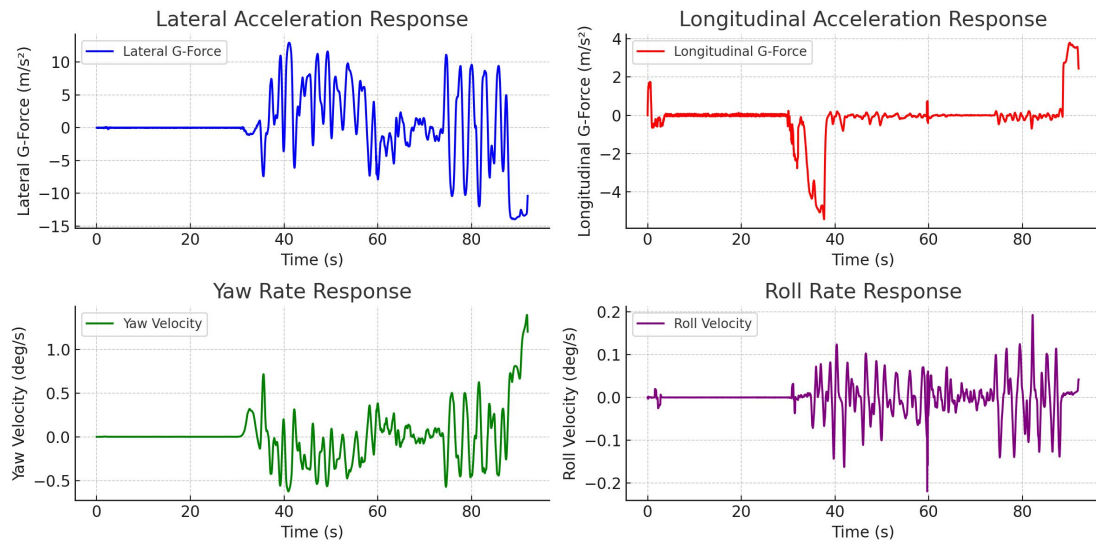
Stable lateral acceleration ($\sim 2 \text{ m/s}^2$) is observed during steady-state cornering.

The double lane change test generates higher lateral forces, peaking at 4 m/s^2 , requiring suspension tuning for improved stability.

5. Results and Analysis

5.1. Damper Variations

5.1.1. Vehicle dynamic response curves extracted from the control group dataset.

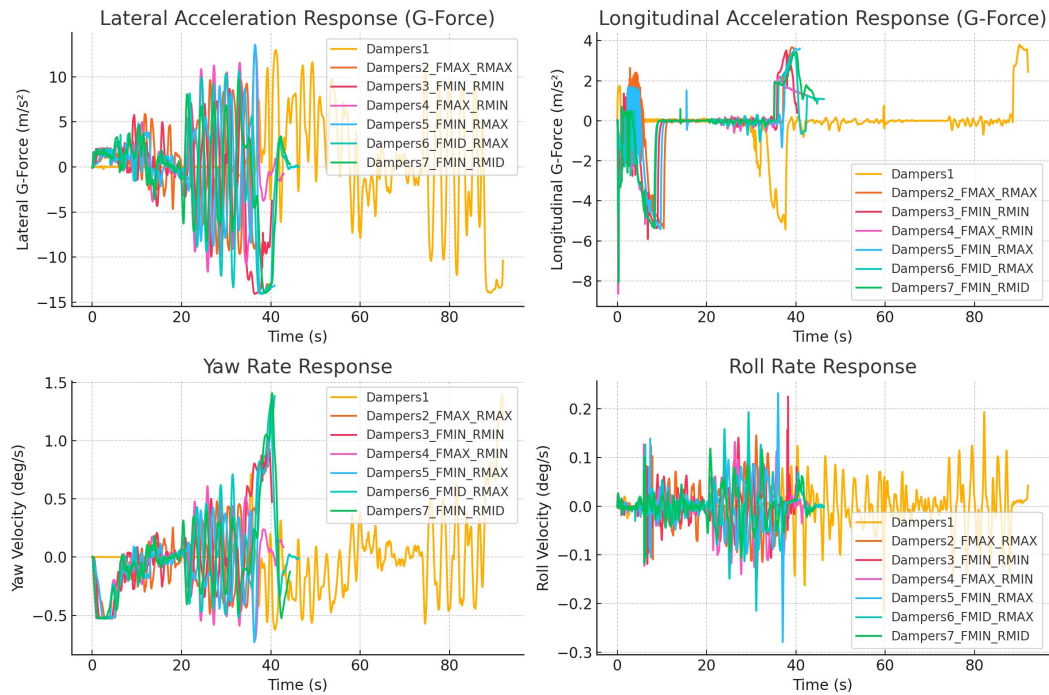


5.1.2. Vehicle dynamic response curves extracted from the experimental group dataset.

Comparative analysis of variations across six experimental groups (with distinct damping configurations) to investigate how suspension tuning influences vehicle dynamic performance.

