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COMPARING THE ACCELERATION CAPABILITY AND POWER TRANSMISSION OF A 4-SPEED AUTOMATIC TRANSMISSION AND A CVT TRANSMISSION IN A TOYOTA VIOS USING DYNAMIC SIMULATION

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Abstract

This study presents a comparative analysis of the acceleration capability and power transmission characteristics of two transmission configurations—a 4-speed automatic transmission (4AT) and a continuously variable transmission (CVT)—equipped on the 2015 and 2016 Toyota Vios. With the same engine platform and specifications, longitudinal dynamic simulation was performed using CarSim software to evaluate the impact of each transmission type on speed, longitudinal acceleration, wheel torque, and longitudinal traction force. The results show that the CVT maintains continuous power transmission and provides better acceleration in the low to medium speed range thanks to its smooth variable transmission ratio and ability to keep the engine operating near its optimal torque range. Conversely, the 4AT generates greater initial wheel torque but experiences torque and acceleration drops during gear shifts, reducing acceleration performance. At high speeds, the difference between the two configurations diminishes due to the predominant influence of aerodynamic drag. The research results confirm the CVT's advantage in terms of continuous power transmission and acceleration efficiency, while also demonstrating the effectiveness of CarSim in simulating and evaluating the drivetrain characteristics of small passenger cars.

Keywords: *4-speed automatic transmission (4AT); Continuously Variable Transmission (CVT); CarSim simulation; Longitudinal dynamics; Wheel traction force; Vehicle acceleration; Power transmission system.*

1. Introduction

In recent years, improving powertrain efficiency, enhancing acceleration capability, and optimizing operational performance have become key priorities in passenger vehicle development. The two most popular transmission technologies today are the multi-speed automatic transmission (AT) and the continuously variable transmission (CVT). Numerous studies have demonstrated that CVT can significantly improve fuel efficiency and reduce emissions by continuously adjusting the gear ratio, enabling the engine to operate in its optimal efficiency range [1], [2]. Simulation results and real-world testing also indicate that, when properly controlled, CVTs can achieve superior performance compared to traditional automatic transmissions and manual transmissions under various operating conditions [3], [4].

In the field of hybrid and electric vehicles, CVTs continue to demonstrate significant advantages. For example, research by Shabbir and Evangelou shows that the transmission ratio control strategy plays a decisive role in the overall efficiency of a series hybrid powertrain [5]. More recent studies focus on optimizing the virtual shift characteristic curve, coordinating the

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power source and CVT to improve energy efficiency and smoothness of the powertrain system [6]. Not only appearing in passenger cars, CVTs have also been extensively studied in two-wheeled vehicles and ATVs, where pulley design optimization, belt friction, and control strategy have been shown to have a particular impact on acceleration capability and powertrain performance [7]–[9].

In terms of modeling and control, many studies have focused on developing detailed dynamic models of CVTs, including belt/chain models, pulley radius variation mechanism models, and clamping force models. Aladağlı's doctoral thesis is one of the foundational studies, comprehensively describing models and advanced control methods for various CVT configurations [10]. Previous studies on V-belt CVTs emphasized the relationship between transmission ratio, clamping force, slip, and efficiency [11]; while Ide analyzed the effect of transmission ratio change speed on vehicle acceleration response [12]. Reviews on CVT control affirm the diversity of control strategies based on torque, power, efficiency, or operational requirements, while emphasizing the importance of accurate dynamic modeling in controller design [13]. Recent works focus on slip control, pulley pressure control, and power transmission stability in CVTs, contributing to improved reliability and operational efficiency [14]–[17]. Additionally, numerous review articles, mathematical models, or experimental evaluations continue to expand understanding of CVTs in various application contexts [18]–[22].

Meanwhile, multi-speed automatic transmissions (AT) remain important in the automotive industry due to their proven durability, load capacity, and operational quality. Research on AT focuses on transmission modeling, kinematic analysis of shifting processes, development of adaptive control strategies, and optimization of shifting quality [23], [24]. Many modern studies emphasize optimizing the shifting process to reduce torque fluctuations and increase smoothness through control algorithms and automatic adjustments [25], [26]. Kinematic models during shifting have also been developed to study torque transmission, torsional vibrations, and shift quality [27], [28].

