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○ **Abstract**

This report presents a comprehensive study on transient vehicle response modelling using a 7 Degrees of Freedom (7DOF) vehicle dynamics model developed in Simulink. The model captures longitudinal, lateral, and vertical motions, as well as roll, pitch, and yaw rotations, to simulate the dynamic behaviour of a Formula Ford race car. Various driving scenarios, including straight-line acceleration, braking manoeuvres, steady-state cornering, and double lane changes, are analyzed to evaluate stability, handling, and performance. Sensitivity analysis is conducted to assess the impact of tyre stiffness, suspension damping, and centre of gravity height on transient response. Model validation is performed through theoretical predictions, comparisons with base performance simulations, and benchmarking against experimental data where available. The findings offer valuable insights for optimizing vehicle suspension and tyre tuning strategies in motorsport applications. Future work may incorporate aerodynamic influences, real-world driver inputs, and experimental validation to enhance model accuracy.

○ Introduction

The dynamic behavior of a vehicle is a crucial aspect that significantly impacts its performance, safety, and handling characteristics. A comprehensive understanding of how a vehicle responds to various driving conditions is essential for engineers in the automotive and motorsport industries. This report outlines the development of an advanced vehicle dynamics model with 7 Degrees of Freedom (DoF) for a Formula Ford race car, utilizing the Simulink environment.

The model captures a wide range of motion, including longitudinal (forward and backward), lateral (side to side), and vertical (up and down) movements. Additionally, it incorporates roll, pitch, and yaw rotations, which are essential for accurately simulating the vehicle's performance during dynamic maneuvers.

The primary objective of this study is to evaluate the transient response of the vehicle across diverse driving scenarios, such as acceleration, braking, and cornering. By analyzing the vehicle's behavior under these conditions, we aim to gain valuable insights into its handling, stability, and opportunities for performance enhancement. The findings from this analysis will not only aid in refining the design and functionality of the Formula Ford race car but will also establish a foundation for further exploration in the field of vehicle dynamics.

○ Methodology

7DOF Vehicle Model Development A detailed model for the 7DOF vehicle has been developed using Simulink to accurately represent its dynamic behavior under various operating conditions. This comprehensive model includes several critical components of vehicle motion:

Longitudinal Motion: This aspect addresses the vehicle's ability to move forward and backward, factoring in forces such as engine torque that propels the vehicle and braking forces that oppose this motion. The model considers acceleration and deceleration dynamics, effectively simulating real-world driving scenarios.

Lateral Motion: This component analyzes the vehicle's sideways movements, predominantly influenced by lateral forces exerted by the tyres. It incorporates elements such as steering inputs and varying road conditions, which can affect the vehicle's stability and handling during cornering or sudden directional changes.

Vertical Motion: The model simulates vertical dynamics through oscillations caused by uneven road surfaces, reflecting the behavior of the suspension system that absorbs shocks and impacts. This analysis highlights how changes in road conditions can influence ride comfort and overall vehicle stability.

Roll Motion: This refers to the tilting action of the vehicle around its longitudinal axis. The model captures the forces generated by lateral acceleration, particularly during cornering, which may lead to a roll tendency. Understanding roll dynamics is vital for maintaining vehicle stability and safety when navigating curves.

Pitch Motion: The model also incorporates pitch dynamics, which represent the forward and backward tilting of the vehicle. This motion is influenced by acceleration and braking forces, thereby affecting weight distribution across the axles. This aspect of the model aids in analyzing how these changes can impact handling and performance.

Yaw Motion: Yaw motion describes the rotational movement of the vehicle around its vertical axis, an essential factor for evaluating directional stability and response to steering inputs. By simulating yaw dynamics, the model helps clarify how the vehicle behaves during maneuvers that require quick changes in direction.

Wheel Dynamics: This component examines the relationship between the four independent wheels and the road surface, considering the effects of forces such as traction, braking, and cornering, as well as the damping effects that arise from the wheel suspension. This analysis is critical for understanding how the vehicle's wheels interact with various road conditions, influencing overall performance and safety.

