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DYNAMIC MODEL DEVELOPMENT AND AUTOMOTIVE DYNAMICS SIMULATION UTILIZING MATLAB/SIMULINK

Truong Van Men[1*], Thanh Duy Cao[2], Huyen Tran Tran[3], Thanh Banh Huynh[4]

Abstract – *Automobiles are recognized as the primary mode of transportation in developed countries, driving increasing demand for vehicles that meet user needs. As a result, significant time and resources have been dedicated to research and advancements in automobile manufacturing. In this study, a dynamic model of an automobile was developed using MATLAB/Simulink. The vehicle's technical specifications were incorporated into the model to enable simulations. Simulations were performed with the vehicle operating on three different road types, under three wind levels, varying overload conditions, and road gradients. The results showed that the dynamic characteristics of the 2020 Toyota Innova 2.0G varied based on speed across three road types: dry asphalt, wet asphalt, and snow-covered roads. Wind speed conditions were found to reduce speed by 4.3% at wind level two and 12.9% at wind level four compared to calm conditions. Overloading was observed to affect the drivetrain and chassis systems, with torque at the driven wheels increasing proportionally to the overload level. During uphill driving, engine power overload occurred during gear shifts at lower transmission ratios, requiring adjustments to the automatic transmission to maintain the appropriate gear position, despite the optimal speed thresholds for shifting. This dynamic automobile model, developed using MATLAB/Simulink, serves as a foundation for further automotive dynamics research. Technical parameters can be modified to match specific input conditions, facilitating the evaluation of dynamic improvements in vehicle design and manufacturing processes. This approach significantly reduces the time and resources needed for research efforts.*

***Keywords:* automotive dynamics, MATLAB/Simulink for the vehicle, Toyota Innova, vehicle simulation.**

[1,2,3,4]Tra Vinh University, Vietnam

*Corresponding author: tvmen@tvu.edu.vn

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I. INTRODUCTION

The field due to its cost-effectiveness and ability to provide precise automotive dynamics has seen a surge in research activity in recent years, with scholars employing various methods to evaluate the dynamic behavior of vehicles, which involves intricate interactions among multiple vehicle components. Among these methods, simulation-based assessments have gained widespread popularity and numerical results promptly. For instance, Ha Huy Giap [1] utilized MATLAB/Simulink to construct a dynamic model simulating automotive dynamics, including wheel interaction with the road surface. The research indicated that the vehicle body's dynamic model interacts with the wheel model and the road surface. Di Martino et al. [2] conducted a study analyzing the impact of tires on automotive dynamics using MATLAB/Simulink. The results showed that different tire specifications affect the vehicle's dynamic characteristics. This allows for optimization of tire specifications depending on various purposes or terrains to enhance automotive dynamics. Shakouri et al. [3] focused on longitudinal vehicle dynamics using MATLAB/Simulink. They concluded that the simulation results exhibit a strong correlation between throttle position variations and vehicle speed concerning the vehicle's dynamic model. Kumar [4] simulated the operation of an electric vehicle's powertrain in the MATLAB/Simulink environment. Monteirol et al. [5] developed a direct dynamic model for passenger cars in MATLAB/Simulink. Their research provides a versatile automotive dynamics model that can be easily adjusted and modified to suit various studies related to automotive dynamics. In addition to developments in electric vehicle technology, researchers like Nayak et al. [6] modeled and analyzed the performance of electric vehicles. Their study assessed the influence of parameters such as voltage and energy of the battery, torque, rated power of the motor, and transmission ratio on vehicle performance and energy consumption. Furthermore, Sziki et al. [7] modeled and simulated the dynamics of a prototype racing car in MATLAB/Simulink, using various types of electric motors. The results demonstrated that both automotive dynamics and electric motor simulation programs operate effectively, yielding congruent measurement and simulation results.

The collective findings from these studies underscore the growing importance of MATLAB/Simulink simulation software in the assessment of automotive dynamics. This trend highlights the software's versatility in constructing dynamic models and evaluating various aspects of vehicle performance, including speed, ride comfort, and acceleration. In line with this trend, our research aims to develop a dynamic simulation model for the Toyota Innova, a popular automobile in Vietnam. By examining the impact of road conditions, wind speed, and vehicle load on the vehicle's motion performance, this study aims to evaluate the suitability of its powertrain system under various operating scenarios. This effort will contribute to the ongoing progress in automotive dynamics research and technology.