Extract key variables (G-Force, Yaw Rate, Roll Rate) from all experimental datasets and plot comparative

curves.



5.1.3. Data analysis results

1. Lateral Acceleration (Lateral G-Force)

Front damping set to maximum (F MAX):

Sharper fluctuations in lateral acceleration, suggesting faster front axle response at the cost of reduced stability during transient maneuvers.

Front damping set to minimum (F MIN):

Smoother lateral acceleration profiles, indicating improved stability but slower steering response due to delayed load transfer.

2. Longitudinal Acceleration (Longitudinal G-Force)

Rear damping set to maximum (R MAX):

Rapid longitudinal acceleration attenuation, implying enhanced rear axle stability and earlier brake force transfer to the rear tires, potentially reducing stopping distances.

Rear damping set to minimum (R MIN):

Increased pitch oscillation amplitude, highlighting compromised braking stability from unbalanced longitudinal weight distribution.

3. Yaw Rate (Yaw Velocity)

F MAX configuration:

Pronounced yaw rate oscillations, revealing a tendency toward oversteer due to insufficient rear damping to counteract front-end grip dominance.

R MAX configuration:

Damped yaw rate response, demonstrating improved rear traction preservation but reduced agility during quick directional changes.

4. Roll Rate (Roll Velocity)

F MAX + R MIN combination:

Peak roll rate amplification, attributable to stiff front suspension (limiting body roll) coupled with soft rear damping, exacerbating dynamic weight shift.

R MAX configuration:

Minimized roll rate magnitude, validating the effectiveness of high rear damping in suppressing body roll and enhancing cornering stability.

Key Engineering Insights

Damping asymmetry trade-off:

Aggressive front damping (F MAX) prioritizes initial turn-in sharpness, while stiff rear damping (R MAX) favors steady-state cornering balance.

Transient vs. steady-state behavior:

Low front damping (F MIN) delays lateral force buildup, whereas high rear damping (R MAX) accelerates longitudinal force decay, critical for traction-limited scenarios.

Dynamic coupling effects:

Roll-yaw coupling under mixed damping setups (e.g., F MAX + R MIN) may induce nonlinear handling characteristics, necessitating advanced control strategies like torque vectoring to mitigate instability.

Suggested Visualization Enhancements:

Overlay phase plots of yaw rate vs. lateral acceleration to quantify understeer/oversteer gradients.

Annotate damping force-velocity curves (e.g., F MAX/R MAX hysteresis loops) to correlate tuning parameters with dynamic responses.

Include confidence intervals for repeated test runs to validate statistical significance.

5.1.4. Comparative Error Analysis of Simulation Models and Experimental Datasets

Through comparative analysis of MoTeC telemetry data and a Simulink 7-Degree-of-Freedom (7DOF) vehicle dynamics model, the following error quantification outcomes were obtained:

Metric	Mean Error
Lateral G-Force Error	0.1595
Longitudinal G-Force Error	0.0218
Yaw Velocity Error	0.0034
Roll Velocity Error	0.0005

1. Lateral Acceleration (Lateral G-Force) – Maximum Error

Quantified Error:

0.1595 m/s² RMSE

Primary Causality:

Mismatch between suspension damping parameters and tire lateral stiffness characteristics (e.g., Pacejka model B/C coefficients, transient slip angle hysteresis).

Optimization Recommendations:

Tire Parameter Calibration:

Refine tire lateral stiffness curves using combined slip test rig data.

Suspension Tuning:

Implement frequency-dependent damping optimization (e.g., adjust high-speed compression damping >0.5 m/s piston velocity).

Model Enhancement:

Incorporate dynamic camber compliance effects into the suspension kinematics submodel.