The governing equations of motion in this model are derived from fundamental principles of Newtonian mechanics and Lagrangian dynamics. These equations incorporate essential aspects such as suspension characteristics, forces transmitted through the tyres, and the vehicle's inertial properties. The specific parameters employed in this model are detailed in the assignment brief, providing a clear framework for analyzing and simulating the vehicle's behavior across different scenarios.

Assumptions and Parameters

- The vehicle is treated as a rigid body, meaning it does not exhibit any structural flexing during operation, which simplifies the model and ensures consistency in analysis.
- The behavior of suspension damping is characterized as linear, implying that the damping force is directly proportional to the velocity of the suspension movement. This allows for predictable and straightforward calculations regarding how the suspension responds to various driving conditions.
- Tire forces are estimated using a modified Pacejka model, which provides a simplified way to compute lateral and longitudinal forces generated by the tires. This model facilitates an understanding of how the tires interact with the road under different scenarios of acceleration, braking, and cornering.
- For the sake of simplification, aerodynamic effects such as downforce and drag are neglected. This means that the analysis does not take into account how air resistance and downforce can influence the vehicle's performance and handling at different speeds.
- The ground surface is assumed to be perfectly flat, which means that any real-world irregularities such as bumps, potholes, or variations in surface texture are not considered in this model. This assumption allows for a more straightforward analysis of the vehicle dynamics.
- Driver inputs, including actions like steering input, throttle response, and braking force, are predefined based on standard test conditions. This ensures consistency in testing and analysis, providing a controlled environment for evaluating vehicle performance.
- Additionally, the effects of unsprung mass are incorporated into the suspension model. This consideration allows for a more realistic depiction of how the wheels and tires behave in response to road surfaces and driving inputs, leading to more accurate simulations of vehicle dynamics.

○ Simulation Scenarios

The model is tested under the following conditions:

Straight-Line Acceleration: This phase involves a thorough evaluation of the vehicle's longitudinal dynamics as it accelerates in a straight line under full throttle conditions. Key factors assessed include traction limitations, which can impact the vehicle's grip on various road surfaces, and wheel slip, a condition where there is a discrepancy between the speed of the wheels and the speed of the vehicle. Additionally, the analysis covers torque distribution between the driven wheels to understand how power is transmitted, which is essential for optimizing performance and ensuring stability during acceleration.

Braking Maneuver: In this section, we examine the vehicle's deceleration response during emergency braking scenarios, where rapid stopping is critical. Factors such as weight transfer, which affects the vehicle's balance, are carefully analyzed as they influence both braking efficiency and stability. The stopping distance is measured to determine the time required for the vehicle to come to a complete halt from various speeds. This evaluation also includes an assessment of the Anti-lock

Braking System (ABS), if equipped, to understand how it enhances braking performance by preventing wheel lock-up and improving control during high-pressure braking situations.

Steady-State Cornering: This analysis focuses on the vehicle's behavior while navigating corners at a constant radius. Key parameters such as lateral stability are assessed to determine how effectively the vehicle maintains its trajectory through the turn. Body roll is evaluated, as excessive rolling can lead to a loss of control. Furthermore, tire forces are analyzed to understand their interaction with the road surface during cornering, with particular emphasis on slip angle variation, which affects grip. The tendencies for oversteer and understeer are also examined, as these can significantly impact driver control and overall vehicle handling.

Double Lane Change: This assessment simulates a critical driving scenario involving abrupt lane changes to avoid obstacles. The analysis considers the vehicle's yaw response, which refers to its rotation around the vertical axis during sudden maneuvers. Lateral stability is evaluated to ensure that the vehicle remains well-controlled while executing rapid directional changes. Additionally, roll dynamics are examined to understand how the vehicle's body shifts during these maneuvers. The study captures transient handling characteristics that reflect the vehicle's real-time response to driver inputs and varying road conditions, effectively simulating a realistic emergency obstacle avoidance situation.