II. MODELING VEHICLE DYNAMIC SYSTEM IN MATLAB/SIMULINK

A. Functional blocks in MATLAB/Simulink for vehicle dynamics

To study the dynamics of the Toyota Innova vehicle using MATLAB/Simulink, the block diagram model is constructed with the following main blocks: (i) The Vehicle Body block plays a central role in connecting various vehicle components. (ii) The powertrain system comprises of main blocks: Engine block, Torque Converter block, 6-Speed Lepelletier, Differential, and Tire block. (iii) Input and Output Block: The Input Control block regulates parameters such as throttle position, wind speed, and the angle of inclination of a road. The Gear Control block determines the gear input conditions based on vehicle speed. The Scope block generates graphical simulation output, while the To Workspace block exports simulation data.

B. Parameters used for simulating the dynamics of the 2020 Toyota Innova 2.0G car

The manufacturer-specified technical parameters are incorporated into the blocks of the model to implement simulation as presented in Table 1. The Magic Formula coefficients and the rolling resistance for different types of roads are shown in Table 2 [8, 9]. Additionally, the relationship between wind level and wind speed is also summarized in Table 3.

Table 1: Specifications of Toyota Innova 2.0G (2020)

Parameters	Value
Overall dimension (length × width × height) (mm)	4735×1830×1795
Wheelbase (mm)	2750
Distance between the center of the front and rear wheel (mm)	1530/1540
Minimum Ground Clearance (mm)	178
Minimum turning radius (m)	54
Kerb weight (kg)	1755
Gross weight (kg)	2380
Maximum output kW @ RPM	102/5600
Maximum torque Nm @ RPM	183/4000

Table 2: The coefficient matrix and rolling resistance of different road types

Type of road	Coefficient matrix				Rolling resistance
	B	***C***	***D***	***E***	
Dry asphalt road	10	1.9	1	0.97	0.011
Wet asphalt road	12	2.3	0.82	1	0.013
Snow road	5	2	0.3	1	0.016

Table 3: Wind level versus wind speed

Wind level	Wind speed (m/s)
0	0
2	2.5
4	6.7

C. Dynamic model of the 2020 Toyota Innova 2.0G car in MATLAB/Simulink

To construct the dynamic model of the Toyota Innova 2.0G vehicle in MATLAB/Simulink, blocks representing each component of the car are established and interconnected. The model is designed to fulfill the functionality of a four-wheel-drive vehicle with a rear drive axle. The Vehicle Body block plays a central role in linking the components together. The Engine block generates power, which is then transmitted to the torque converter and subsequently to the 6-speed automatic transmission (6-Speed Lepelletier) block. This Transmission block is controlled by the Gear Control block, which sets the gear based on the vehicle's speed and outputs a signal to the transmission. The torque after the transmission is transmitted to the differential, which distributes force to the two driven wheels. The Input Control block sets the throttle angle to control the engine's operating mode and also sets the road gradient and wind speed affecting the vehicle while running. This data is fed into the Vehicle Body block. The Scope block and the To Workspace block, which outputs simulation data, are connected to the Vehicle Body block to capture speed, power from the engine, and slip coefficient from the wheels. The MATLAB/Simulink model for simulating the vehicle dynamics of Toyota Innova 2.0G is depicted in Figure 1.

To obtain research results, several hypotheses were formulated for real-world driving scenarios:

(i) The vehicle is driven on three common road types, experiencing three levels of wind, and then evaluated based on the rolling resistance of each road type, which affects the vehicle's dynamics in terms of speed and engine power.

(ii) Evaluating how overloading the vehicle by 10% and 20% affects its dynamic behavior.

(iii) Assuming the vehicle drives uphill linearly after 50 seconds of simulation, starting with inclines of 4, 7, and 10 degrees.

III. SIMULATION RESULTS AND DISCUSSION

A. Effects of road conditions and wind speed on vehicle dynamics

In this study, the vehicle's performance was simulated across three road types: dry asphalt, wet asphalt, and snowy surfaces. Each road condition was evaluated under three wind levels: 0, 2, and 4. The results, as shown in Figure 2, demonstrate that both the Magic Formula coefficient and rolling resistance coefficient significantly influence vehicle dynamics.