The trend of integrated control between the engine and transmission is also growing. For CVTs, coordinated control has been shown to improve both fuel economy and smoothness [29]. For ATs, automatic calibration methods help shorten experimental calibration time and improve shift quality [30]. At the system level, real-time simulation and driver simulation are widely used in powertrain development and control strategy development [31], [32].

In the field of vehicle longitudinal dynamics, many studies have developed models for estimating traction force, longitudinal dynamic characteristics, and vehicle parameters from measured or simulated data [33], [34]. Longitudinal models are also applied to speed control, traction control, and energy consumption optimization in many types of vehicles [35], [36]. Studies on longitudinal force distribution and the relationship between traction and acceleration capability show a significant impact on powertrain performance and motion stability [37]. Automotive powertrains are also affected by torsional vibrations, and numerous studies have analyzed the impact of elastic elements, drive shafts, couplings, and dampers on vibration, noise, and shift quality [38]–[41].

The rapid development of traffic simulation, power transmission, and vehicle automation continues to increase the demand for accurate power transmission models [42], [43]. At the same time, CAE tools remain crucial in power transmission simulation and design, laying the foundation for modern simulation methods [44]. Numerous in-depth studies on hydraulic

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control, shift quality analysis, belt slip simulation, and self-excited vibration in transmission systems have provided the theoretical basis for detailed evaluation of transmission systems [45]–[49].

In recent years, research in the Asian region has also focused on CVT modeling, test bench design, power transmission surveys, and transmission simulation using specialized software [50]–[52]. Several theses and dissertations have studied CVT tuning, transmission ratio control, and powertrain performance simulation [53]. Additionally, research on optimizing power transmission losses, improving energy efficiency, and lubrication design in transmissions continues to expand [54], [55]. Optimization methods for vehicle and powertrain parameters based on dynamic models also indicate a growing reliance on simulation for evaluating and selecting powertrain configurations [56].

Although there have been many in-depth studies on CVT, AT, and vehicle longitudinal dynamics, a scientific gap remains: very few studies have directly compared the acceleration capabilities and transmission characteristics between two different types of transmissions on the same vehicle platform, with all other parameters held constant. Most previous studies used different vehicle models or inconsistent test conditions, making it difficult to accurately conclude the extent of each transmission type's influence.

This study aims to address that gap by performing longitudinal dynamic simulations to compare the systems between a 4-speed automatic transmission (4AT) and a continuously variable transmission (CVT), equipped respectively on two versions of the 2015 Toyota Vios and 2016 Toyota Vios. These are two vehicle versions with the same mechanical platform, the same 1.5L gasoline engine, the same geometric parameters and mass, and the only significant difference lies in the type of transmission. Therefore, any differences in acceleration, wheel torque, longitudinal traction, and operational response can be directly attributed to the characteristics of the powertrain system.

2. System Model

2.1. Overall powertrain model

In longitudinal dynamics simulation of automobiles, the powertrain model plays a crucial role in determining how engine torque is transmitted to the wheels and converted into traction force acting on the vehicle. To ensure an objective comparison between the 4AT and CVT transmissions, this study establishes a general powertrain model applicable to both vehicle configurations. This model describes the kinematic, dynamic, and motion equations of the vehicle.

2.1.1. Kinematic relationship between the wheels and the transmission output shaft

In a front-wheel drive powertrain system, the rotational speed of the output shaft of the transmission is determined by the speed of the two driven wheels and the differential gear ratio.

$$\omega_g = 0.5(\omega_{whLF} + \omega_{whLF})N_{diffF} \tag{1}$$

Where:

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ω_g: angular speed of the transmission output shaft

ω_{whLF}: angular velocity of the left front wheel

ω_{whLF}: angular velocity of the right front wheel

N_{diffF}: Front differential gear ratio

The formula shows that the differential performs the function of adjusting the speed between the transmission shaft and the wheels, while reflecting the direct relationship between vehicle speed and the speed of the drivetrain. This relationship is an important basis for determining the response speed of the transmission, especially when comparing AT and CVT transmissions.

2.1.2. Torque distribution through the differential

After torque from the transmission is transmitted to the differential, the differential distributes torque to the two driven wheels. In the case of straight-line driving and normal drivetrain operation, torque is evenly distributed to both wheels according to the formulas:

$$M_{yLF} = 0.5T_g N_{diffF} E_{diffF} \tag{2}$$

$$M_{yRF} = 0.5T_g N_{diffF} E_{diffF} \tag{3}$$

Where:

M_{yLF}, M_{yRF}: torque at the left and right wheels

T_g: torque at the transmission output shaft

E_{diffF}: power transmission efficiency of the differential

The two formulas above describe the ideal torque distribution mechanism in the differential, while also considering the efficiency factor – a factor that significantly affects the actual power transmission capacity of the vehicle.

