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Two-Speed Transmission Structure and Optimization Design for Electric Vehicles

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Abstract: The trend in the global automotive industry is moving towards electric vehicles that do not emit exhaust gases and use eco-friendly fuel. Electric vehicles are more eco-friendly compared to internal combustion engine vehicles, as they emit less carbon dioxide and pollutants. Research and development are actively underway to produce new electric vehicle models in the rapidly growing electric car market. In this study, a 2-speed transmission for electric vehicles, applicable to 300 Nm-class electric cars, has been developed. The 2-speed transmission structure enables efficient energy use and utilizes a planetary gear set and wet multi-plate clutch, which are effective in the power transmission process. The 2-speed transmission developed through the research results of this paper has a compact structure optimized for electric vehicles. The design feasibility of the transmission was verified through performance tests of the prototype, contributing to fuel efficiency improvement and environmental enhancement.

Keywords: electric vehicles; transmission; planetary gear; power transmission efficiency; gear ratio

1. Introduction

In the past, the global automotive industry was centered around the development and distribution of Internal Combustion Engine (ICE) vehicles that primarily used fossil fuels. As concerns over serious issues such as air pollution and global warming have risen (in part due to exhaust gases emitted by internal combustion engine vehicles that primarily use fossil fuels), major countries around the world are strengthening environmental regulations in response to climate change [1–5]. Reducing the consumption of fossil fuels is currently considered a critical issue in the automotive industry. The trend in the global automotive industry is shifting towards Electric Vehicles (Evs) that do not emit exhaust gases and use eco-friendly fuel [6–8]. Electric vehicles are more eco-friendly than internal combustion engine vehicles, as they emit significantly less carbon dioxide and pollutants. Additionally, compared to internal combustion engines and hybrid vehicles, electric vehicles can use energy more efficiently, incur lower fuel and maintenance costs, and offer a quieter driving experience, thus providing convenience to users [9,10].

Global automotive companies are actively engaged in research and development to produce new electric vehicle models in the rapidly growing electric car market. Traditional electric vehicles are equipped with a single reduction gear, featuring a fixed gear ratio and no transmission, designed to increase torque from the motor's high-speed and low-torque input. While they can actively handle typical speeds, achieving maximum speed requires the motor to exert significant power, which in turn necessitates a larger battery capacity. Consequently, this can lead to issues in various controller systems, including the motor and the inverter that controls it, especially with speed shifting [11]. If the speed range could be divided into several sections, allowing the motor to run at a constant speed within each section and optimizing speed shifting for operation, this issue could be resolved [12,13]. The key component that satisfies these technical requirements is, indeed, the transmission system for electric vehicles.

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Currently, transmission technology for electric vehicles is focused on research and application of pioneering technologies at an experimental scale, aimed at enhancing vehicle performance and efficiency through various innovative technological developments. This research provides a crucial foundation for the advancement of transmission technology in electric vehicles and contributes significantly to the enhancement of future electric vehicle performance. Transmissions incorporating synchronizer technology, which reduces synchronized lateral speed during high gear shifts and increases it during low gear shifts, contribute to improved drivability and efficiency [14]. While they offer superior power transmission and smooth shifting, making them comfortable for drivers, they have the disadvantage of a complex structure that results in higher maintenance costs. Dual Clutch Transmissions (DCT) that utilize dual clutches to address the shortcomings of a single clutch can improve average motor efficiency, enhance operational range, or reduce the required motor size [15]. While they provide rapid shifting and superior driving efficiency, a major downside is their structural complexity, which leads to higher maintenance costs. To optimize key performance indicators (KPIs) such as energy consumption, system cost, and performance, Continuously Variable Transmissions (CVT) [16] enable continuous and efficient shifting due to their stepless nature, providing a smooth driving experience for the driver. However, their technical complexity and limited torque handling capacity remain as challenges. The 2speed DCT electric drivetrain, consisting only of a pair of gears in the 2-speed transmission and final drive gears [17], allows for structural simplification and improved efficiency. However, its limitations include a restricted shifting range and performance constraints under certain driving conditions. This can lead to performance degradation under complex driving conditions. The automated manual transmission with a main reducer and automatic devices [18] improves the driving experience and increases energy efficiency through advanced automated control. However, such systems have the disadvantage of structural complexity and high maintenance costs. The clutch-less automated manual transmission, incorporating a synchronizer mechanism [14], provides smooth gear transitions and an enhanced driving experience for the operator. However, improvements are needed in terms of reliability and durability. The one-way clutch 2speed transmission using band brakes [19] provides an efficient shifting process and reduced mechanical wear. However, it presents new technical complexities and challenges in practical application. The torque-based transmission that allows for multi-stage shifting with dual clutches [20] provides high torque capacity, a rapid shifting system, and excellent driving performance and efficiency. However, its complex structure leads to high manufacturing costs, and it also has disadvantages in terms of maintenance expenses.

Global automotive manufacturers are actively engaged in research and development activities for technological innovations in electric vehicle transmissions. These efforts are focused on improving the energy efficiency, performance, and user experience of vehicles, and are aimed at responding to the continuous growth and evolution of the electric vehicle industry. The research and development by these global automotive manufacturers are making significant contributions to the advancement of electric vehicle technology and paving new paths for the sustainable development of future vehicle technologies. In this process, various innovative transmission technologies are being introduced, playing a crucial role in enhancing the performance of electric vehicle transmissions with a focus on cost efficiency and environmental sustainability. GKN Automotive has achieved significant advancements in the field of electric vehicle technology. In particular, they gained considerable attention for developing the first-ever 2-speed eAxle model. Particularly, by supplying this technology to the BMW i8 plug-in hybrid sports car, its utility has been proven [21–23]. The advantages of GKN's 2-speed eAxle model are numerous. Firstly, the helical gears applied in both the first and second stages provide superior mesh performance, low vibration, and low noise. Additionally, this design allows for a high transmission torque, and it boasts impressive performance figures such as a maximum output of 96 kW, maximum torque of 250 Nm, and a top speed of 250 km/h. However, this system also has certain disadvantages. Its technically complex design can lead to high costs and the need for specialized expertise

during maintenance and repair. Furthermore, the use of high-performance gearboxes can increase manufacturing costs, which may in turn affect the overall price of the vehicle. Thus, while GKN's 2-speed eAxle model offers outstanding performance and innovation, it also presents challenges in terms of high cost and complex maintenance.