Under windless conditions, the maximum speeds achieved were 177.2 km/h on dry asphalt, 169.7 km/h on wet asphalt (a 4.2% reduction), and 141.2 km/h on snowy roads (a 20.4% reduction compared to dry asphalt) as presented in Figures 2(1a), 2(1b), and 2(1c). Increasing wind levels resulted in reduced maximum speeds. For instance, on dry asphalt, the maximum speed decreased by 4.3% at wind level 2 and by 12.9% at level 4 (as shown in Figure 2(1a). Similar patterns were observed for wet asphalt and snowy roads as presented in Figures 2(1b), and 2(1c). Acceleration performance varied across road types. Dry asphalt had the shortest time to reach 100 km/h (22.9 s) (Figure 2(1a)), followed by wet asphalt (26.4 s) (Figure 2(1b)) and snowy roads (36.4 s) (Figure 2(1c)). Higher wind levels extended the time required to reach 100 km/h. From Figure 2(2a–2c), it can be seen that under windless conditions and on dry asphalt, the engine delivered a maximum power of 95.4 kW, which represents 93.53% of the manufacturer's specified maximum power of 102 kW. On wet asphalt, engine power was 93 kW, and on snowy roads, it was 62.6 kW. At wind levels 2 and 4, engine power dropped to 93 kW and 88.3 kW, respectively.

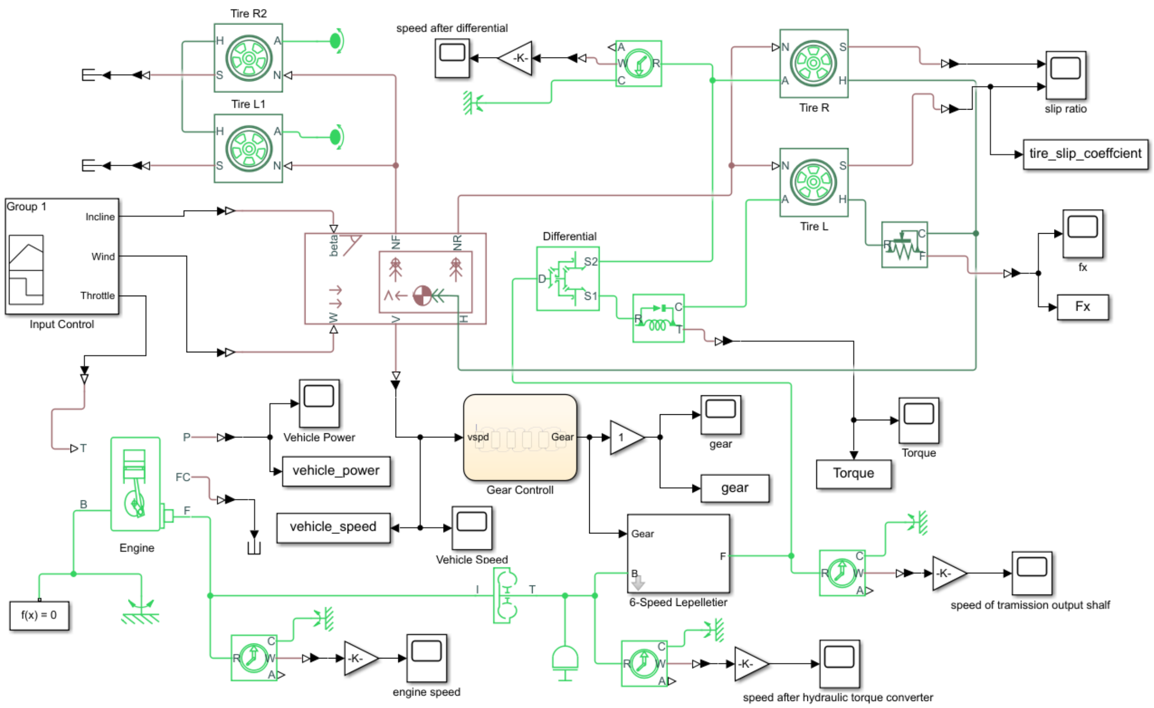

Fig. 1: The automotive dynamics model in MATLAB/Simulink

Maximum torque was observed at step 2 under windless conditions, reaching 1649.8 Nm on dry asphalt (Figure 2(4a)). For wet asphalt and snowy roads, maximum torque values were 1367.6 Nm and 509.2 Nm, (Figure 2(4b–4c)), respectively. Notably, higher wind levels did not alter maximum torque at time step 2. The slip coefficient, which reflects tire-wheel torque, peaked during maximum torque. Higher rolling resistance coefficients increased slip values. Under windless conditions, the maximum slip coefficient at peak torque was 0.41 on dry asphalt, 0.48 on wet asphalt (a 17% increase), and 0.9 on snowy roads (a 119.5% increase) as observed in Figure 2(5a–5c).

This simulation highlights how specific road characteristics, defined by the Magic Formula coefficient and rolling resistance coefficient, affect vehicle velocity. Additionally, elevated wind levels reduce vehicle speed and acceleration capabilities, resulting in longer times to achieve the desired speed.

