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Evolution of gear shift patterns for six speed automatic transmission vehicle

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Abstract
The increasing level of stringent exhaust emission regulations and the rising index of carbon dioxide emissions from the road transport sector have pushed vehicle manufacturers and designers to develop solutions for more efficient vehicles, with well-designed vehicle transmission and gear shift patterns among the alternative approaches employed. For a six speed automatic transmission, the current article proposes a design method for developing a suitable gear ratio set and gear shift patterns. The MATLAB/Simulink platform was used to create the Maruti Suzuki 2020 four speed transmission model and the results were verified using experiment data. The effectiveness of the new selected gear ratio set and gear shift patterns was then evaluated using a six speed transmission model based on the validated four speed transmission model. To investigate fuel consumption and acceleration performance, all models were simulated based on motor vehicle emissions groups. Sport mode, eco mode, and combined both mode patterns were developed and analyzed. Based on the eco mode pattern, the six speed transmission model has a 2.74% lower fuel consumption rate than the four speed transmission model, indicating that the proposed design method is feasible and effective.

Keywords: Fuel consumption, automatic transmission, gear shifting pattern, simulation modeling

1. Introduction
The rising global carbon dioxide emissions index is always a major source of concern for people, with the transportation sector accounting for about 24.6 percent of total global CO_2 emissions and ranking second among all sectors [1]. The combustion of petroleum-based products, such as diesel and gasoline, in internal combustion engines is known as the largest source of man-made CO_2 emissions [2]. Despite the recent technological trend toward hybridization and electrification, the majority of road vehicles are still powered by internal combustion engines. To reduce the amount of CO_2 produced and released by ICE vehicles, it is critical to keep the engine operating at its most efficient region, where a good driving dynamic can be achieved while using the least amount of fuel. One way to accomplish this is through a well-designed vehicle transmission and gear shift pattern. A vehicle transmission with a higher number of gears has a higher overall transmission ratio and ratio spread between gears, resulting in better drivability, fuel economy, driving experience, and shifting quality. This is due to the closer spacing of gear ratios, which contributed to shorter shift times and lower rotating inertias [3, 4]. Since its introduction in 1999, the six-speed automatic transmission (6 AT) has surpassed the four speed automatic transmission (4 AT) in transmission market share. In 2020, it was estimated that 6 AT would account for 16 percent of total transmission production [2]. Transmission control unit controls gear shifts based on real-time driving conditions and demand from the driver by transmitting and receiving signals from other vehicle control units. As a result, gear shift pattern has a significant impact on vehicle fuel efficiency and acceleration [4]. The development of advanced automotive technologies is accelerating in the twenty-first century, with computer simulation modeling playing an important role. A simulation modeling technique is a computer-based tool that uses algorithms and equations to solve real-world problems. With the correct and proper analysis method, one can easily obtain insights and reviews for a complex system by using the simulation modeling technique, thus enjoying benefits such as design flexibility, time and resource savings, result visualization, and optimization [5]. Different researchers have taken different approaches to simulating and analyzing the gear-shifting pattern using computer simulation modeling techniques. In terms of New European Driving Cycle fuel consumption performance, Casavola *et al*. [6, 7] analyzed and compared two gear shifting optimization strategies: Efficient Gear Actuator and Genetic and Fuzzy Algorithm.

According to the results, the fuel consumption for an optimized power shift schedule was nearly the same as for an optimized economical shifting schedule, but it took a shorter trip time than the optimized economical shifting schedule. Lu *et al*. [8], on the other hand, used a Genetic Algorithm to optimize a traditional two parameter shift schedule, with road slope recognition as the optimization parameter. The simulation results demonstrated that the optimized shift schedule was capable of reducing frequent gearshifts and improving drivability on ramp. Ngo *et al*. [9] optimized the shift schedule of an automatic manual transmission vehicle using the dynamic programming technique. Using the optimized shift schedule instead of the original shift schedule based on the motor vehicle emissions groups test resulted in a 17.5 percent improvement in fuel economy. Zhao *et al*. [10]. The DP algorithm was also used to optimize the gear shifting strategy for an off-road vehicle by weighing the trade-offs between two factors: trip time and vehicle fuel consumption. In their study, Miao, Liu, and Zhu [4] also used the DP technique and the Moving Least Square method to generate and optimize the gear-shifting schedule and shifting sequence. While numerous studies have been conducted to optimize the existing gear shift pattern using various optimization tools, only a few researchers have focused on the method for developing a gear ratio set and gear shift pattern for a vehicle transmission. Among the studies are [4, 11-14]. The development of the gear shift pattern is based on three parameters, which requires extra calibration and complicated procedures when compared to two parameters. Nonetheless, Section 2 refers to and discusses some of their techniques. As a result, the goal of this research is to propose simple yet feasible two-parameter development methods for gear ratio set and gear shift pattern for a 6 AT gasoline ICE vehicle. Model based design was used to create the vehicle power train model on the MATLAB/Simulink platform. These proposed methods are capable of providing a more straightforward and comprehensive understanding, particularly for those with a basic understanding of gear ratio set and gear shift development. Three modes of gear shift pattern were developed in this study: sport mode for the best acceleration performance, eco-mode for the best fuel economy, and combined mode for the best of both sport and eco-mode. These patterns are created using the motor vehicle emissions groups and two input parameters are throttle opening position and vehicle speed. Using simulation modeling, the effect and significance of the gear shift pattern on vehicle fuel consumption and acceleration performance were investigated.