Research is also actively underway in university laboratories, among which the Robotics Laboratory of the Department of Mechanical Engineering at Chung-Ang University has conducted various research and development projects for the technological advancement of electric vehicle transmissions. They designed a 2-speed electric vehicle transmission equipped with an optimized gearbox control process using Inventogram, allowing for selective fixation of either the primary ring gear or the secondary ring gear [24]. This research made it possible to improve spatial efficiency and durability while enabling optimized control according to driving conditions. Next, they conducted a study on the design of a compact electric vehicle 2-speed transmission using a dual brake system with a new structure that integrates two pairs of planetary gear modules and selectively fixes the sun gear of the planetary gear unit [25]. This research focused on the integrated serial structure design of the planetary gear unit for compact transmissions for electric vehicles. This design reduces shift shock and energy requirements, and enhances the efficiency of the gears. Safety was ensured by calculating the bending strength and surface durability of each gear according to JGMA [26,27] standards, and research was conducted on the structure and optimal gear tooth design of a 2-speed electric vehicle transmission using multiple planetary gear sets [28]. In this study, a new 2-speed transmission for electric vehicles was designed, offering advantages such as ensuring spatial efficiency and safety, and high transmission efficiency. Additionally, it is advantageous for battery-powered electric vehicles that require low shift shock and energy.

Globally, no production car models equipped with pure electric vehicle transmissions have been commercialized so far. In the future, electric vehicles with a 2-speed or higher transmission system will be essential. This necessitates a departure from the traditional concept of internal combustion engine transmissions, requiring the design and development of new electric vehicle technologies, along with the continuous development of advanced technologies.

In this paper, we designed a 300 Nm class electric vehicle 2-speed transmission using planetary gears and a wet multi-plate clutch. The gear ratio was designed considering the step ratio, acceleration, hill climbing performance, and maximum vehicle speed. The feasibility of the gears was verified through stress analysis and efficiency analysis, and a prototype of the 2-speed transmission was designed and manufactured.

2. Need for Research

Necessity for Research on Electric Vehicle 2-Speed Transmission

Currently, most electric vehicles can be driven with a simple single reduction gear, as they can operate over a wider range and utilize maximum torque at lower rotational speeds compared to internal combustion engine vehicles. Furthermore, motors that can produce a stable rotation speed without a transmission are used, leading many to believe that electric vehicles do not need a transmission. Electric vehicles utilize stored electrical energy from batteries as their energy source, and their motor drive systems convert the battery's output power into rotational energy for the wheels, enabling the operation of the electric vehicle. Therefore, the automotive industry is focusing intensely on securing battery technology, which in turn is slowing down the research and development pace of electric vehicle transmissions. Internal combustion engines have multiple gears and require multi-speed transmissions to deliver the right amount of power at the correct speed, as maximum torque is only produced when the engine reaches a certain RPM, preventing the engine from stalling. In contrast, electric vehicles can exert maximum torque immediately upon operation due to the characteristics of electric motors, and they can operate within a 2–3 times higher permissible rotational range compared to internal combustion engines. The reason electric vehicles can achieve brisker acceleration

compared to equivalent internal combustion engine vehicles is that they exert maximum torque the moment electric energy is supplied to the driving motor, and there is no need for shift time. Transmissions used in conventional electric vehicles include single gear transmissions, multi-speed gear transmissions, Continuously Variable Transmissions (CVT), planetary gear transmissions, and Regunox planetary gear transmissions. Multi-speed gear transmissions, used in some high-performance electric vehicles, usually apply two or three gear ratios to improve acceleration and top speed, optimizing motor efficiency. However, they have the disadvantage of increased manufacturing and maintenance costs due to their complex structure, which can increase the weight of the vehicle and decrease the overall energy efficiency of the vehicle due to energy loss during gear shifting. CVTs, with an infinite range of gear ratios, allow engines or motors to operate at their most efficient speeds and have a simple structure. However, they may have durability issues under high torque conditions and sometimes fail to deliver optimal performance in high-performance vehicles, with the possibility of noise and vibration. Planetary gear transmissions are efficient in power transmission and can improve overall energy efficiency. They can also be used efficiently due to their structure, have strong durability for long-term use, and allow for smooth gear shifts. They effectively manage torque due to the characteristics of electric motors that produce maximum torque. However, their complex structure can be a burden in terms of maintenance costs and weight. Regunox planetary gear transmissions use sets of planetary gears of different sizes to provide various gear ratios. They enable efficient power transmission and smooth gear shifting, with a compact design. However, despite their compact design, they can be heavier compared to other simpler transmission systems [29]. However, many electric vehicles use single gear transmissions with a fixed gear ratio, generally having a lower top speed and lower efficiency at high speeds compared to internal combustion engine vehicles, which is a disadvantage for high-speed driving compared to urban driving. Therefore, it is argued that transmissions for electric vehicles are necessary to increase the efficiency of electric vehicles. Like internal combustion engine vehicles, it is necessary to reduce the rotational speed of the electric motor during high-speed driving to increase efficiency. However, it is still difficult to find mass-produced electric vehicle models equipped with transmissions, and models with planned installations are not common. Additionally, it is not easy to find companies actively developing transmissions for electric vehicles.

3. Design and Fabrication of 2-Speed Transmission for Electric Vehicles

3.1. Two-Speed Transmission Design for Electric Vehicles

For conventional electric vehicle 2-speed transmissions, shifting from first to second gear requires a process to forcibly synchronize the speeds between the input and output shafts using components like synchronizer rings, and there is a possibility of shock during shifting, necessitating higher transmission control performance. Transmissions for electric vehicles are driven by electricity, the power source from the drive motor, and are composed of three different axes: the motor shaft, the planetary gear unit shaft, and the differential gear shaft [30].