B. Effects of overloading on vehicle dynamics across different road types

In this study, overloading beyond the manufacturer's specifications was introduced to assess its effects on vehicle performance. Simulations were conducted for the vehicle operating on three road types, including dry asphalt, wet asphalt, and snowy roads. Each road type was evaluated under three loading conditions: full load (2,380 kg), 10% overload (2,618 kg), and 20% overload (2,856 kg), with wind conditions fixed at level 2. The simulation results are presented in Figure 3. The findings revealed that overloading had minimal impact on the vehicle's maximum speed across all road types. On dry asphalt, the maximum speed was 169.8 km/h at full load, 169.2 km/h with a 10% overload, and 168.7 km/h with a 20% overload (Figure 3(1a)). On wet asphalt and snowy roads, speed variations were slight, remaining within a 5 km/h range (Figure 3(1b–1c)). However, overloading significantly affected the

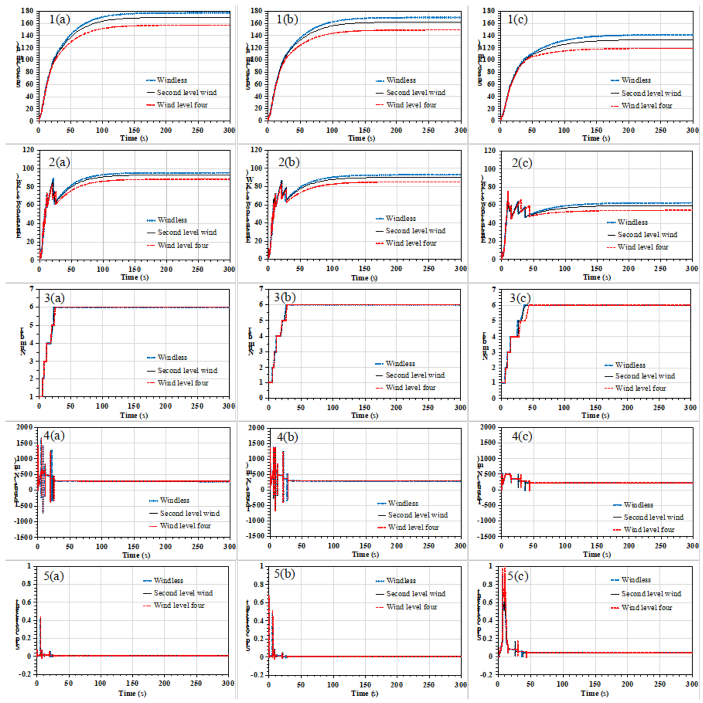

Fig. 2: The influence of road type and wind level on automotive dynamics: (a) dry asphalt road, (b) wet asphalt road, (c) snowy road

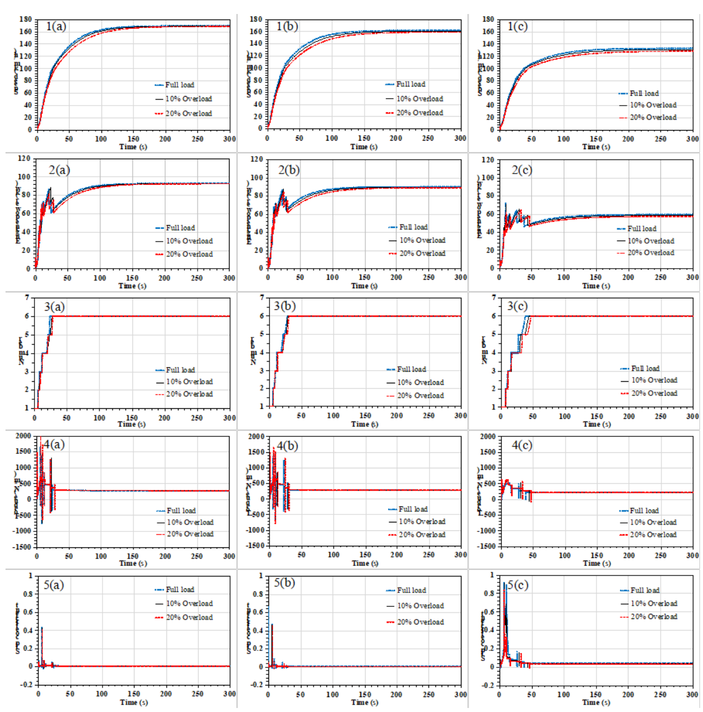

Fig. 3: The effect of load on automotive dynamics at different road types: (a) dry asphalt, (b) wet asphalt, (c) snowy roads

vehicle's acceleration performance. For instance, on dry asphalt, the time to reach a standardized speed of 168 km/h increased from 139.8 seconds at full load to 159 seconds under a 10% overload (a 14.2% increase) and 197.2 seconds under a 20% overload (a 41% increase).