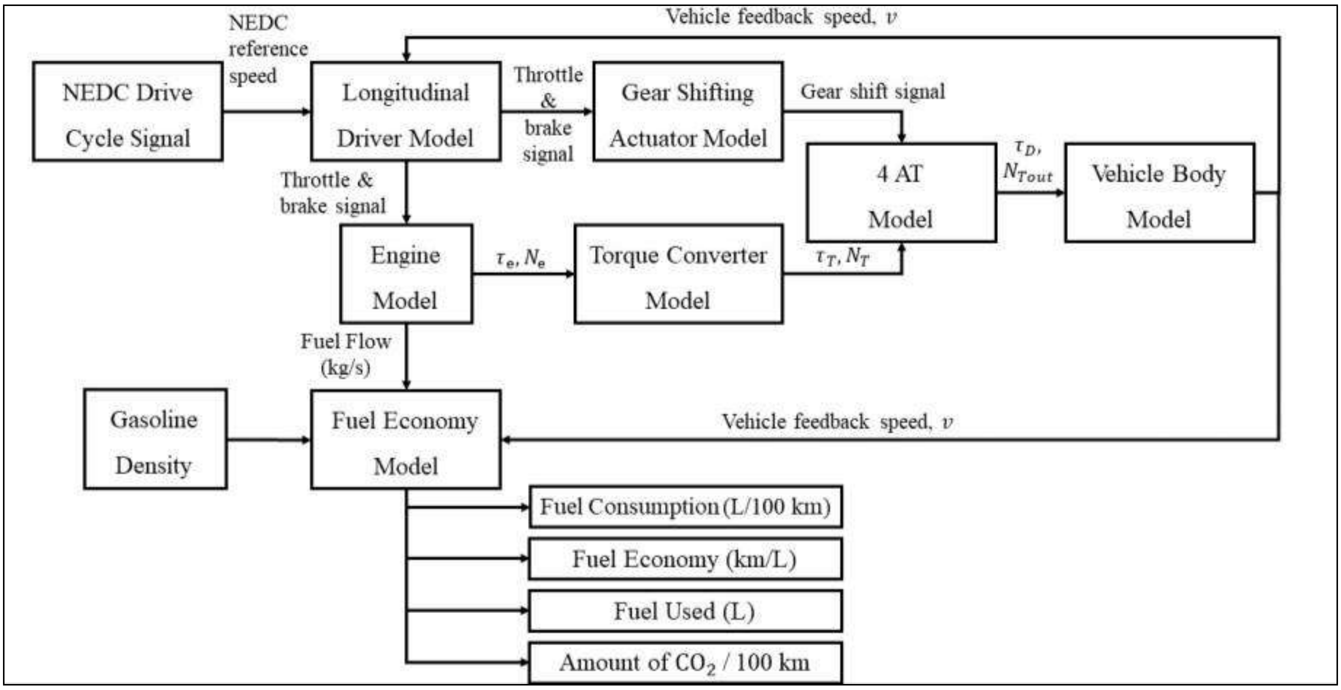


Fig 1: AT vehicle model

2. Methodology

The simulation model was built around the Maruti Suzuki 2020 4 AT. The simulation results were compared to measured data from a chassis dynamometer test for validation. Figure 1 shows a simplified block diagram of a 4 AT vehicle power train model created using the model-based design method on the MATLAB/Simulink platform. The schematic diagram of the model is shown in detail in Fig. 1. The 4 AT model includes the engine, torque converter, transmission, vehicle body, gear shifting actuator, driver, and fuel economy models. The validated 4 AT vehicle power train model was used to build the 6AT's base model.

Table 1: Maruthi Suzuki 2020 vehicle parameters

Vehicle Parameters	Specifications
Engine	1197 cc, 4 Cylinders Inline, 4 Valves/Cylinder, DOHC
Engine Type	1.2L Dual Jet
Fuel Type	Petrol
Max Power (bhp@rpm)	89 bhp @ 6000 rpm
Max Torque (Nm@rpm)	113 Nm @ 4400 rpm
Mileage (ARAI)	23.2 kmpl
Driving Range	858 Km
Drive train	FWD
Wheelbase	2450 mm
Emission Standard	BS 6

2.1 Best fuel economy shift pattern (eco-mode)

An upshift was made in this shift strategy when the BSFC value on a higher gear was less than the current gear. Marking the intersection point of the BSFC curve between the gears determined the shifting points. The upshift speeds corresponding to specific throttle pedal opening signals of 10%, 20% and 30% were obtained from the engine's BSFC contour map plot. By connecting all of the points, an economy upshift line for each gear could be obtained. The economic downshift lines were calculated using the same linear convergence algorithm method as before.