The 2-speed transmission for electric vehicles we aim to develop is coupled to the drive motor, forming a coaxial arrangement with the input shaft and the shifting shaft. The drive sun gear is directly connected to the motor, forming a single axis. The structure involves the motor (screw) rotational motion → rack gear translational motion → cam, shift rail (integrated with cam) rotational motion → translational motion of the first gear fork and angular motion of the second gear fork hinge (lever ratio effect) due to the groove shape relation between the cam and the first gear fork, leading to engagement of the dog clutch (first gear) by the movement of the first gear fork or the wet multi-plate clutch (second gear) by the movement of the second gear fork. This is the design for the 2-speed transmission for electric vehicles.

Figure 1 is a schematic of the 2-speed transmission we aim to develop. The 2-speed transmission consists of a Differential (DIFF), Output Shaft, Transfer Driven Gear, Planetary

Gear Set, Multi-Plate Clutch, Transfer Drive Gear (Carrier), Dog Clutch, One-Way Clutch (OWC), and Input Shaft.

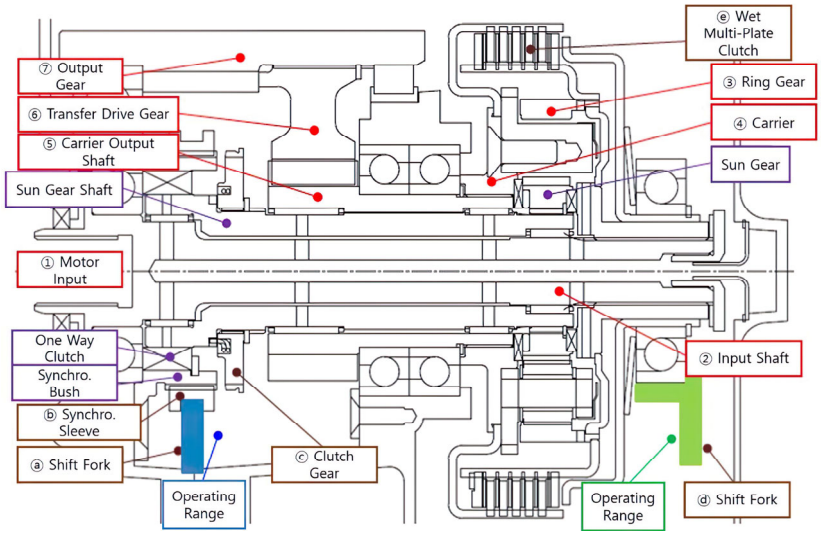


Figure 1. Schematic of 2-speed transmission.

The power of the transmission is inputted through the motor shaft gear and is transferred to the final reduction gear DIFF through either the first or second stage planetary reduction module. The first stage drive power is transmitted as follows: Motor → Input Shaft (Ring Gear) → OWC (fixed Sun Gear) → Transfer Drive Gear (Carrier) → Transfer Driven Gear → Output Shaft → DIFF. The second stage drive is transmitted as follows: Motor → Input Shaft (Ring Gear) → Wet Multi-Plate Clutch → Transfer Drive Gear (Carrier) → Transfer Driven Gear → Output Shaft → DIFF. For clarity, Figures 2 and 3 depict the drive power of the first and second stage of the 2-speed transmission.

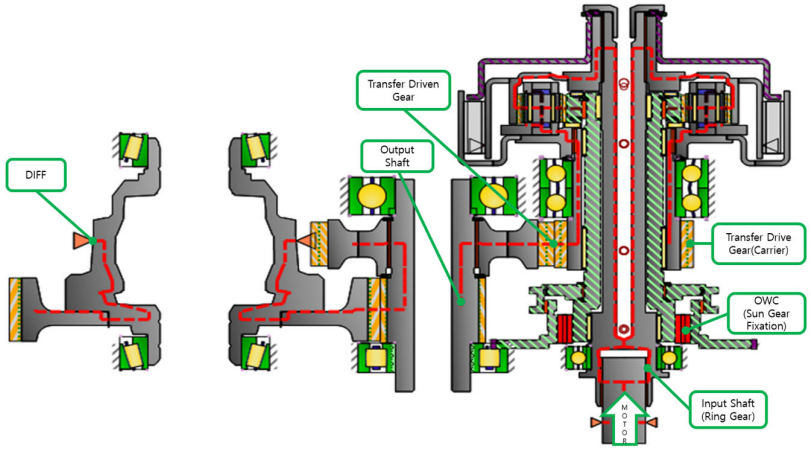


Figure 2. Drive power of the first stage of the 2-speed transmission.

To calculate the gear ratio of the 2-speed transmission using the planetary reduction module, the gear ratio was computed using the following formula based on the gear specifications in Table 1. The gear ratio has a significant impact on the motor's efficiency, acceleration, energy usage, and driving range, and selecting the appropriate gear ratio plays a crucial role in optimizing the overall performance and battery efficiency of the electric vehicle.

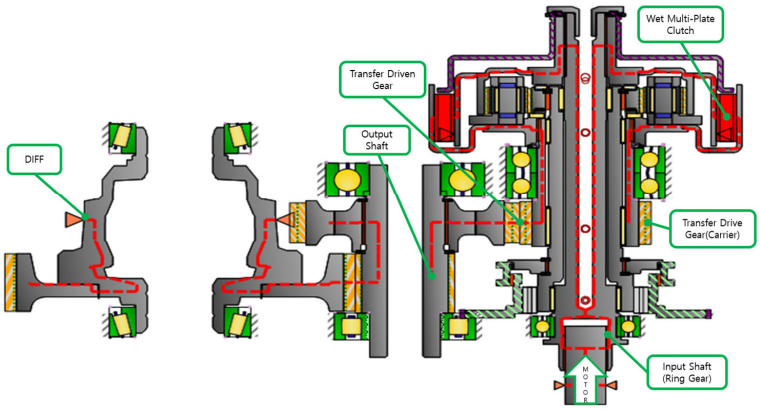


Figure 3. Drive power of the second stage of the 2-speed transmission.

Table 1. Gear specifications.