Engine power consumption was minimally influenced by overloading. From Figure 3(2a–2c), on dry asphalt, the engine consumed 93 kW at full load, decreasing slightly to 92.8 kW with a 10% overload and 92.5 kW with a 20% overload. Overloading primarily affected gear shifting dynamics, delaying shifts and increasing torque at the driven wheels proportionally to the degree of overloading. On dry asphalt, maximum torque at gear level 2 was 1,650 Nm at full load, rising to 1,816.7 Nm under a 10% overload (a 10.1% increase) and 1,981.22 Nm under a 20% overload (a 20% increase) as presented in Figure 3(4a–4c). The slip coefficient decreased as vehicle weight increased. On dry asphalt, the slip coefficient was 0.44 at full load, 0.43 under a 10% overload (a 2.3% decrease), and 0.40 under a 20% overload (a 9% decrease) (Figure 3(5a–5c). These changes indicated a reduced tire-slip interaction with increased load.

In summary, the overloaded scenario showed that torque at the driven wheels increased proportionally with load, enhancing interaction forces between the wheels and the chassis across all road types. This highlights that overloading primarily impacts the vehicle's transmission system and chassis, emphasizing the importance of maintaining load limits for optimal performance and durability.

C. The effect of road inclination angle on vehicle dynamics

In this investigation, the vehicle will initially move on a flat road for 50 seconds before transitioning to slopes of 4, 7, or 10 degrees. To replicate real-world conditions, simulation parameters were set for the vehicle to traverse three distinct road types: dry asphalt, wet asphalt, and snowy roads, with a fixed wind at level 2, equivalent to 2.5 m/s. The outcomes of these simulations are presented in Figure 4. The results revealed that the vehicle attained its highest speeds on dry asphalt across all slope gradients compared to wet asphalt and snowy roads. However, challenges emerge on 4^o and 10^o inclination angles, where the vehicle experiences instability. For instance, on a 4^o slope, the vehicle's velocity drops to 88.7 km/h while in gear 5 as shown in Figure 4(1a). Despite accelerating to 100 km/h at 222.1 seconds, the automatic transmission shifts to gear 6, leading to an inability to sustain speed due to engine power overload. This results in a gradual speed reduction below 90 km/h, prompting a downshift to gear 5. Although reducing engine power momentarily restores speed to 100 km/h and triggers an upshift to gear 6, the cycle repeats due to recurring engine power overload, leading to instability. Similar challenges occur on a 10^o slope but at lower gear levels. Conversely, on wet asphalt as plotted in Figure 4(1b), the vehicle maintains stability across all slope gradients, while on snowy roads, stability is achieved only on 4^o and 7^o slopes. Notably, when simulating snowy conditions, the onset of linear slope increase after 50 seconds initiates a sequence where the vehicle initially ascends due to inertia. Subsequently, speed and gear level decrease, triggering slippage at time step 3 (106 seconds). This necessitates a downshift to gear 2 (115 seconds) and further to gear 1 (121 seconds), culminating in complete slippage when the slip coefficient exceeds 1. The torque chart reveals significant negative values during gear shifts from high to low, indicating engine-driven torque disconnection from the driven wheels, resulting in uphill resistance force acting oppositely on the wheels (Figure 4(4a–4c)). However, this brief occurrence does not affect vehicle smoothness, as the duration is minimal. For instance, on dry asphalt with a 10^o slope, the largest negative torque value occurs at gear 5, measuring 421 Nm at 103.54 seconds, decreasing to (-1798.8 Nm) at gear 4 after a mere 0.07 seconds, imperceptible to occupants. Overall, these findings underscore the vehicle's dynamic instability upon reaching optimal speed thresholds for gear shifts,