2.2 Combination shift pattern (combined-mode)

It combined the gear shift patterns from sport and eco-mode for this shift strategy. The combination method was usually created to mimic the typical driving behavior and style of a real driver. When low-speed driving is required, this combined-mode shift pattern can provide the best fuel economy without sacrificing dynamic performance. The shift map was divided in half by the combined mode shift pattern. Eco-mode was used when the throttle pedal opening signal was less than 50%, while sport-mode was used when the throttle pedal opening signal was greater than 50%. The linearity connecting method was used to connect the throttle pedal opening signal between 50% and 100%.

The 4 AT vehicle powertrain model shown in Fig. 1 was used to construct the 6 AT vehicle power train model by replacing the transmission model and gear shifting actuator models to 6 AT based. Fig. 2 shows the simplified block diagram of 6 AT vehicle powertrain model. Comparing to Fig. 1, all models are similar except for the transmission model and gear shifting actuator models. For the vehicle model, all vehicle parameters were kept constant except its gross mass due to the additional mass from the 6 AT itself. The models that are affected are shown in the red line block. The detail schematic diagram of 6 AT can be referred in Fig. 2. The 4 AT vehicle powertrain model shown in Fig. 1 was used to build the 6 AT vehicle power train model by swapping out the transmission and gear shifting actuator models for 6 AT models.

The simplified block diagram of a 6 AT vehicle power train model is shown in Fig. 2. Except for the transmission and gear shifting actuator models, all models are similar to Fig. 1. All vehicle parameters were kept constant for the vehicle model, with the exception of its gross mass, which was increased due to the additional mass from the 6 AT itself. The affected models are depicted in the red line block. Fig. 2 shows the detailed schematic diagram of 6 AT. The gear shift patterns were installed within the gear shifting actuator model as the gear shifting control algorithm using a two-dimensional lookup table method in the 6 AT transmission model, which used a Lepelletier gear set mechanism. The vehicle powertrain model used in this study was built to resemble a real Maruti Suzuki 2020. Many sensitive vehicular data such as the internal combustion engine, torque converter, gear shift pattern, and BSFC contour map are unable to be included in this document due to the confidentiality issue.

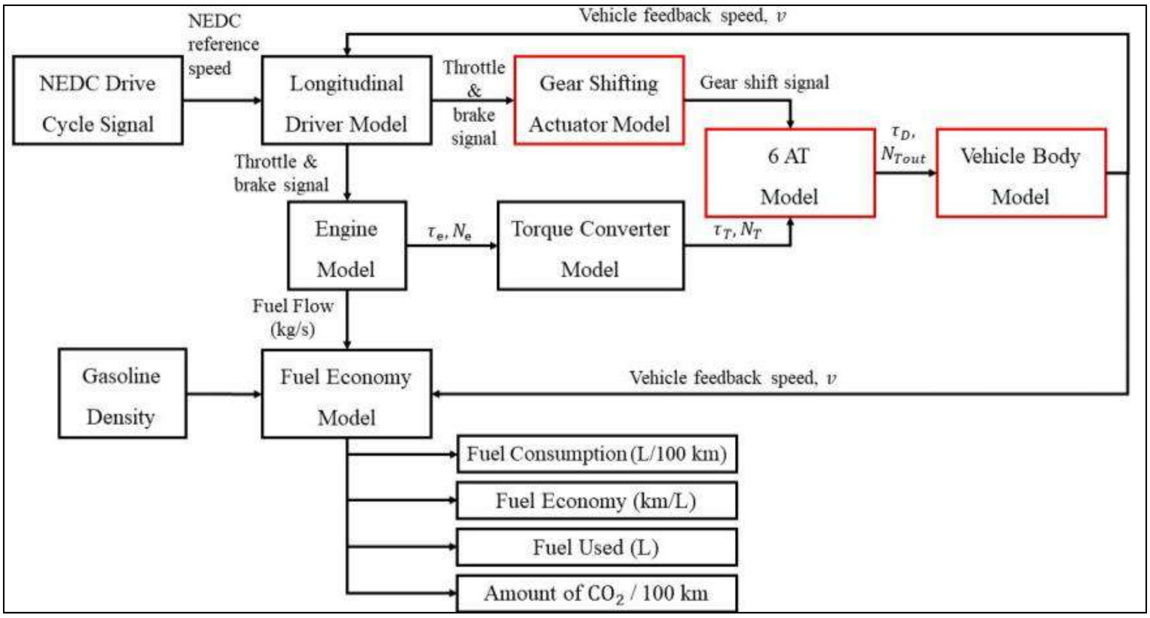


Fig 2: AT vehicle model

Results and Discussions

Simulation result

The 4 AT was simulated using NEDC to test the model's validity by comparing the obtained fuel consumption result to the actual experimental result. The comparison of the obtained velocity speed profile with the NEDC reference speed profile is shown in Fig. 3. The vehicle model in Fig. 1 drives in accordance with the NEDC reference speed profile, as can be seen. The vehicle feedback speed shows no significant fluctuations throughout the NEDC cycle, implying that the developed vehicle model is reliable.