Item	Planetary Gear			Output Gear		Final Gear	
Position	**Ring Gear**	**Pinion Gear × 6ea**	**Sun Gear**	**Ring Gear**	**Sun Gear**	**Ring Gear**	**Sun Gear**
Number of Teeth (ea)	82	17	50	51	29	67	19
Normal Module (mm)	1.218			2.1		2.7	
Normal Pressure Angle (°)	20			18		20	
Helix Angle (°)	22.45			34.8		24	
Torsional Direction	R	R	L	R	L	L	R
Tip Diameter (mm)	108.5	25.4	66.8	81.6	135.3	65.9	203.3
Root Diameter (mm)	114.1	19.8	61	67.6	121.3	49.8	187.3
Face Width (mm)	18.3	17.4	16.8	29	27	42	39

The Planetary Gear Ratio is defined when the carrier is fixed, input is from the sun gear and output to the ring gear, and can be defined by the following formula:

$$\omega_p = \frac{Z_r}{Z_s} \tag{1}$$

where ω_p is the planetary gear ratio, Z_r is the number of ring gear teeth, and Z_s is the number of sun gear teeth.

The Output Gear Ratio represents the relative rotational speed difference between the ring gear and sun gear, and can be defined by the following formula:

$$\omega_o = \frac{Z_r + Z_s}{Z_s} \tag{2}$$

where ω_p is the output gear ratio, Z_r is the number of ring gear teeth, and Z_s is the number of sun gear teeth.

The Final Gear Ratio must consider the relationship between the number of teeth on the ring gear and the sun gear. In a planetary gear system, when the sun gear is fixed, the rotation of the ring gear occurs in the opposite direction to the sun gear, and this ratio can represent the relative rotational speed difference between them. The Final Gear Ratio is calculated as the ratio of the number of teeth between the ring gear and the sun gear plus one, and can be defined by the following formula:

$$\omega_f = 1 + \frac{Z_r}{Z_s} \tag{3}$$

where ω_f is the final gear ratio , Z_r is the number of ring gear teeth, and Z_s is the number of sun gear teeth

The Total Gear Ratio's first gear ratio is defined when the sun gear is fixed, input is from the ring gear and output to the carrier, and the second gear ratio is defined when the entire system is fixed, as per the following formulas:

$$i_1 = \frac{Z_r + Z_s}{Z_r} \times \frac{Z_{or}}{Z_{os}} \times \frac{Z_{fr}}{Z_{fs}} \tag{4}$$

$$i_2 = 1 \times \frac{Z_{or}}{Z_{os}} \times \frac{Z_{fr}}{Z_{fs}} \tag{5}$$

where i_1 is the first gear ratio, i_2 is the second gear ratio, Z_r is the number of ring gear teeth, Z_s is the number of sun gear teeth, Z_{or} is the number of ring gear teeth of output gear, Z_{os} is the number of sun gear teeth of output gear, Z_{fr} is the number of ring gear teeth of final gear, and Z_{fs} is the number of sun gear teeth of final gear.

Based on the structure and specifications of the transmission, a 2-speed transmission design layout was carried out as shown in Figure 4. The detailed mechanism of the 2-speed transmission we aim to develop is depicted in 3D in Figure 5. The 3D drawings and key design specifications of the 2-speed transmission are summarized in Table 2.

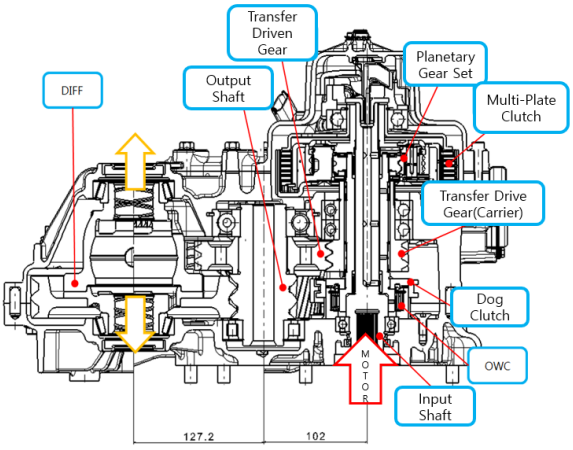


Figure 4. Design layout of proposed 2-speed transmission.

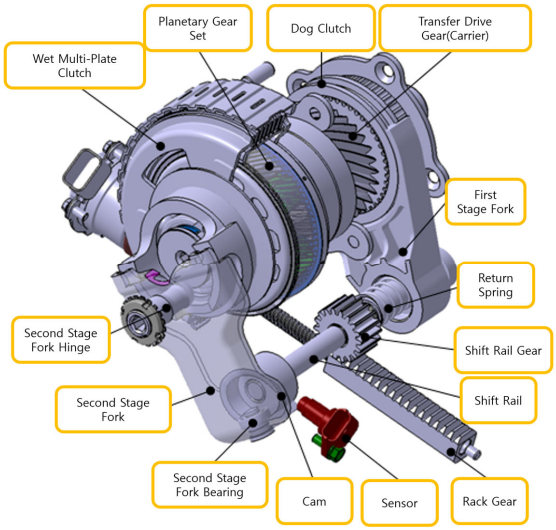
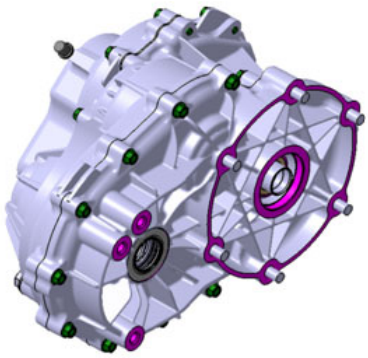
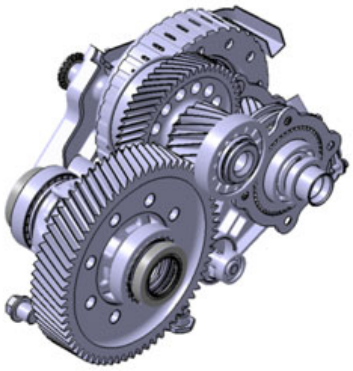


Figure 5. Two-speed transmission detailed mechanism.

Table 2. Summary of key design specifications of proposed 2-speed transmission.