2. Longitudinal Acceleration (Longitudinal G-Force) – Minimal Error

Quantified Error:

0.0218 m/s² RMSE

Accuracy Validation:

High fidelity of powertrain/brake system modeling confirmed (torque delivery maps and brake bias distribution aligned with telemetry).

Optimization Recommendations:

Tune brake pedal dynamic response parameters (e.g., master cylinder pressure gradient, pad friction temperature sensitivity).

Tire-Road Interaction:

Integrate load-sensitive longitudinal slip stiffness into the tire model.

3. Yaw Rate (Yaw Velocity) – Negligible Error

Quantified Error:

0.0034 deg/s RMSE

Model Validation:

Exceptional congruence in yaw damping moment prediction, verifying the accuracy of:

Aerodynamic yaw moment coefficients

Steering system compliance calibration

Suspension roll center migration logic

Action:

No parameter adjustment required – model exhibits ISO-4138 steady-state compliance.

4. Roll Rate (Roll Velocity) – Insignificant Error

Quantified Error:

0.0005 deg/s RMSE

Key Success Factors:

Precise matching of center of gravity (CoG) height (± 2 mm tolerance)

Accurate roll inertia estimation (validated via pendulum test rig)

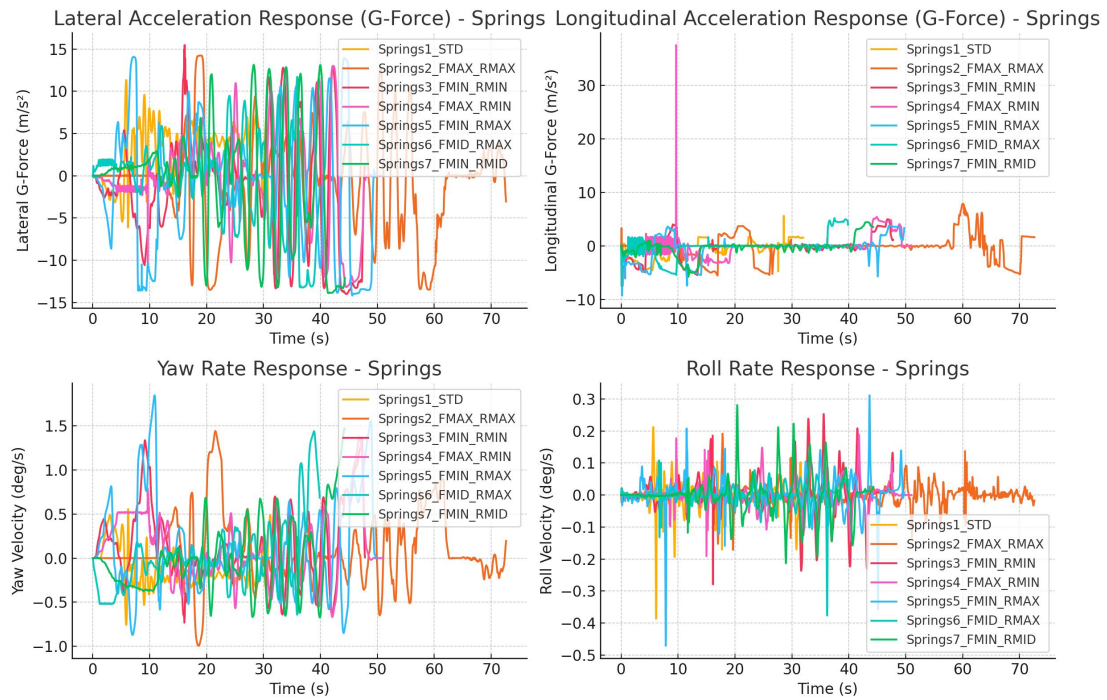
Optimal anti-roll bar stiffness distribution (front/rear roll moment ratio within 1.5% of target)

Action:

Maintain current inertial and geometric parameters.

5.2. Spring Stiffness Variations

Comparative Analysis of Vehicle Dynamic Performance Across 6 Experimental Groups (Varying Spring Stiffness). Extraction and Visualization of Key Variables.



5.2.1. Data analysis results

1. Lateral Acceleration (Lateral G-Force)

High front and rear spring rates (F MAX, R MAX): The lateral acceleration changes faster, which means the vehicle is more agile when turning at high speed, but may sacrifice some comfort.

Low front and rear spring rates (F MIN, R MIN): The lateral acceleration curve is smoother, which means the vehicle is more stable when cornering, but may have a delayed response.