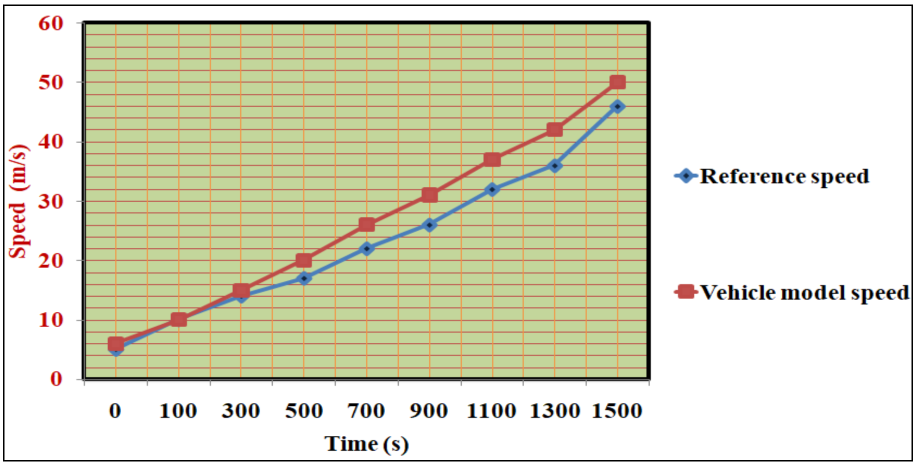


Fig 3: Shows the obtained velocity speed profile compared to the NEDC reference speed

According to Table 2, the 4 AT model has a NEDC estimated fuel consumption of 6.934 L/100 km, with a 1.97% error. The difference in error is primarily due to the 4 AT gearbox model's exclusion of a lock-up gear-shifting schedule, which would have increased design complexity and used more computational resources. Furthermore, external variables such as engine working temperature, power consumption of electrical auxiliary systems, and the test driver's driving style pattern were not taken into account in the vehicle power train model. Because the error rate of 1.97% is considered acceptable, the 4 AT vehicle model was validated. Then, using the aforementioned methods, the gear ratio sets for 6 AT were created. The results of the generated gear ratio sets for 6 AT are shown in Table 3. The first and top gear ratios are similar in both design methods, but the intermediate gear ratios are different. From lower to higher gear, the progressive method has a decreasing ratio spread. This means that the lower gear has a larger speed difference v and the higher gear has a smaller speed difference v, resulting in better drivability, acceleration performance, and fuel economy.

Table 2: Comparison of the fuel consumption rate between the actual experimental result and simulated result of 2020.

Result type	Fuel consumption rate	Error Percentage
Actual experimental result	5.2 L / 100 km	-
Simulation result	7.32 L / 100 km	1.49%

The geometric progression method maintains a consistent ratio spread across all gears, resulting in improved driving comfort and a smoother shift process. Both gear ratio sets were tested to see if they adhered to the Lepelletier gear set mechanism's design configuration and limit. The evaluation results for both gear ratio set design methods are shown in Table 4. According to Table 4, the gear ratio set generated using the geometric progression method does not meet the design configuration and limit of the Lepelletier gear set mechanism because g1 is less than 1 and g3 is less than g2. As a result, the progressive method gear ratio set is chosen because it meets the design requirement and limitation of the Lepelletier gear set mechanism. The driving condition and power-speed diagrams of the selected gear ratio set for the 6 AT at maximum throttle were then constructed, as shown in Figs. 4 and 5, respectively. The dashed-black lines in these figures represent road load resistance and road load power at various road gradients. As shown in Fig. 4, the developed gear ratio set based on progressive design is feasible. The first gear ratio is capable of providing sufficient traction force greater than the initial design gradeability assumption of 15%, with adequate reserve traction force in the event that extra vehicle load is applied.

Table 3: Designed gear ratio sets for 6 AT based on two different methods.