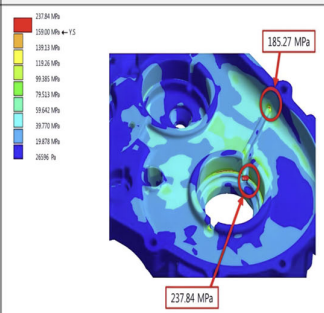
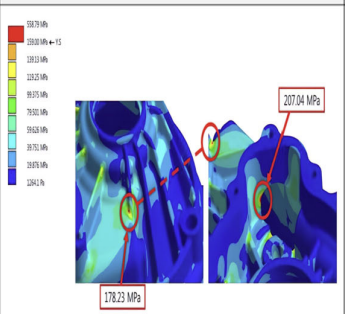
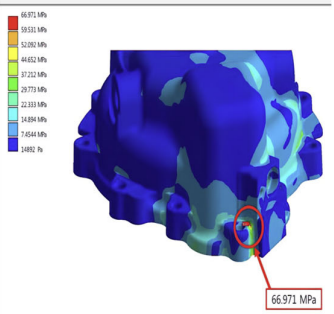


Category		Two-Speed Reducer	
		First	Second
Maximum Torque (Nm)		300	
Total Length (mm)		310.9	
Wheelbase (mm)	Input–Output	102	
	Output–DIFF	127.2	
	Input–DIFF	188.98	
Planetary Gear Ratio		1.64	1
Transfer Gear Ratio		2.76	
Final Gear Ratio		4.53	
Total Gear Ratio		9.98	6.2
Intermittent Ratio		1.64	
3D Weight (kg)	DRY	35.8	
	WET	36.8	
Oil	Capacity (L)	1.2 (Density: 833 kg/mˆ3)	
	Specifications	ATF SHELL TF0870B, SAE 75W	
Others		Planetary Gear, OWC, Dog Clutch, Application of Multi-Plate Clutch	

3.2. Two-Speed Transmission Stress Analysis

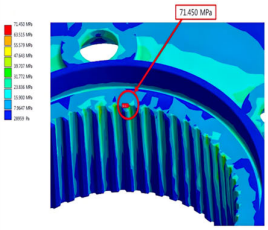
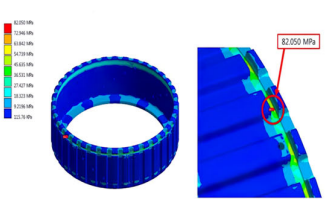
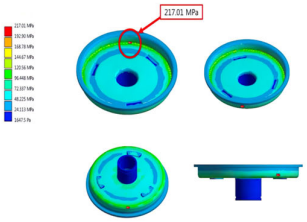
Abaqus is a finite element analysis software that offers modeling of various physical phenomena, finite element analysis, modeling of composite materials and structures, coupled analysis, mesh generation, result analysis, user customization, and a comprehensive simulation environment. This enables accurate simulations for engineering and physical problems, and the program is widely used in industrial and research fields. Using the ABAQUS program, stress analysis of case and clutch components was conducted. Among aluminum die-cast materials, Al-Si-Cu alloy, known for its excellent strength and good castability, was used for the case components (FRONT HOUSING, CASE, REAR COVER). This alloy, particularly ADC10, is well balanced and commonly used in automotive applications. SCM420H + Carburizing, suitable for carburizing heat treatment under carburizing conditions due to its hardenability, weldability, machinability, cold deformation plasticity, and minimal temper brittleness and cold cracking tendencies, was used for DRUM ASSY, HUB ASSY. SAPH440, frequently used in automotive structures, was utilized for the REAR COVER. The results of the stress analysis for each case and clutch component are shown in Figures 6 and 7, and the safety factor (yield strength/maximum stress) is over 1. To briefly explain the calculation method, 'maximum stress' refers to the stress or load applied to

a structure under load, and 'allowable stress' is the stress or load that the structure can withstand. Generally, a structure is considered safe when the safety factor is greater than 1, and risky when it is less than 1.

-	FRONT HOUSING	CASE	REAR COVER
Maximum Stress Position			
Material	ADC10	ADC10	ADC10
Yield Strength(MPa)	160	160	160
Maximum Stress(MPa)	237.84	207.04	66.971
Safety Factor	1.49	1.29	0.42

※ Safety Factor = Yield Strength/ Maximum Stress

Figure 6. Stress analysis results of case.

-	DRUM ASSY	HUB ASSY	PISTON
Maximum Stress Position			
Material	SCM420H + Carburizing	SCM420H + Carburizing	SAPH440
Yield Strength(MPa)	≥ 685	≥ 685	275 ~ 305
Maximum Stress(MPa)	71.450	82.050	217.01
Safety Factor	9.58	8.34	1.27 ~ 1.41

※ Safety Factor = Yield Strength/ Maximum Stress

Figure 7. Flow stress analysis results of clutch.

3.3. Fabrication of Two-Speed Transmission

Based on the design content and stress analysis, the transmission design was revised and supplemented. The production of a prototype was carried out as shown in Figure 8, based on the final design drawings.

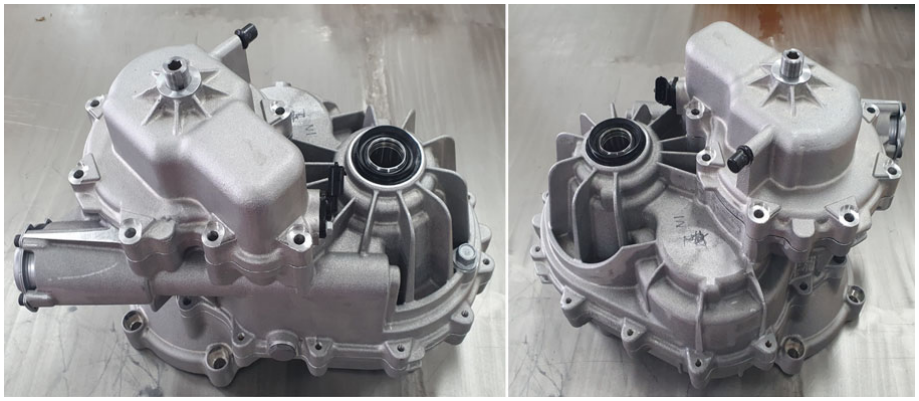


Figure 8. Prototype of proposed 2-speed transmission.