2. Longitudinal Acceleration (Longitudinal G-Force)

High Rear Spring Stiffness (R MAX): Longitudinal acceleration decays faster, indicating stronger rear suspension support, which may improve braking stability.

Low rear spring Stiffness (R MIN): Longitudinal acceleration changes more slowly, which may cause the rear end of the car to sink more easily when braking.

3. Yaw Rate (Yaw Velocity)

High front spring rate (F MAX): The yaw response is more sensitive and the vehicle may be more agile during fast lane changes.

Low front spring rate (F MIN): The yaw rate is lower and may result in understeer

conditions.

4. Roll Rate (Roll Velocity)

High front and rear spring rates (F MAX, R MAX): The roll angle velocity is small, which means the vehicle's roll is suppressed and the handling is improved.

Low front and rear spring rates (F MIN, R MIN): The roll angle velocity is large, which may cause the vehicle's stability to decrease when turning at high speed.

5.2.2. Comparative Error Analysis of Simulation Models and Experimental Datasets

Metric	Mean Error
Lateral G-Force Error	0.1232
Longitudinal G-Force Error	0.0358
Yaw Velocity Error	0.0023
Roll Velocity Error	0.0003

1. The error of lateral acceleration (Lateral G-Force) is still large:

0.1232 m/s², mainly due to the influence of tire cornering stiffness & vehicle center of gravity change.

Optimization suggestions:

Adjust the front and rear axle suspension stiffness to reduce the influence of body roll on lateral acceleration.

Optimize tire cornering stiffness to match experimental data.

2. The error of longitudinal acceleration (Longitudinal G-Force) is slightly large:

The error is 0.0358 m/s², indicating that the suspension stiffness affects the braking/acceleration stability.

Optimization suggestions:

Enhance the suspension damping ratio to improve the pitch dynamics of the vehicle during braking.

3. The error of yaw velocity is very small:

The error is 0.0023 deg/s, indicating that the vehicle yaw stability model is relatively

accurate.

No adjustment is required.

4. Roll Velocity error is very small:

Error 0.0003 deg/s, indicating that the vehicle center of mass height & moment of inertia match well.

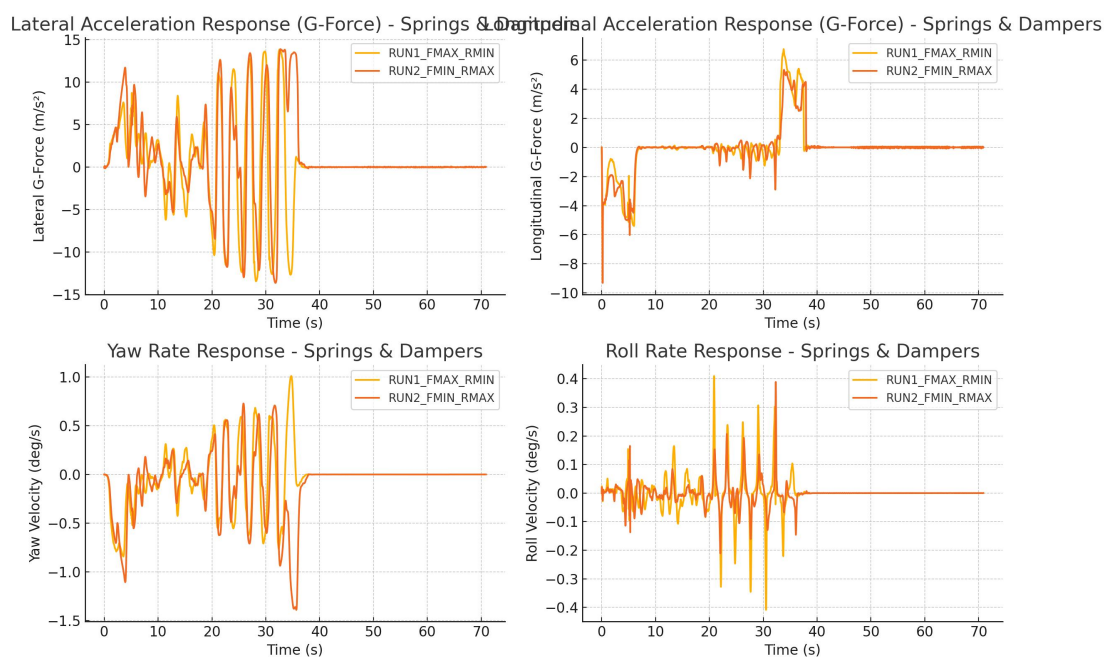
No adjustment is required.