2.1.3. Differential lock torque model

Under actual operating conditions, a speed difference between the two wheels may occur, causing slippage. To simulate this situation, the differential model includes an additional differential lock torque component, described by the formula

$$T_{lock} = K_{lockF}(\varphi_{LF} - \varphi_{RF}) + D_{lockF}(\omega_{LF} - \omega_{RF}) \tag{4}$$

T_{lock}: the additional locking torque acting on the differential.

K_{lockF}: torsional stiffness coefficient, describing the ability to resist angular position differences between the two output shafts of the differential.

D_{lockF}: damping coefficient, describing the ability to resist speed differences between the two wheels.

φ_{LF}, φ_{RF}: angular position of the two driven wheels.

ω_{LF}, ω_{RF}: Angular speed of the two wheels.

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This mechanism enhances vehicle stability during rapid acceleration or when driving on slippery surfaces, while also improving traction.

2.1.4. Longitudinal traction at the wheels

After the torque has been distributed to each wheel, the longitudinal traction force is determined using the formula:

$$F_x = \frac{M_y}{r_w} \tag{5}$$

Where:

F_x: longitudinal traction force acting on the wheel.
M_y: torque acting on the wheel.
r_w: rolling radius of the wheel.

The total traction force affecting the vehicle's motion is the sum of the forces acting on the two driven wheels:

$$F_{tractive} = F_{xLF} + F_{xRF} \tag{6}$$

2.1.5. Longitudinal dynamic equation of the vehicle

The longitudinal motion of the vehicle is described by the equation:

$$m\dot{v} = F_{tractive} - F_{drag} + F_{roll} \tag{7}$$

Where:

m: total mass of the vehicle.

$\dot{v}$: longitudinal acceleration of the vehicle.

F_{drag}: aerodynamic drag force, which increases with the square of the velocity.

F_{roll}: rolling resistance of the tires.

This equation allows the simulation of velocity and acceleration over time based on the traction force generated by the wheel torque.

2.2. 4-speed automatic transmission model

The 4-speed automatic transmission (4AT) of the 2015 Toyota Vios is a planetary gear transmission that uses a torque converter to amplify torque in the initial stage and transmit power through fixed gear ratios. Unlike CVT, the 4AT transmission has four discrete gear ratios, selected according to vehicle operating conditions and shift map. Therefore, the mathematical model describing the 4AT transmission is developed based on three main components: gear ratio model, torque transmitted through the transmission, and power transmission efficiency.

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2.2.1. Gear ratio model of the 4AT transmission

In an automatic transmission, the gear ratio is determined for each gear level g=1,2,3,4. The discrete gear ratio selection model is represented as:

$$N_{AT} = N_g N_{diffF} \tag{8}$$

Where:

N_{AT}: total transmission ratio of the power transmission system (transmission + differential).
N_g: the individual gear ratio for each gear, obtained from technical data.

This gear ratio determines the output shaft speed of the transmission and directly affects the output torque, traction force, and acceleration capability.

At each simulation point, the transmission selects a single gear ratio according to the shift map. This is the fundamental difference between 4AT and CVT, as CVT has a continuously variable transmission ratio.

2.2.2. Torque transmitted through the transmission

The output torque of the transmission T_g is determined from the engine torque after passing through the converter and the planetary gear system.

$$T_{gF} = T_{in} N_g E_{AT} N_{trcase} E_{trcase} \tag{9}$$

Where:

T_{gF}: Torque at the output shaft of the transmission, transmitted to the differential.

T_{in}: Torque at the input shaft of the transmission (engine → torque converter).

This model allows the calculation of torque at the transmission output shaft for each gear ratio, thereby determining the torque at the wheel using the formula presented in Section 2.1.

2.2.3. Transmission efficiency of the gearbox

Power transmission efficiency plays a crucial role in determining output torque. In the original document, the efficiency of the transmission components is described as a function dependent on the torque transmission state:

$$E = \begin{cases} E_{drive}, & T_{in} \geq 0 \\ E_{rev}, & T_{in} < 0 \end{cases} \tag{11}$$

Variable meanings:

E_{drive}: efficiency when transmitting power in the forward direction (engine → wheel).