4. Performance Testing and Verification of Proposed 2-Speed Transmission for Electric Vehicles

4.1. Gear Ratio Test

During the performance testing of the 2-speed transmission prototype, gear ratio evaluation tests were conducted. The transmission gear ratio test is a critical process for assessing a vehicle's performance, fuel efficiency, driving convenience, and durability to provide an optimal driving experience and vehicle performance. Through this test, by setting the appropriate gear ratio, fuel efficiency can be improved, and the vehicle's durability and reliability can be evaluated by verifying operation under various driving conditions. The test was conducted using the speed [rpm] values of the input and output parts for each gear of the 2-speed transmission prototype at different times, as specified in Table 3 and Figure 9. The equipment used in the test uses one input motor from Germany's AKH company and two output motors from Germany's SIEMENS company, and the actual configuration of the test equipment is shown in Figure 10.

Table 3. Gear Ratio Evaluation Code.

STEP	1 ↔ 2	2 ↔ 3	Measurement Section	
Time Required for Each Section	30 s	Continuation	First	30–40 s
Cumulative Time	30 s	Continuation		
Output Target Standard	Constant-Velocity Section	100 rpm	Second	50–60 s

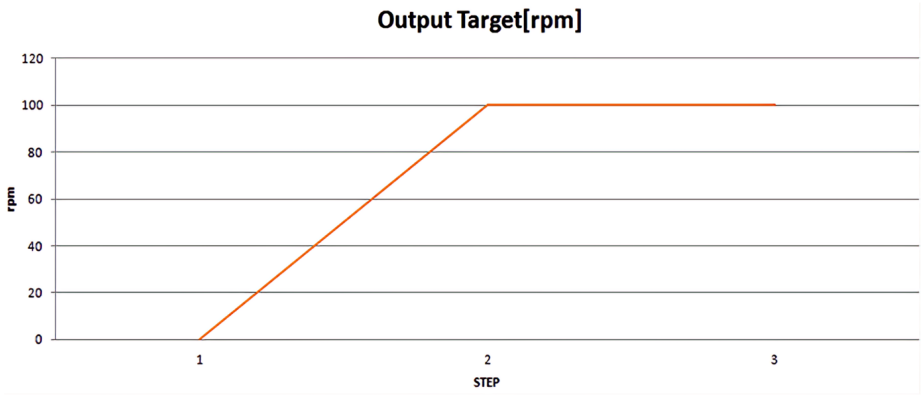


Figure 9. Gear Ratio Evaluation Code Graph.

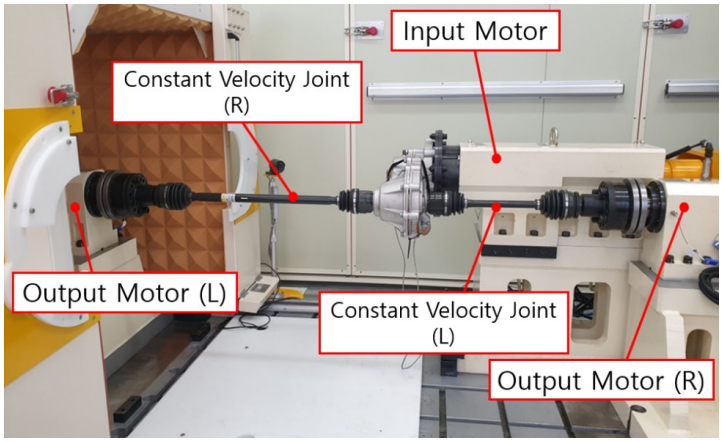


Figure 10. Transmission efficiency testing device.

For the test, the first gear was operated at an average input speed of 997.76 rpm during the 30 s to 40 s interval, and the second gear at an average speed of 619.61 rpm during the 50 s to 60 s interval. The gear ratios for each stage were calculated to be 10 for the first gear and 6.2 for the second gear. The gear ratios were calculated using the formula below, based on the ratio of the input rpm values measured in the first and second gears:

$$n = \frac{\omega_i}{\omega_o} \tag{6}$$

where n is the gear ratio of each stage, ω_i is the average input speed [rpm], and ω_o is the average output speed [rpm], and:

$$n_{2s} = \frac{n_1}{n_2} \tag{7}$$

where n_{2s} is the prototype gear ratio (First gear/Second gear), n_1 is the first gear ratio, and n_2 is the second gear ratio.

The calculated result showed that the first/second gear ratio was 1.61, which is above the development target of 1.60, leading to a satisfactory outcome. The test results are summarized in Table 4 and Figure 11.

Table 4. First and second gear ratio test results of 2-speed transmission.

Test Mode	Measurement Section [s]	Average Input Speed (ω_0) [rpm]	Gear Ratio of Each Stage (n)	Gear Ratio (n_{2s}) [First/Second]
First	30–40 s	997.76	10	1.61
Second	50–60 s	619.61	6.2	

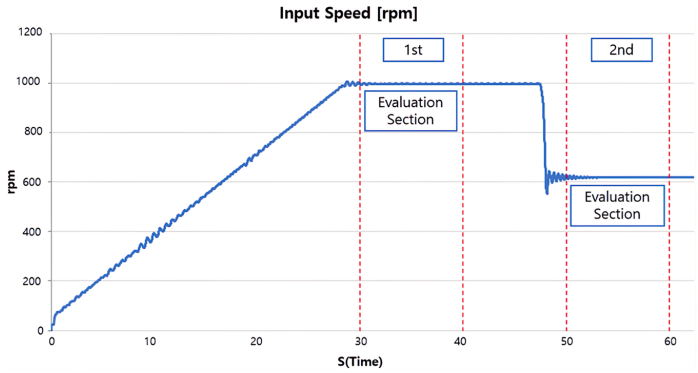


Figure 11. First and second gear ratio test graph of 2-speed transmission.

4.2. Gear Conversion Operation Time Test

During the performance testing of the 2-speed transmission prototype, a test for gear shift operation time was conducted. This test measures the time it takes to change gears in order to improve the vehicle's driving convenience, fuel efficiency, durability, and safety. Fast gear shifting can enhance the driver's convenience, as well as the vehicle's performance and fuel efficiency, and also contributes to the assessment of durability and safety. Consequently, this test plays a vital role in optimizing the quality of the vehicle. Using the specified evaluation code in Table 5 and Figure 12, the operation time for changing gears from first to second was measured. The equipment used in the test uses one input motor from Germany's AKH company and two output motors from Germany's SIEMENS company, and the actual configuration of the test equipment is shown in Figure 10.