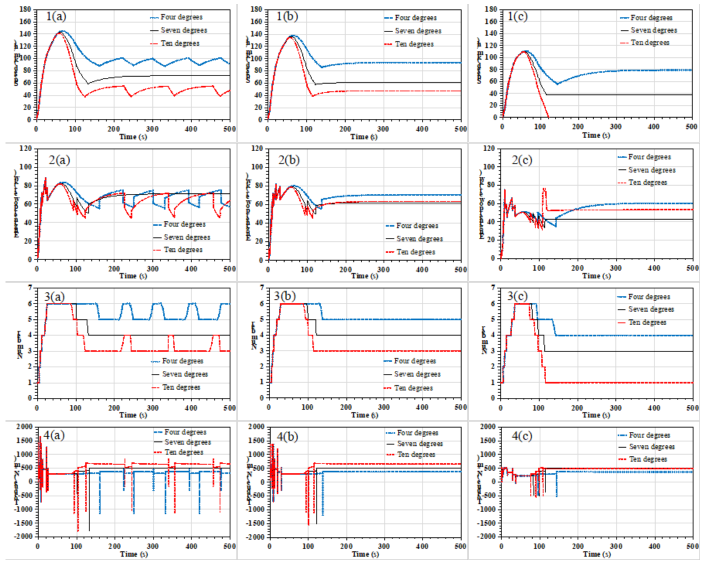

Fig. 4: The influence of road gradient on the dynamics of automobiles across different road types: (a) dry asphalt, (b) wet asphalt, and (c) snowy roads

accentuating the need for gearbox adjustments to maintain suitable gear levels despite appropriate shifting speed thresholds.

D. The impact of degraded engine power on the vehicle dynamics

In this simulation scenario, it is assumed that the engine power degraded over operational time, affecting the vehicle's dynamics. In addition, simulation conditions for the vehicle were on three different road types: dry asphalt, wet asphalt, and snowy roads, with the wind level fixed at level two. The engine power was simulated at three hypothetical levels: maximum power as per the manufacturer's specification (102 kW), degraded by 10% (91.8 kW) and degraded by 20% (81.6 kW). The simulation results demonstrated that engine power significantly influenced the vehicle's dynamics. Specifically, on dry asphalt as plotted in Figure 5(1a), when the engine power is not reduced, the vehicle achieves a maximum speed of 169.7 km/h. When the engine power is reduced by 10%, the vehicle's speed decreases to 161.4 km/h (a 4.9% decrease), and when the engine power is reduced by 20%, the speed further decreases to 152.2 km/h (a 10.3% decrease). Similar trends are observed on wet asphalt and snowy roads, where the vehicle's speed decreases as the engine power decreases. The decrease in engine power results in a power deficit compared to the specified rating. For example, from Figure 5(2a), on dry asphalt, with the specified maximum engine power of 102 kW, the actual engine power output is 93 kW, resulting in an 8.8% deficit. When the engine power is reduced by 10% to 91.8 kW, the actual engine power output decreases to 80.8 kW (a 12% deficit), and when reduced by 20% to 81.6 kW, the actual engine power output decreases to 68.8 kW (a 15.6% deficit). The downshifting process is affected by the decrease in engine power, as it causes a decrease in vehicle acceleration, leading to delayed downshifting. For instance, on dry asphalt, the time taken for downshifting at gear 6 increases from 23.6 seconds when the engine power is not reduced to 30 seconds when reduced by 10%, and further to 34.2 seconds when reduced by 20%. The decrease in engine power also leads to a reduction in torque at the driven wheels, especially at high gear ratios (Figure 5(4a–4c)). For example, on dry asphalt, at gear position 5, the maximum torque is 1,249.8 Nm when the

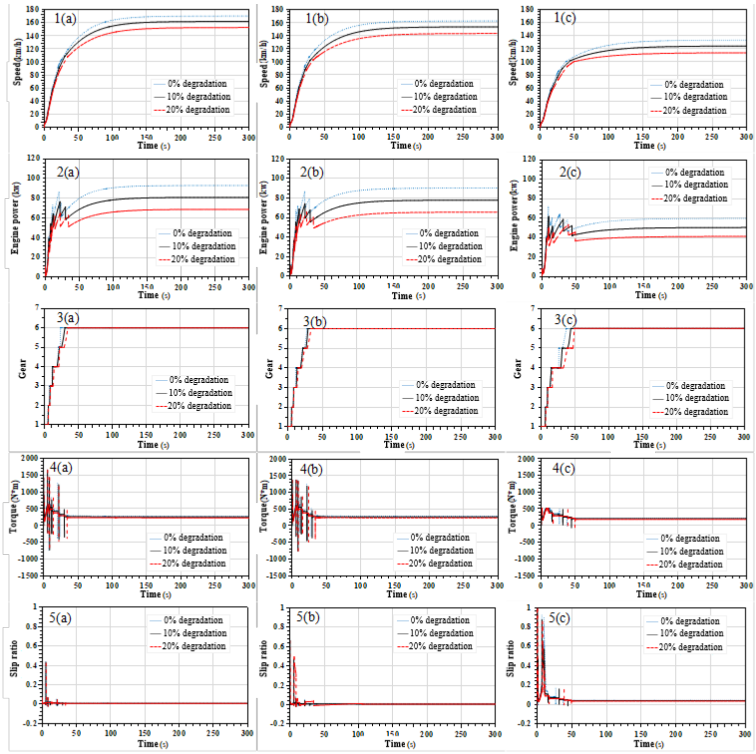

Fig. 5: The effect of degraded engine power on vehicle dynamics on various road types: dry asphalt (a) dry asphalt, (b) wet asphalt, and (c) snowy roads