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E_{rev}: efficiency when driving force is transmitted from the wheel back to the engine (deceleration).

In the 4AT transmission, efficiency is modeled according to the above structure because the planetary gear transmission has different losses in the two load states. This directly affects acceleration capability and the ability to maintain speed when the vehicle is going downhill.

2.3. CVT Transmission Model

The continuously variable transmission (CVT) of the 2016 Toyota Vios operates on the principle of continuously changing the transmission ratio through a pair of pulleys with variable effective radii. Unlike a 4-speed automatic transmission (4AT), which uses discrete gear ratios, CVT allows real-time adjustment of the gear ratio to optimize engine speed and power transmission efficiency. In longitudinal dynamics simulation, accurately modeling the CVT transmission is crucial, as it determines the relationship between engine speed, transmission torque, and vehicle acceleration capability.

2.3.1. CVT gear ratio model

In the original document, the transmission ratio of the mechanical transmission is defined based on the angular speed relationship between the input shaft and output shaft

$$N_{CVT} = \frac{\omega_{in}}{\omega_g} \tag{12}$$

Where:

N_{CVT}: CVT transmission ratio.

ω_{in}: angular velocity of the CVT input shaft (from the engine through the torque converter).

ω_g: angular velocity of the CVT output shaft (differential input shaft).

2.3.3. Torque transmission model through CVT

According to the torque transmission structure of the transmission system, the torque at the CVT output shaft is described by:

$$T_{out} = T_{inCVT} N_{CVT} E_{CVT} \tag{13}$$

Where:

T_{out}: Torque at the CVT output shaft (torque transmitted to the differential).

T_{inCVT}: Torque at the CVT input shaft (engine → converter → CVT).

N_{CVT}: transmission ratio at the simulation time.

E_{CVT}: CVT power transmission efficiency.

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The efficiency E_{CVT} is obtained from the general efficiency model of the mechanical transmission system:

$$E_{CVT} = \begin{cases} E_{driveCVT}, & T_{inCVT} \geq 0 \\ E_{revCVT}, & T_{inCVT} < 0 \end{cases} \quad (14)$$

Explanation:

$E_{driveCVT}$: Efficiency when the vehicle is transmitting power in the forward direction (engine pulling the vehicle).

E_{revCVT}: efficiency when power is transmitted backward to the engine (deceleration, engine braking).

3. Results

In this study, the CarSim dynamic simulation software was used to analyze and compare the power transmission capabilities of two transmission configurations: a 4-speed automatic transmission (4AT – Toyota Vios 2015) and a CVT transmission (Toyota Vios 2016). CarSim is one of the most widely used automotive simulation tools in industry and research due to its ability to accurately model vehicle kinematics and dynamics, including power transmission models, suspension systems, engine models, and real-world operating conditions.

Using CarSim allows for the accurate reproduction of the vehicle's acceleration process under standardized conditions, while isolating the influence of each component in the powertrain. To ensure that differences in simulation results stem solely from the structure and characteristics of the transmission, other vehicle specifications—including the engine, vehicle mass, aerodynamic characteristics, geometric dimensions, and tire parameters—are kept identical between the two models. This allows for the elimination of unwanted noise factors, ensuring reliability when evaluating the individual impact of the 4AT and CVT transmission mechanisms.

The simulation input data was set based on the actual parameters of the 2015–2016 Toyota Vios model, combined with the standard vehicle database in CarSim. The main parameters are listed in Table 1.

Table 1. Technical specifications of the vehicle used in the simulation

Parameter Group	Value / Description
Overall dimensions (L × W × H)	4410 × 1700 × 1475 mm
Wheelbase	2550 mm
Unloaded weight	1050 kg
Engine	1.5L, I4, DOHC, VVT-i (code 2NR-FE)
Cylinder capacity	1496 cm³
Maximum power	109 horsepower at 6000 rpm
Maximum torque	141 Nm at 4200 rpm
Drivetrain	FWD – front-engine, front-wheel drive
Wheelbase	0.29 m
Common tire size	185/60R15

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Rolling resistance coefficient (CR)	0.010–0.012 (based on CarSim simulation assumptions)
Aerodynamic drag coefficient (Cd)	0.30–0.32
Wind resistance area (A)	2.0–2.1 m²
Front differential	Fixed gear ratio, common to both models