Geometric progression method			Progressive method		
Gear number	**Gear ratio**	**Ratio spread**	**Gear number**	**Gear ratio**	**Ratio spread**
$i1$	4.1	-	$i1$	4.73	-
$i2$	2.9	1.83	$i2$	2.82	1.390
$i3$	2.3	1.83	$i3$	1.53	1.293
$i4$	1.23	1.83	$i4$	1.023	1.23
$i5$	0.83	1.83	$i5$	0.64	1.20
$i6$	0.62	1.83	$i6$	0.287	1.17

Using the power-speed diagram shown in, the best acceleration performance up shift points was determined.

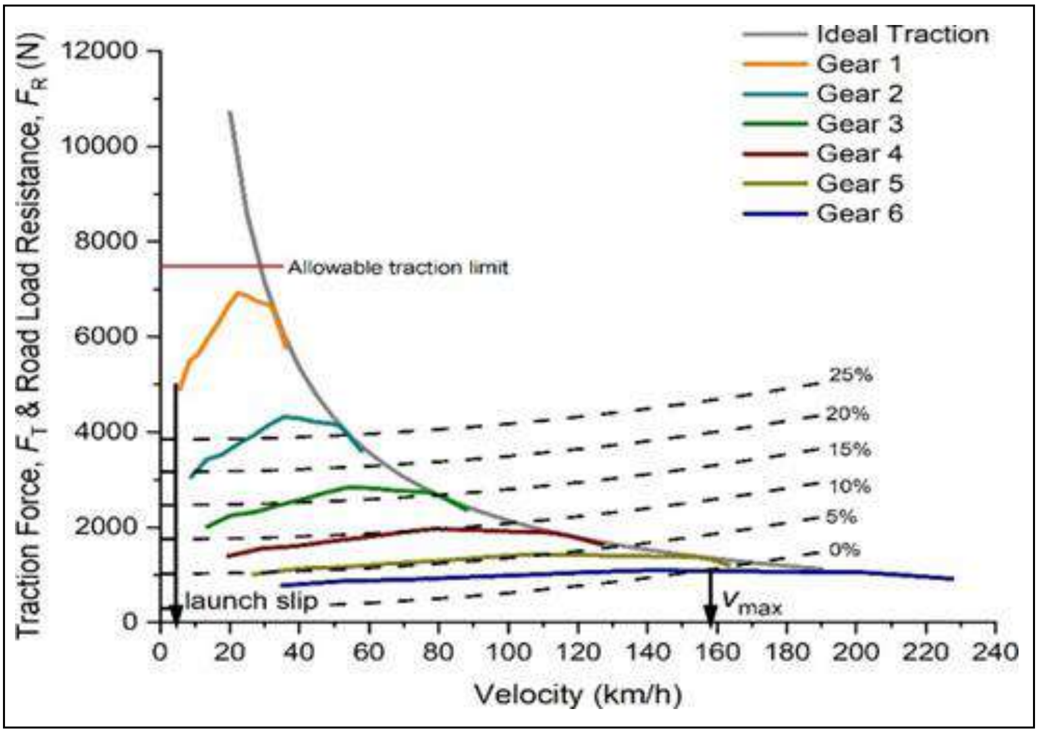


Fig 4: depicts the driving conditions of a 6 AT with the selected gear ratio set to maximum throttle

The BSFC contour map of the engine was used to evaluate the fuel consumption performance of each gear. The fuel consumption performance of each gear at maximum throttle is shown in Figure 6. Upshift points are determined by the intersection points between BSFC curve lines, as indicated by the black circles, for the best fuel economy shift pattern. For each gear, the dashed-black lines represent the vehicle's upshifting and downshifting speed.