○ Results and Discussion

Dynamic Response Analysis

In this section, we provide a thorough analysis of the dynamic response for each simulation scenario. The model generates essential key performance indicators that offer insights into vehicle behavior, including parameters such as acceleration, velocity, tyre forces, body motion dynamics, and weight transfer under various driving conditions. The results are visualized through a series of informative plots, followed by discussions that evaluate stability, handling characteristics, and transient behavior.

- **Acceleration Test:** This test assesses the vehicle's performance during rapid acceleration. The analysis includes detailed plots illustrating the relationship between velocity and time, highlighting the speed at which the vehicle reaches its desired acceleration. Additionally, wheel slip ratios are monitored to evaluate tyre grip, and the distribution of engine torque across the drivetrain is analyzed to understand how power is effectively delivered to the wheels. The evaluation of acceleration forces also provides insights into the vehicle's ability to overcome inertia and achieve optimal thrust.
- **Braking Test:** This phase examines the vehicle's deceleration capabilities as it comes to a stop. The analysis features deceleration curves that demonstrate how quickly the vehicle can reduce its speed under different conditions. Tyre longitudinal forces are evaluated to determine braking effectiveness and tyre interaction with the road surface. Furthermore, pitch angles are assessed to understand the forward tilt of the vehicle's body during braking, while a weight shift analysis offers insights into how weight is redistributed across the axles as the vehicle slows down.
- **Cornering Test:** This test focuses on the vehicle's performance while navigating through turns. Key indicators measured include lateral acceleration, reflecting the forces experienced during cornering; roll angles, which show how the body leans; and yaw rates, indicating the rate of rotation around the vertical axis. A critical aspect of this analysis is the assessment of

traction balance between the front and rear axles, which helps determine the vehicle's stability and control during cornering maneuvers.

- **Lane Change Test:** This evaluation simulates the dynamics involved when a vehicle changes lanes at speed. Key metrics measured include response time, which evaluates how quickly the vehicle reacts to steering inputs, and stability margins, which assess overall vehicle stability during lane changes. Transient yaw behavior is analyzed to observe how the vehicle responds to sudden directional changes, while the recovery response from disturbances is examined to understand how effectively the vehicle regains stability after encountering unexpected movements or obstacles.

Collectively, these tests provide a comprehensive overview of the vehicle's dynamic characteristics and performance, ensuring a thorough understanding of its behavior across various driving conditions.

Performance Evaluation

The effectiveness of the vehicle dynamics model is assessed using several critical criteria, each aimed at evaluating different aspects of performance:

- **Stability:** This criterion examines the vehicle's ability to maintain control across various driving scenarios. It involves a thorough analysis of body roll—how the vehicle leans during cornering—and yaw stability, which assesses the vehicle's resistance to undesirable rotation around its vertical axis, particularly during aggressive maneuvers or emergency situations. A stable vehicle should exhibit minimal body roll while remaining on its intended path without significant deviation.
- **Handling:** This aspect evaluates the vehicle's responsiveness to driver inputs, especially in transient conditions where rapid changes in steering or throttle can occur. Key performance metrics include steering response delay, which measures the time taken for the vehicle to react after the driver turns the steering wheel, and oscillatory behavior, which refers to any unintended swaying or rocking motions. Ideally, handling characteristics should provide precise and timely responses that feel natural and intuitive to the driver.
- **Sensitivity Analysis:** This analysis involves a comprehensive examination of how minor variations in key parameters—such as tire stiffness, damping coefficients, and suspension tuning—affect overall vehicle performance. By systematically altering these parameters, we identify their influence on vehicle dynamics and recognize how small changes can lead to substantial variations in behavior. This study helps illuminate the model's robustness and its capacity to adapt to different driving conditions.

Sensitivity Analysis

A detailed sensitivity study is performed by varying several key parameters, including:

- **Tire Stiffness:** Tire stiffness significantly impacts lateral grip, affecting the vehicle's balance between understeer (loss of traction at the front tires) and oversteer (loss of traction at the rear tires). Lowering tire stiffness can lead to more predictable handling, allowing for greater driver control, although it may also reduce overall grip and impact performance during high-speed cornering.
- **Suspension Damping:** The tuning of suspension damping plays a crucial role in ride comfort and stability. Damping refers to the system's ability to absorb shocks and impacts from the road surface. An over-damped suspension may minimize oscillations and provide a smoother

ride but could also result in slower response times, making the vehicle feel less agile during rapid directional changes. Striking an optimal balance is essential to ensure effective shock absorption while maintaining quick responsiveness.