3.1. Vehicle speed versus time graph

The vehicle speed versus time graph is one of the key indicators for evaluating the acceleration capability of the powertrain during startup and full acceleration. In the longitudinal dynamics model, vehicle speed v(t)v(t)v(t) directly reflects the coordination efficiency between the engine and transmission, while also indicating the degree of wheel torque utilization throughout the acceleration phase. Since the two powertrain configurations—4-speed automatic transmission (4AT) and CVT—use the same engine and simulation conditions, the differences in the velocity graphs fully reflect the differences in the transmission mechanisms of each transmission type.

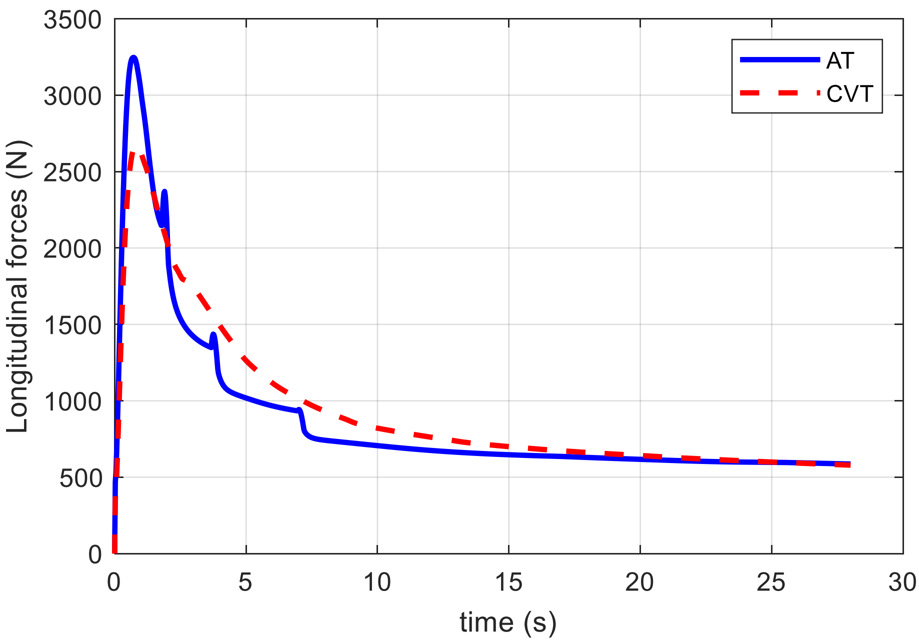

Figure 1. Vehicle speed graph

Figure 1 shows the speed progression of the 2015 Vios (4AT) and 2016 Vios (CVT) during acceleration from a stationary state. It can be seen that the speed curve of the CVT transmission increases continuously and more smoothly than that of the 4AT transmission. In the initial phase (0–40 km/h), the vehicle using CVT achieves a higher speed due to the continuously variable transmission ratio, allowing the engine to remain in the optimal torque range throughout the acceleration process. Conversely, the speed curve of the 4AT transmission exhibits characteristic "breaks" at the 1→2 and 2→3 gear shifts, reducing wheel torque and causing a temporary drop in speed.

This difference is particularly evident in the 0–6 second interval, when the 4AT transmission changes gears and causes torque interruption. After this phase, the two speed curves gradually

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converge as the vehicle reaches medium–high speeds, indicating that the power transmission efficiency of both transmissions becomes comparable as the gear ratio approaches a stable range.

3.2. Acceleration vs. time graph

Longitudinal acceleration a(t)a(t)a(t) is a quantity that directly reflects the traction capability of the powertrain during full acceleration. Unlike speed, which is accumulated over time, acceleration is an instantaneous indicator, allowing for a clearer observation of the differences in transmission characteristics between the two types of transmissions. In CarSim dynamic simulations, longitudinal acceleration is calculated from the total force acting on the vehicle in the longitudinal direction and normalized in g units, helping to evaluate the driver's acceleration sensation during operation.