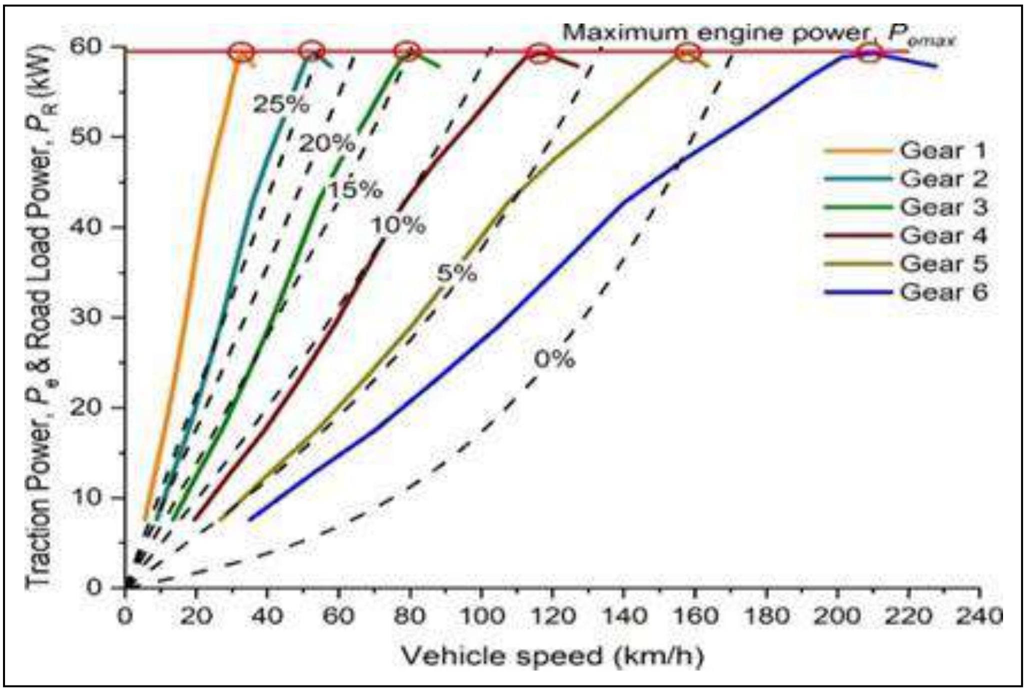


Fig 5: Power-speed diagram of 6 AT with the selected gear ratio set at maximum throttle

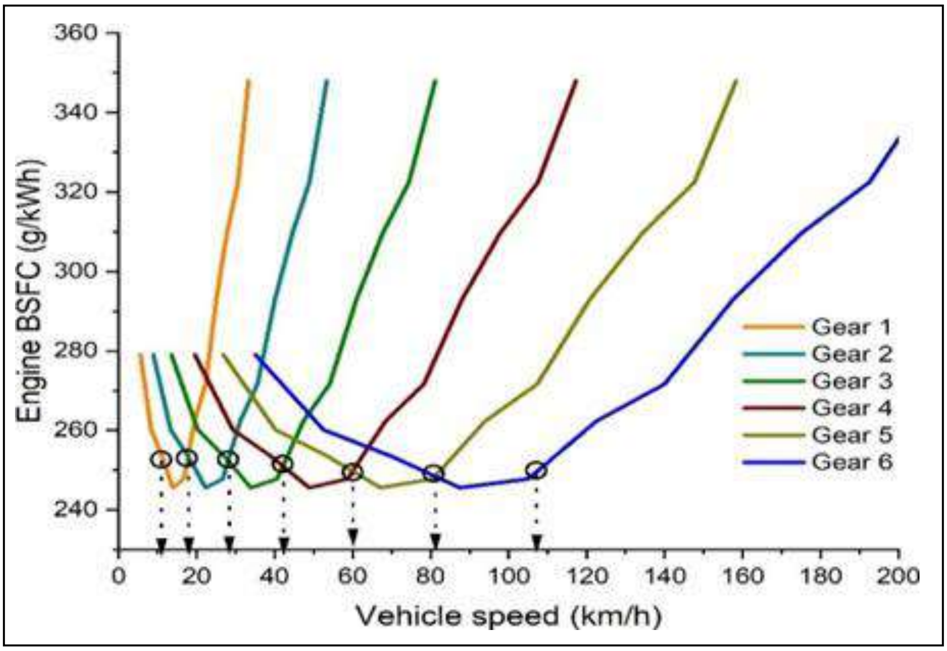
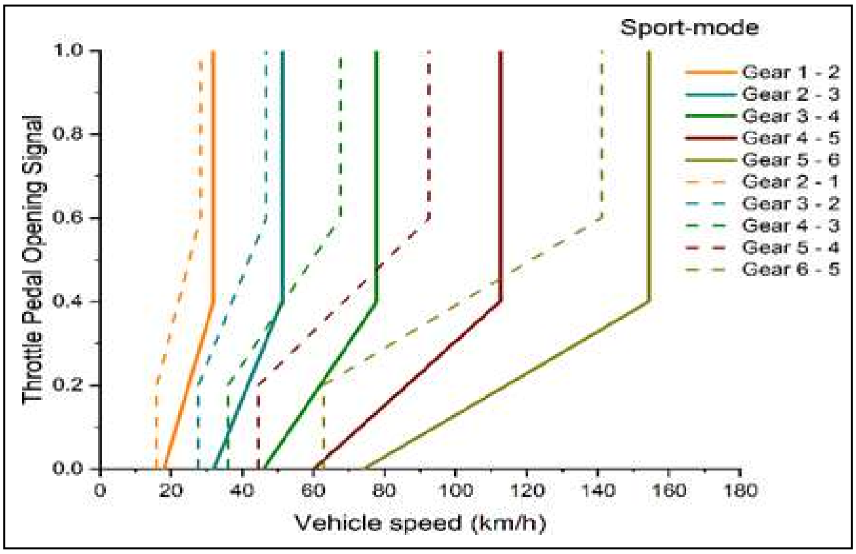
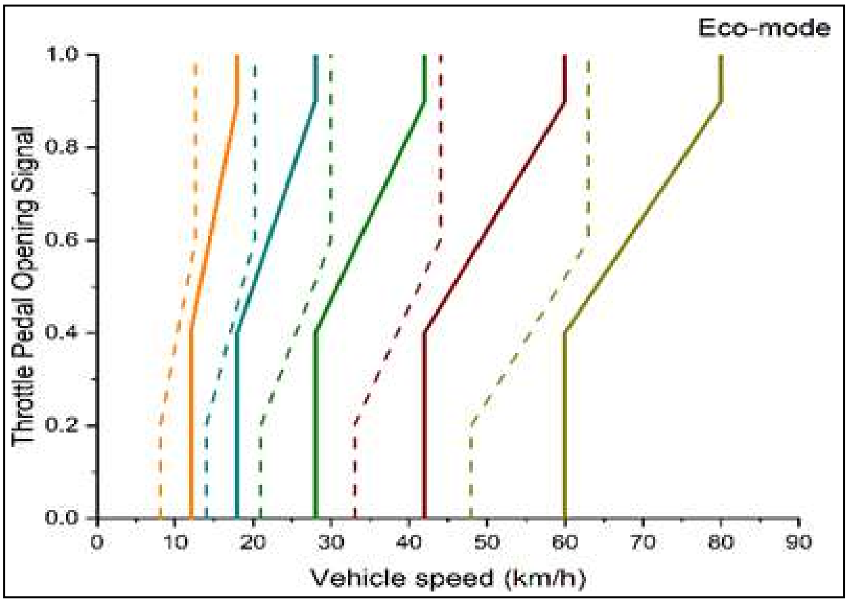