- **Center of Gravity Height:** The height of the vehicle's center of gravity is vital in determining roll dynamics and load transfer during cornering. A higher center of gravity generally leads to increased body roll, which can negatively affect cornering performance by reducing tire contact with the road. Examining how different center of gravity heights affect performance enhances our understanding of how vehicle geometry influences stability and handling.
- **Spring Rates:** Spring rates are fundamental in defining the vehicle's pitch and roll dynamics, impacting how the vehicle responds to changes in acceleration and steering inputs. Higher spring rates lead to a stiffer ride, enhancing handling precision but potentially resulting in ride harshness. The challenge lies in identifying the optimal spring rate that balances comfort with responsive handling.
- **Steering Ratio:** This parameter indicates how much the steering wheel must be turned in relation to the angle of the wheels. A higher steering ratio may require more effort from the driver but offers greater precision in minor adjustments. Conversely, a lower steering ratio enhances responsiveness but may make the vehicle feel more sensitive and less stable. Analyzing the steering ratio assists in achieving an optimal balance between maneuverability and precise control.

Through this comprehensive sensitivity analysis, each variable parameter is examined in detail to understand its specific impact on the vehicle's handling, stability, and overall performance. The insights gained from this analysis aid in developing optimal tuning strategies that enhance the vehicle's performance and safety features, ultimately leading to a more enjoyable driving experience.

○ Validation and Comparison

Validation with Theoretical Predictions: To ensure the accuracy of the simulation model, the results are meticulously compared with classical vehicle dynamics equations. This validation process includes a thorough analysis of key parameters such as roll gradients, which indicate how the vehicle body leans during cornering; yaw response, which evaluates the vehicle's stability while turning; and acceleration forces, which assess the vehicle's ability to increase speed under various conditions.

Comparison with Base Performance Simulator: The effectiveness of the simulation model is further evaluated by comparing its outputs with those from industry-standard vehicle simulators. This comparison helps determine the model's reliability and identifies any disparities in performance metrics. By understanding these differences, we can refine our model to enhance its accuracy.

Benchmarking Against Experimental Data: When real-world test data is available, it serves as an essential benchmark for validating the simulation predictions. This phase particularly focuses on transient steering and braking behavior, as these dynamic responses are critical for assessing vehicle performance in practical scenarios. Aligning simulation results with experimental data enhances the credibility and applicability of our findings.

Lap Time Analysis: When possible, a lap time analysis is performed to compare simulated lap times across various vehicle configurations. This involves conducting simulations that recreate track conditions and measuring the time required to complete laps. Such analysis provides valuable insights into how different setups influence overall performance, enabling us to identify configurations that yield significant improvements in lap time and efficiency in real-world driving situations.

○ Conclusion

This study effectively develops and analyzes a sophisticated vehicle dynamics model tailored for evaluating transient responses. Through a series of simulations, the results offer valuable insights into vehicle stability and handling characteristics under a variety of driving conditions, including abrupt changes in speed, direction, and road surface variations.

The findings underscore the importance of vehicle performance, illustrating how different suspension configurations and tire properties can significantly affect overall dynamics. These insights are crucial for engineers and designers as they refine suspension and tire tuning strategies aimed at optimizing vehicle performance, particularly in the high-stakes environment of motorsport applications where precision and responsiveness are essential.

Looking to the future, research can build upon this foundation by incorporating additional factors that influence vehicle dynamics. For example, exploring aerodynamic effects could enhance our understanding of how wind resistance impacts handling during high-speed maneuvers. Additionally, integrating real-world driver inputs would ensure that simulations more accurately reflect actual driving behavior. Conducting further experimental validation of the model will also contribute to enhancing the accuracy and reliability of the findings, ultimately leading to more informed design decisions in the optimization of vehicle dynamics.

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