Table 5. Gear conversion operation time evaluation code.

STEP	1 ↔ 2	2 ↔ 3
Time Required for Each Section	30 s	Continuation
Cumulative Time	30 s	Continuation
Output Target Standard	Constant-Velocity Section	120 rpm

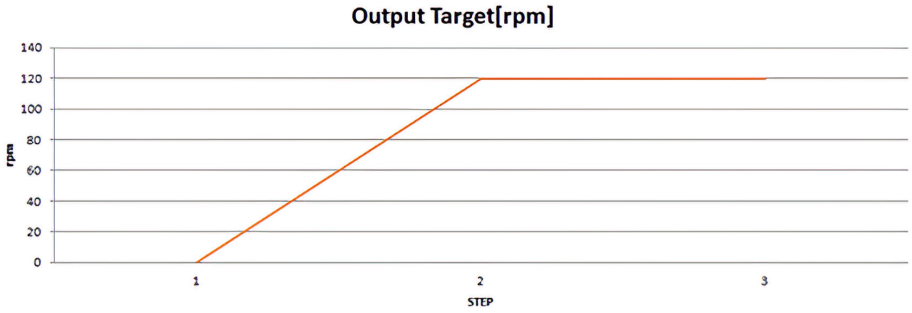


Figure 12. Gear conversion evaluation code graph.

The time required to change gear speeds was calculated by subtracting the start time of speed change from the end time of speed change.

The test began shifting at 1198 rpm and ended at 608 rpm. The times corresponding to the start and end of shifting were 55.94 s and 56.37 s, respectively, and a satisfactory shift time of 0.43 s was obtained, which was within the development target of 0.8 s. The test results are summarized in Table 6, and the configuration of the testing equipment is as shown in Figure 13.

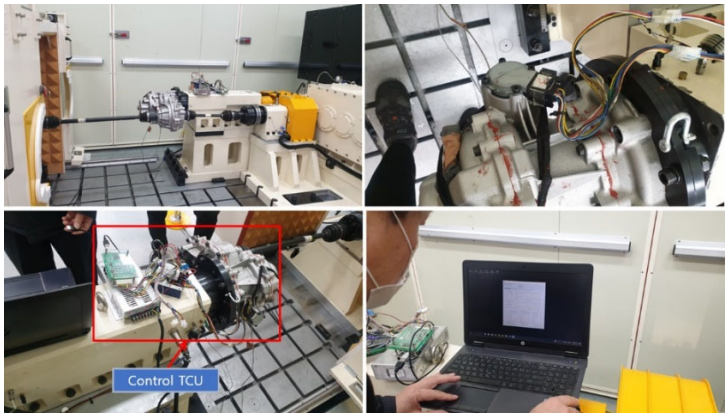


Figure 13. Gear conversion test device.

Table 6. Gear conversion operation time test.

Test Mode	Time (s)	Input Speed [rpm]	Converter Drive Position Time
Converter Drive Position Start	55.94	1198	0.43
Converter Drive Position End	56.37	608	

4.3. Torque Capacity Test

During the performance testing of the 2-speed transmission prototype, a Torque capacity test was conducted. This test determines how effectively the transmission of a vehicle can transfer torque. The test evaluates system safety, vehicle performance, durability, design optimization, and safety, contributing to the development of reliable products. Using the specified evaluation code in Table 7 and Figure 14, the test was carried out to reach the development target of a Max Torque of 300 Nm, and the torque capacity was measured by applying 300 Nm of Torque to the input part of the 2-speed transmission prototype.

Table 7. Torque capacity test.

STEP	1 ↔ 2	2 ↔ 3	3 ↔ 4	4 ↔ 5	5 ↔ 6	6 ↔ 7	7 ↔ 8	8 ↔ 9	9 ↔ 10	10 ↔ 11	11 ↔ 12
Time Required for Each Section	10 s	10 s	20 s	10 s	30 s	5 s	25 s	10 s	20 s	10 s	5 s
Cumulative Time	10 s	20 s	40 s	50 s	80 s	85 s	110 s	120 s	140 s	150 s	155 s
Input Target Criteria	Constant-Velocity Section	−50 Nm	Constant-Velocity Section	−100 Nm	Constant-Velocity Section	−300 Nm	Deceleration Section	−100 Nm	Deceleration Section	−50 Nm	Deceleration Section

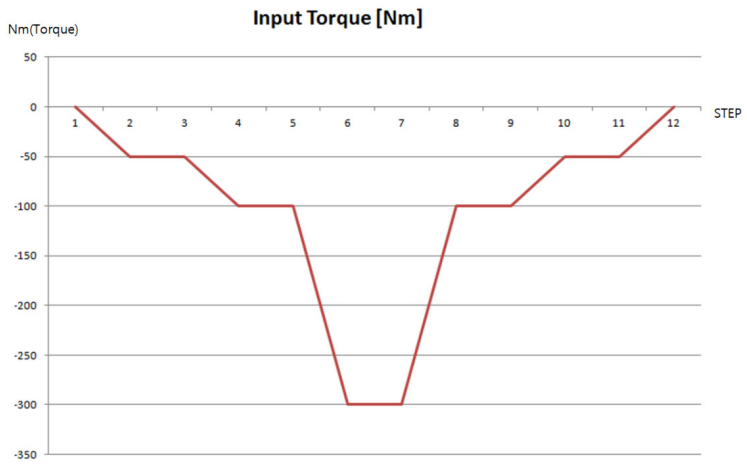


Figure 14. Torque capacity measurement program and evaluation graph.

The equipment used in the test uses one input motor from Germany's AKH company and two output motors from Germany's SIEMENS company, and the actual configuration of the test equipment is shown in Figure 10.

The test results confirmed that there were no issues in reaching a Max Torque of 300 Nm in the 6 ↔ 7 interval. The measured results of the Torque capacity for each interval are shown in Figure 15.