Fig 6: Fuel consumption performance of each gear at max throttle condition.

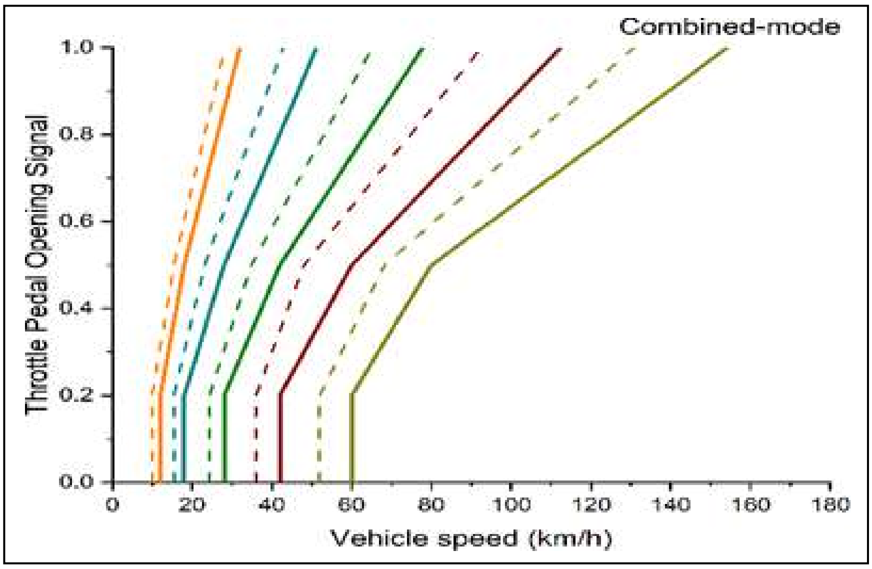
After knowing the upshift points for both shift patterns, the downshift points were calculated using the linear convergence algorithm method. The entire gear shift pattern was then developed in terms of best acceleration performance (sport-mode) and best fuel economy (eco-mode). In addition, a combined gear shift (combined-mode) was built. The developed gear shift patterns are shown in Figure 7(a-c). The sport-mode shift pattern is designed to maximize engine output power while accelerating the vehicle by delaying upshifting speeds. The upshift lines were made in a linear form to reflect the desired acceleration performance for the throttle pedal opening signal ranged from 0 to 30%, as shown in Fig. 7(a). Within this range, the more the driver depresses the throttle pedal, the longer the vehicle remains in the current gear, increasing engine speed and allowing for better acceleration. The upshift threshold speed for each gear was designed with the same constant value as the upshift threshold speed at maximum throttle pedal condition for 40 percent throttle pedal opening signal and onwards. Because the likelihood of a driver actuating the throttle pedal to its maximum position is very low in real world applications, the 40 percent throttle opening signal can provide a quick and dynamic response to the vehicle, allowing it to perform an upshift even if the driver does not actuate the throttle pedal to its maximum position. This has no effect on the vehicle's drivability or maximum acceleration performance because the engine speed is still required to reach the maximum power speed for making a gear shift at 40% throttle pedal opening signal and higher. The main goal of the eco-mode shift pattern is to improve fuel economy by lowering the sensitivity of the vehicle's response to throttle pedal input. The upshift threshold lines in Fig. 7(b) have a constant upshift speed for the throttle pedal signal ranging from 0 to 40%, lowering the acceleration response. As a result, earlier upshifts were made to correspond to lighter throttle pedal openings, allowing the vehicle operation status to reach higher gears faster, resulting in better fuel economy because the engine operation speed and upshift speed are both lower than in sport mode. If the driver requires more traction power, the upshifts are delayed to allow the driving wheels to obtain more traction force from the engine as the engine speed gradually increases. However, the amount of traction force that can be generated to the driving wheels in this mode is limited, with delivered output torque that is close to but not quite equal to the peak torque value at engine speeds less than 2500 rpm. As a result, unlike in sport mode, the driver will not get the desired feeling of vehicle acceleration capability. The combined mode, as shown in Fig. 7(c), allows the driver to enjoy both sport and eco-mode benefits. This pattern maximizes fuel efficiency at low vehicle speeds without sacrificing vehicle response when acceleration is required. The effectiveness of the generated gear-shifting patterns was evaluated after obtaining all of the required gear ratio sets and gear-shifting patterns for the 6 AT. Using the two-dimensional lookup table method, the developed gear shift patterns were imported into the gear shifting control algorithm within the gear shifting actuator model. For the 6 AT transmission model, the gear ratio calculated from Table 4 was used as the input. In Table 5, the simulation results for all gear-shifting patterns were recorded and tabulated.