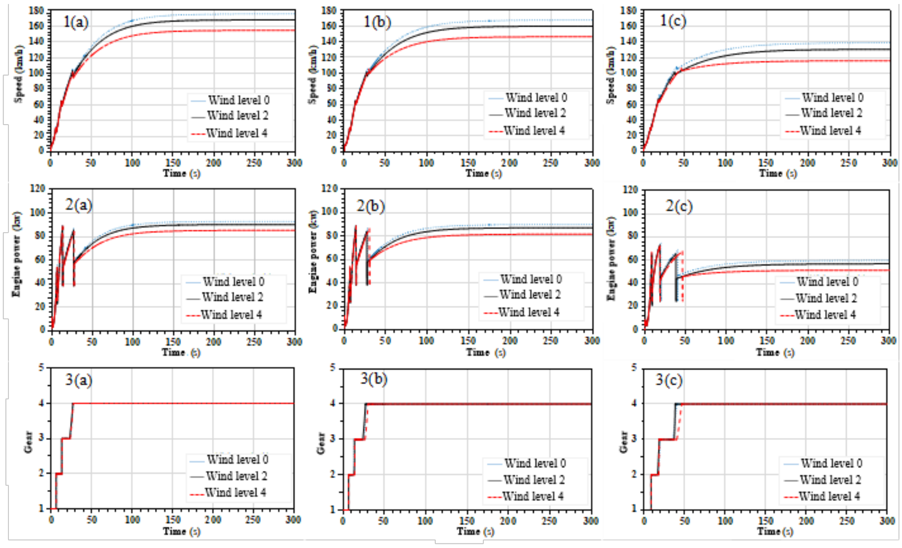

Fig. 6: The impact of gear ratios in a 4-speed transmission on different road surfaces: (a) dry asphalt, (b) wet asphalt, (c) snowy

engine power is not reduced. When the engine power is reduced by 10%, the torque decreases to 1,218 Nm (a 2.5% decrease), and when reduced by 20%, the torque decreases further to 1,160.5 Nm (a 7.1% decrease). Additionally, the decrease in engine power results in a decrease in the slip coefficient on snowy roads. For example, at gear position 3, the maximum slip coefficient is 0.89 when the engine power is not reduced. When the engine power is reduced by 10%, the slip coefficient decreases to 0.42, and when reduced by 20%, it further decreases to 0.27 as depicted in Figure 5(5c).

Overall, the simulation results indicate that a degradation in engine performance led to a reduction in acceleration and maximum vehicle speed. The torque at the driven wheels is affected only at high gear ratios, and the slip coefficient decreases as the engine power decreases.

E. Effect of the number of transmission gear ratio on vehicle dynamics

In this simulation case, the configuration parameters for the vehicle were tested across three different road surfaces: dry asphalt, wet asphalt, and snowy roads. Each road condition was simulated under three wind levels: windless condition, moderate breeze (level two), and strong wind (level four). The comparison was made between a 4-speed automatic transmission and a 6-speed automatic transmission system. The simulation results for the 4-speed automatic transmission are depicted in Figure 6(1a–3c), while those for the 6-speed automatic transmission are shown in Figure 7(1a–3c). Regarding maximum vehicle speeds, both transmission systems exhibit minor disparities. Specifically, on dry asphalt without wind (Figure 6(1a)), the 4-speed automatic transmission achieves a top speed of 175.5 km/h, while with a level two wind, it reaches 167.8 km/h, and with a level four wind, it attains 154.6 km/h. Whereas, the 6-speed automatic transmission achieves slightly higher speeds, reaching 177.2 km/h without wind, 169.8 km/h with a level two wind, and 156.9 km/h with a level four wind as presented in Figure 7(1a). However, there is a notable difference in acceleration performance between the two transmission systems as observed in these figures. On dry asphalt, the 6-speed automatic transmission demonstrates faster acceleration from 0 to 100 km/h compared to the 4-speed automatic transmission. For instance, without wind, the 6-speed transmission achieves this in 22.9 seconds, while the 4-speed transmission takes 25.5 seconds. Furthermore, the speed profiles depicted in Figure 7(1a–1c) reveal that the 4-speed automatic transmission experiences a decrease in speed during gear shifts, particularly noticeable on dry asphalt. For instance, when shifting to fourth gear on dry asphalt without wind, the vehicle's speed drops from 105.2 km/h to 98.7 km/h before gradually increasing again. This drawback is significant when comparing vehicles equipped with fewer gear ratios to those with six or more, as the latter provides smoother speed transitions, enhancing user comfort. In terms of engine power (as shown in Figure 7(2a–2c)), vehicles equipped with the 4-speed automatic transmission exhibit significant power fluctuations during gear shifts compared to those with the 6-speed transmission. For example, when shifting to third gear on dry asphalt without wind, the engine power output for the 4-speed transmission drops abruptly from 89.5 kW to 38.3 kW within 0.3 seconds. Conversely, the engine power fluctuation is less pronounced with the 6-speed transmission, with a decrease from 52.7 kW to 38 kW over 0.19 seconds under similar conditions. While both transmission systems show similar torque profiles and slip coefficients, the evaluation indicates that the 4-speed automatic transmission suffers from drawbacks such as speed instability and significant engine influence during gear engagement. However, despite its economic advantages, the 6-speed automatic transmission incurs higher costs and maintenance expenses.