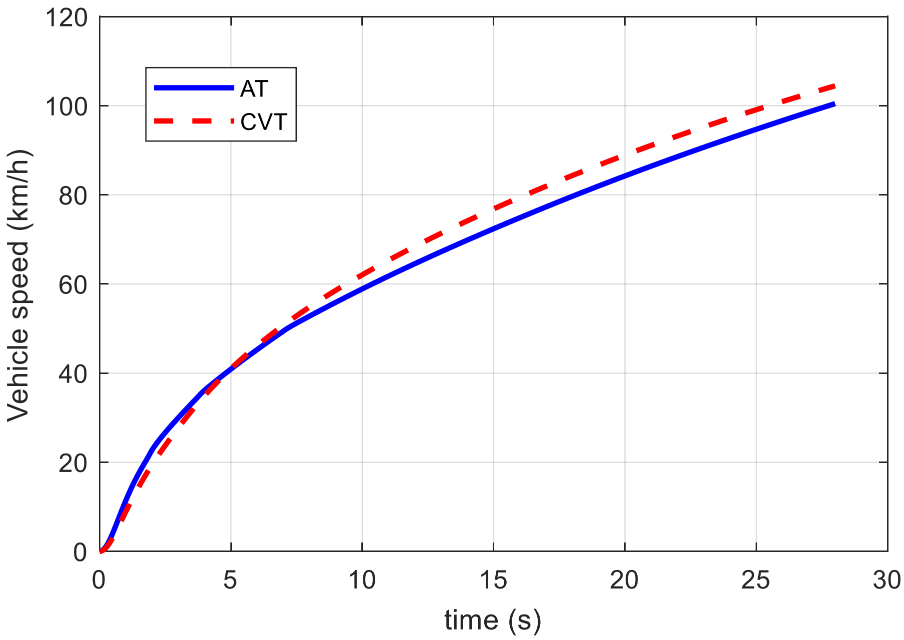

Figure 2. Vertical acceleration graph over time

Figure 2 shows the longitudinal acceleration of a vehicle using a 4-speed automatic transmission (AT) and a CVT transmission during 30 seconds of acceleration. In the initial phase (0–3 s), the acceleration of both configurations reaches its maximum value, corresponding to the maximum traction force at the wheels. However, the acceleration curve of the CVT vehicle declines more smoothly and evenly, reflecting the continuously variable transmission mechanism that helps maintain effective traction torque at the optimal RPM range. In contrast, the acceleration of the 4AT configuration exhibits distinct "peaks" and "troughs" at shift points. Each shift from 1→2, 2→3, and 3→4 creates a power transmission delay, leading to a temporary drop in acceleration before recovery.

This difference highlights the nature of the two transmission types: the AT transmission has discrete gears, causing power transmission to be interrupted during gear shifts, while the CVT transmission keeps the engine operating continuously within the efficient torque range without creating large impulses or oscillations. Therefore, the longitudinal acceleration of the CVT

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transmission is not only higher in the initial phase but also remains more stable throughout the entire acceleration cycle.

It is noteworthy that after about 8–10 seconds, the longitudinal acceleration of the two configurations gradually converges to equivalent values as the vehicle transitions to a slow acceleration state, at which point aerodynamic drag and rolling friction dominate. This shows that the advantage of CVT mainly lies in the low to medium speed range, where high traction torque is required and the engine must change speed quickly.

3.3. Active Wheel Torque Graph

Active wheel torque is a key parameter reflecting the efficiency of the transmission system in amplifying torque from the engine to the road surface. This quantity determines traction capability and directly affects the vehicle's longitudinal acceleration during acceleration. The difference in transmission structure between a 4-speed automatic transmission (AT) and a continuously variable transmission (CVT) is most evident in the variation of wheel torque over time, as the two transmission types have completely different ways of changing the transmission ratio.