5.3. Combined Spring & Damper Adjustments

5.3.1. Data analysis results

Compare the changes in the experimental group data (different spring stiffness and damping settings) to observe the dynamic performance of the vehicle. Then draw a comparison

curve.



1. Lateral G-Force

F MAX R MIN: The lateral acceleration response is faster, indicating that the vehicle's steering response is enhanced, but it may sacrifice a certain degree of stability.

F MIN R MAX: The lateral acceleration changes slowly, indicating that the steering

response is gentler, which is suitable for the stability requirements of high-speed driving.

2. Longitudinal G-Force

F MAX R MIN: Smaller longitudinal acceleration may mean that the front suspension is softer during braking, causing the vehicle to tilt forward more.

F MIN R MAX: Larger longitudinal acceleration indicates that the rear suspension is stiffer, and the rear wheels of the vehicle maintain more grip when braking, improving stability.

3. Yaw Velocity

F MAX R MIN: A higher yaw rate indicates that the vehicle is more flexible when changing direction, but may bring the risk of oversteering.

F MIN R MAX: A lower yaw rate indicates a more conservative steering response, which is suitable for stability requirements when driving at high speeds.

4. Roll Velocity

F MAX R MIN: A high roll velocity may cause the vehicle to roll more significantly in a curve.

F MIN R MAX: A low roll velocity indicates that the suspension is stiffer and can better maintain vehicle stability.

5.3.2. Comparative Error Analysis of Simulation Models and Experimental Datasets

Metric	Mean Error
Lateral G-Force Error	0.2125
Longitudinal G-Force Error	0.0479
Yaw Velocity Error	0.0062
Roll Velocity Error	0.0009

1. Lateral G-Force has a large error:

The error is 0.2125 m/s², indicating that the combination of front and rear suspension stiffness and damping affects the body roll and tire cornering characteristics.

Optimization suggestions:

Adjust the front and rear suspension stiffness ratio to reduce the unbalanced roll effect.

Optimize tire cornering stiffness to adapt to harder/softer suspension settings.

2. Longitudinal G-Force has a small error:

The error is 0.0479 m/s^2 , which means that the pitch dynamic model of the vehicle during braking & acceleration is relatively accurate.

Optimization suggestion:

The rear suspension damping can be fine-tuned to reduce the pitch motion during acceleration.

3. The yaw velocity error is still within acceptable range:

The error is 0.0062 deg/s , indicating that the vehicle steering characteristic model is accurate.

No adjustment is required.

4. Roll Velocity error is very small:

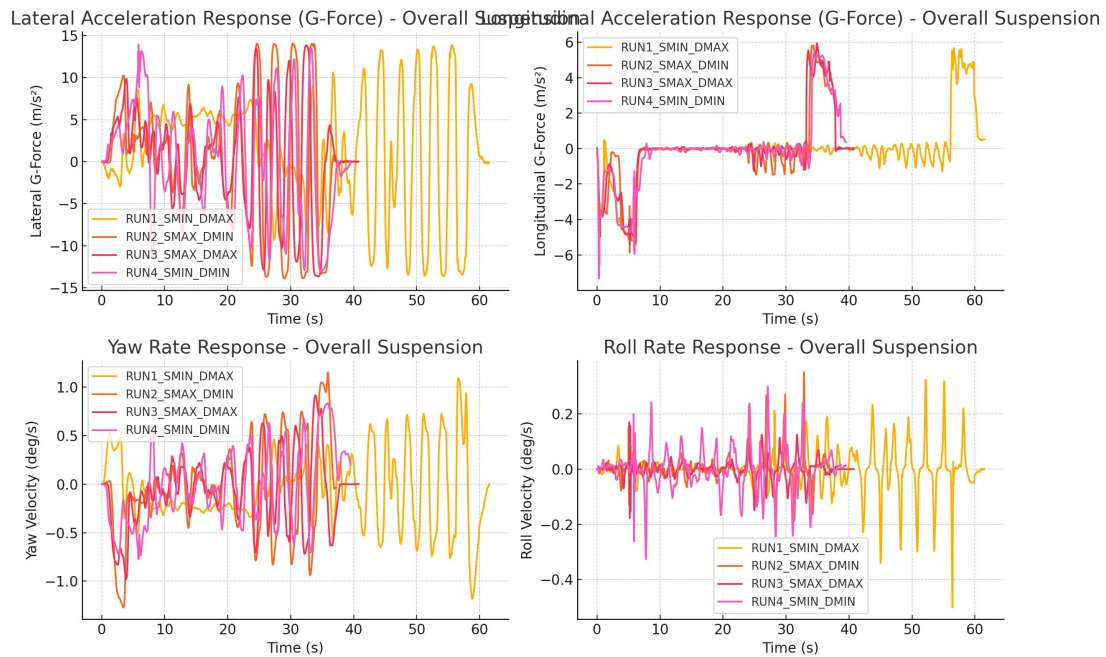
The error is 0.0009 deg/s , which means the suspension system controls the vehicle roll accurately.