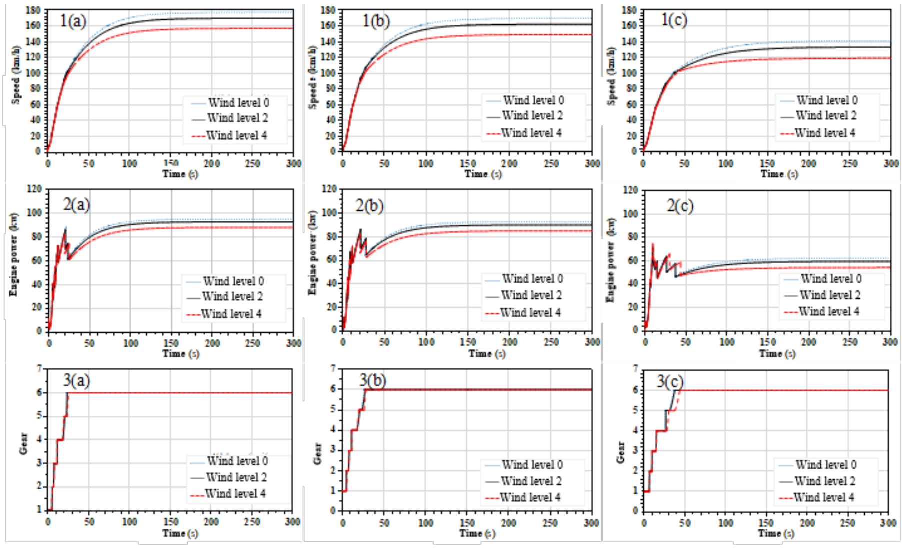

Fig. 7: The effect of gear ratios in a 6-speed transmission across different road surfaces: (a) dry asphalt, (b) wet asphalt, (c) snowy roads

IV. CONCLUSION

In summary, this study effectively employed MATLAB/Simulink software to create a dynamic simulation model for the 2020 Toyota Innova 2.0G. It highlighted the significant influence of diverse road surfaces, characterized by varying 'Magic Formula' coefficients and rolling resistance, on the vehicle's dynamics. Notably, the vehicle attained a speed of 177.2 km/h on dry asphalt, with reductions of 4.2% and 20.4% on wet asphalt and snowy roads, respectively. Wind intensity also played a pivotal role, with level two and level four winds resulting in speed decreases of 4.3% and 12.9% compared to calm conditions. Furthermore, overloading impacted both the transmission system and chassis, evidenced by the proportional increase in wheel torque with overloading levels. Climbing slopes exacerbated engine power overload during gear shifts with lower transmission ratios, necessitating adjustments to maintain appropriate gear positions despite suitable speed thresholds for shifting. Additionally, the study highlighted the significant impact of transmission gear ratios on vehicle smoothness, with the 6-speed automatic transmission exhibiting smoother acceleration than the 4-speed counterpart. Overall, the dynamic model of the Toyota Innova, developed using MATLAB/Simulink, proves to be a versatile platform for automotive dynamics research. By conveniently adjusting technical parameters within blocks and input conditions, such as engine, transmission system, vehicle body, and wheels, researchers can efficiently conduct various related studies, leading to time and cost efficiencies in research endeavors.

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