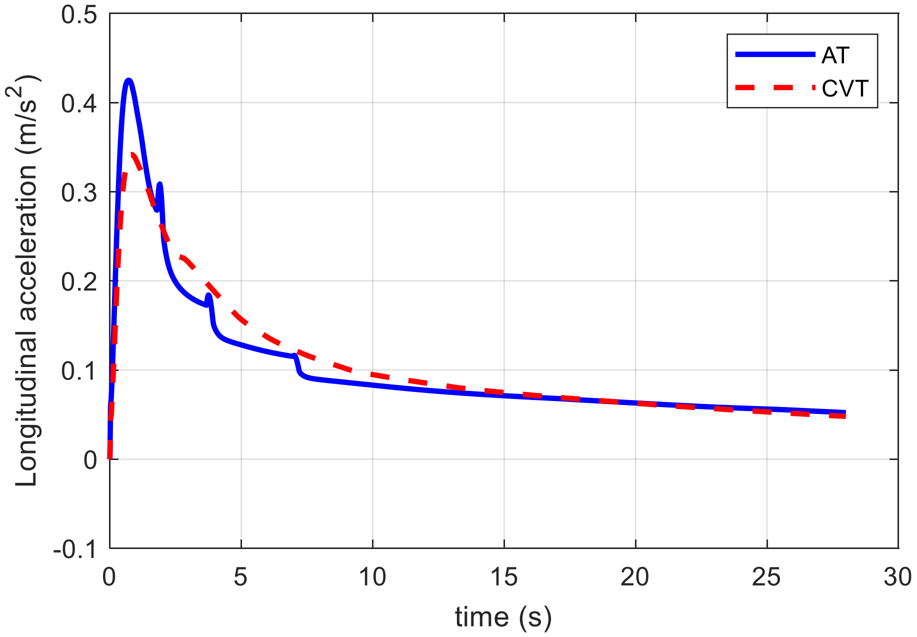

Figure 3. Active wheel torque graph

Figure 3 illustrates the active wheel torque obtained from dynamic simulation using CarSim. At the start of acceleration (0–1 s), the wheel torque of both configurations reaches its maximum value, corresponding to high engine torque combined with a high initial transmission ratio. However, the torque of the AT configuration always exhibits "sharp peaks" and sudden drops during gear shifts. When the AT transmission shifts from 1st to 2nd gear, the sudden decrease in gear ratio causes the wheel torque to decrease, then increase again as the engine recovers rotational speed. This process repeats during subsequent gear shifts (2→3, 3→4), creating a characteristic broken line graph.

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In contrast, the wheel torque of the CVT configuration decreases smoothly and continuously. Because the transmission ratio changes continuously, the engine is always maintained near the optimal torque range, resulting in a wheel torque curve without the strong fluctuations seen in an AT transmission. This allows the CVT to maintain more stable traction during low to moderate acceleration phases, consistent with the longitudinal acceleration results analyzed in the previous section.

A notable feature is that in the 0–4 s range, the wheel torque of the AT transmission is initially higher than that of the CVT due to the larger first gear ratio. However, immediately after the first gear shift, the torque drops sharply and remains lower than the CVT model for most of the remaining time. This explains why the CVT vehicle achieves higher speeds at the same time despite having lower initial torque: the continuity in power transmission creates the ability to maintain traction more effectively.

As the simulation time progresses to 20–30 s, the wheel torque of the two configurations approaches nearly equivalent values. At high speeds, the CVT's gear ratio approaches a low value, while the AT transmission stabilizes at the highest gear, making the power transmission efficiency of the two systems similar. At this point, aerodynamic drag and friction become the dominant factors.

4. Conclusion

The longitudinal dynamics simulation results of the Toyota Vios show that the transmission type plays a decisive role in the acceleration capability and power transmission characteristics of the drivetrain. With the same engine platform and simulation conditions, the difference between the 4-speed automatic transmission (4AT) and the continuously variable transmission (CVT) is clearly evident in the dynamic parameters obtained from CarSim. Specifically, the vehicle using the CVT achieves higher speeds during most of the acceleration phase due to its ability to maintain a continuous transmission ratio in the engine's optimal operating range, while the 4AT experiences torque interruption during gear shifts, causing localized speed reductions. This is also clearly reflected in longitudinal acceleration: CVT provides smooth, stable acceleration without large fluctuations; conversely, 4AT exhibits acceleration "drops" corresponding to gear shifts. The wheel torque and traction results show that the 4AT generates greater initial torque thanks to its high first gear ratio, but loses its advantage immediately after the first gear shift; meanwhile, the CVT maintains more stable torque and traction throughout the low to medium speed range. At high speeds, the difference between the two configurations diminishes as the CVT's gear ratio approaches a low value and the 4AT reaches its highest gear, causing traction to be dominated primarily by aerodynamic drag. In summary, the study confirms the advantage of CVT in maintaining continuous power transmission and improving acceleration efficiency, while demonstrating that CarSim simulation is an effective tool for analyzing and optimizing the transmission characteristics of small passenger cars. Future research could extend to different load conditions, transmission control models, and experimental comparisons to improve the reliability of the model.

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