a) Best acceleration performance shift pattern



b) Best fuel economy shift pattern



c) Combination best performance and fuel economy shift pattern.

Fig 7: Shift patterns at different modes

Table 5 shows that all gear shift patterns are good and workable, with an error percentage of less than 1% between the vehicle feedback speed and the NEDC reference speed profile. When using three different gear-shifting patterns, the 6 AT vehicle model can drive according to the NEDC reference speed details.

Table 4: Designed gear ratio sets for 6 AT based on two different methods.

Gear ratio set	$g1$	$g2$	$g3$
Geometric progression method	0.945	2.145	2.087
Progressive method	1.309	2.145	2.435

Table 5: Overall simulation result for all gear-shifting patterns.

Type of shifting pattern	Fuel consumption rate	0–100 km/h acceleration	Error in vehicle speed with reference speed
Best acceleration performance	6.03 L/70 km	10 s	0.68%
Best fuel economy	5.47L/800 km	12 s	0.52%
Combination	6.28 L/90 km	12 s	0.42%

Eco-mode has the lowest fuel consumption rate of 6.03 L/70 km, which is about 2.48 percent lower than the 4 AT model, according to the NEDC simulation test. During the chassis dynamometer test, the 4 AT model was also using its original calibrated fuel economy eco-shift pattern. This demonstrates that the 6 AT simulation result with the developed eco-mode has a higher fuel economy than the 4 AT simulation result. The combination method shifting pattern is in the middle, with the best acceleration performance shifting pattern having the highest fuel consumption rate. The 2.48 percent fuel economy improvement obtained by using 6 AT is consistent with the experimental results and findings obtained by the National Research Council and the International Council of Clean Transportation, which reported that a vehicle equipped with 6 AT can reduce fuel consumption by 1.7–2.3 percent when compared to a vehicle equipped with 4 AT [24, 25], and that the gear shift pattern has a significant impact on the fuel economy. The 6 AT model includes a wide-open throttle analysis to evaluate the dynamic performance of the gear shift patterns. The eco-mode pattern takes the longest time to accelerate from 0 to 100 km/h, about 15 seconds, which is 2 seconds slower than the sport-mode and combined-mode patterns. Because the combined mode has the same shifting pattern design after the 50 percent throttle pedal opening signal section, it has the same 0–100 km/h acceleration result as the sport-mode pattern, which is approximately 12 s. However, when compared to the sport-mode pattern, the normal driving gear-shifting pattern in an actual vehicle will not have the same 0–100 km/h acceleration performance.

Conclusion

This paper proposes a method for determining the gear ratio set and gear shift pattern for a six-speed Lepelletier automatic transmission. According to the simulation results, a similar vehicle with a transmission with a higher number of gear ratios has better fuel economy than a vehicle with a transmission with a lower number of gear ratios. The simulation results also show that the gear shifting pattern has a significant impact on the vehicle's acceleration, fuel economy, and shifting experience. More importantly, it has been demonstrated that using computer simulation technology to study vehicle performance can be done effectively and efficiently, with the prerequisite of having a correct, accurate, and validated model. In comparison to the traditional method, computer simulation technology is an effective method for assisting the automotive industry during the research and development stages, as it reduces the required development time, cost, effort, and resources. By simply changing the vehicle parameters to the corresponding data, the vehicle power-train model developed in this study can be used to quickly assess the fuel consumption performance of any internal combustion engine vehicle. As a result, the design method proposed in this article for determining the gear ratio set and gear-shifting pattern of a vehicle transmission is feasible and effective, and it can be used as a great starting point for future research on Optimization of gear shift operations in automatic transmissions.

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