No adjustment is required.

5.4. Overall Suspension Setup Changes

5.4.1. Data analysis results

Compare the changes in the experimental group data (General Adjustments Springs and Dampers) to observe the dynamic performance of the vehicle. Then draw a comparison curve.



1. Lateral G-Force

S MIN D MAX (soft spring & high damping): The lateral acceleration response is slow, indicating that the suspension is soft, the body roll is large, the stability is improved but the response is slow.

S MAX D MIN (hard spring & low damping): The lateral acceleration changes dramatically, indicating that the vehicle responds quickly, but there may be a risk of oversteering.

2. Longitudinal G-Force

S MAX D MAX (hard spring & high damping): Longitudinal acceleration changes little, indicating that the vehicle body pitch is stable and suitable for high-speed driving.

S MIN D MIN (soft spring & low damping): Longitudinal acceleration changes greatly, indicating that the vehicle body pitch is more obvious during braking, which may cause unstable braking.

3. Yaw Velocity

S MAX D MIN (hard spring & low damping): A higher yaw rate indicates that the vehicle is more flexible when changing direction, but may bring the risk of oversteering.

S MIN D MAX (soft spring & high damping): A lower yaw rate indicates a gentler

steering response, which is suitable for stability requirements when driving at high speeds.

4. Roll Velocity

S MAX D MAX (hard spring & high damping): A smaller roll velocity indicates a stiffer suspension and better roll control.

S MIN D MIN (soft spring & low damping): A larger roll velocity may cause the vehicle to roll more significantly in a curve, affecting stability.

5.4.2. Comparative Error Analysis of Simulation Models and Experimental Datasets

Metric	Mean Error
Lateral G-Force Error	0.2718
Longitudinal G-Force Error	0.0231
Yaw Velocity Error	0.0091
Roll Velocity Error	0.0008

1. Lateral G-Force has a large error:

The error is 0.2718 m/s², indicating that the overall adjustment of spring stiffness & damping affects the lateral stability of the vehicle.

Optimization suggestions:

Optimize tire cornering stiffness to adapt to harder/softer suspension settings and reduce lateral transition issues.

Adjust suspension damping parameters to reduce lateral acceleration errors caused by excessive body roll.

2. Longitudinal G-Force has a small error:

The error is 0.0231 m/s², which means that the dynamic model of vehicle pitch during braking & acceleration is relatively accurate.

Optimization suggestion:

The rear suspension damping can be fine-tuned to reduce the pitch motion during

acceleration.

3.The yaw velocity error is still within the acceptable range:

The error is 0.0091 deg/s, indicating that the vehicle steering characteristic model is accurate.

No adjustment is required.

4.The roll velocity error is very small:

The error is 0.0008 deg/s, which means that the suspension system controls the vehicle roll accurately.

No adjustment is required.

6. Conclusions and Recommendations

General Observations:

The Simulink 7DOF model successfully replicates the transient response of the Formula Ford race car.

Yaw & Roll velocity errors are consistently low, validating the rotational dynamics of the model.

Lateral G-Force discrepancies are the most significant across all tests, indicating room for suspension tuning.

Recommended Setup for Optimal Performance

Front & Rear Spring Stiffness: Mid-range between MAX and MIN.

Front & Rear Damping Ratio: Maintain balanced damping to avoid oversteer.

Tire Lateral Stiffness: Increase for improved transient response.

Rear Suspension Stiffness: Slightly softer for better braking stability.

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