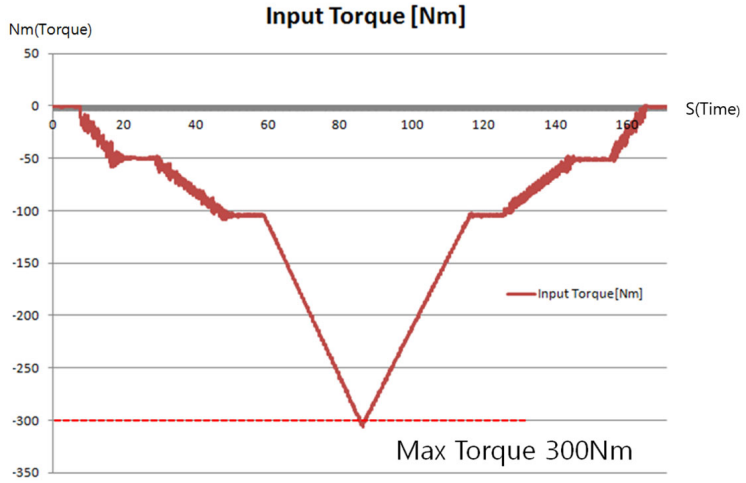


Figure 15. Torque capacity measurement results.

4.4. Torque Capacity Measurement Results

During the performance testing of the 2-speed transmission prototype, a power transmission efficiency test was conducted. This test assesses the efficiency of the transmission in a vehicle in transferring the engine's rotational speed and torque to the driving wheels. To verify the efficiency of the developed 2-speed transmission prototype, the test was carried out using the specified evaluation code in Table 8 and Figure 16.

Table 8. Power transmission efficiency evaluation code.

STEP	1 ↔ 2	2 ↔ 3	3 ↔ 4
Time Required for Each Section	40 s	90 s	20 s
Cumulative Time	40 s	130 s	150 s
Input Target Criteria	−120 Nm	Constant-Velocity Section	Deceleration Section
Output Target Criteria	200 rpm	Constant-Velocity Section	Deceleration Section

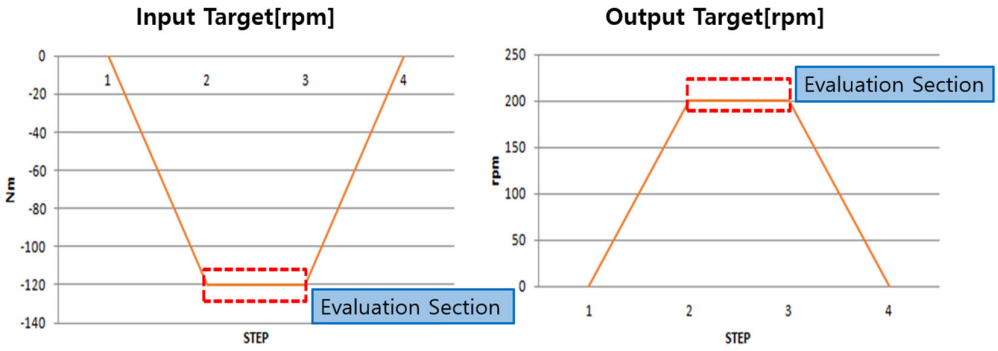


Figure 16. Graph of power transmission efficiency evaluation codes.

The overview of the test apparatus is as shown in Figure 17. The equipment used for the test includes one input motor from AKH in Germany and two output motors from SIEMENS in Germany. The actual configuration of the testing equipment is as shown in Figure 10.

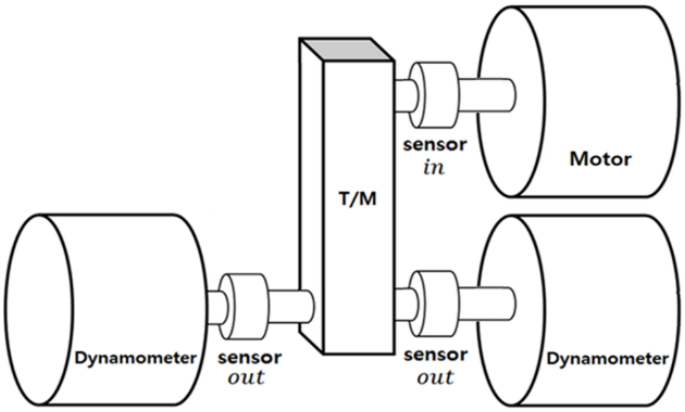


Figure 17. Configuration of transmission efficiency test.

The power transmission efficiency was calculated using the following formula, based on the torque [Nm] and speed [rpm] values of the input and output parts at different times for both the first and second gears of the 2-speed transmission prototype.

Equation (8) represents η, the overall power transmission efficiency of the prototype in percentage. P_{out} denotes the output power (W) and P_{in} the input power (W):

$$\eta = \frac{(P_{out})}{(P_{in})} \times 100\ [\%] \tag{8}$$

where η is the prototype overall power transmission efficiency [%], P_{out} is the output power [W], and P_{in} is the input power [W].

Equation (9) defines P_{out} as the output power in watts (W). T_o is the output torque expressed in Newton meters (Nm), and ω_o is the output speed in revolutions per minute (rpm). This equation is used to calculate the power of a rotating object, where the power is derived from the product of torque and rotational speed. The factor $2\pi/60$ is used as a unit conversion coefficient, converting revolutions per minute (rpm) to radians per second. This converted value is then expressed in power (W).

$$P_{out} = \frac{2\pi}{60} \times (T_o \times \omega_o)[\mathcal{W}] \tag{9}$$

where P_{out} is the output power [W], T_o is the output torque [Nm], and ω_o is the output speed [rpm].

Equation (10) defines P_{in} as the input power in watts (W). T_i represents the input torque, expressed in Newton meters (Nm), and indicates the rotational force exerted on the rotating shaft. ω_i is the input speed, expressed in revolutions per minute (rpm). The power is derived from the product of torque and rotational speed. The factor $2\pi/60$ is used as a unit conversion coefficient, converting revolutions per minute (rpm) to radians per second. This converted value is then expressed in power (W).

$$P_{in} = \frac{2\pi}{60} \times (T_i \times \omega_i)[\mathcal{W}] \tag{10}$$

where P_{in} is the input power [W], T_i is the input torque [Nm], and ω_i is the input speed [rpm].

Equation (11) represents η_{2s}, the power transmission efficiency of the prototype, expressed as a percentage. η_1 denotes the power transmission efficiency of the first gear (first) as a percentage, and η_2 represents the power transmission efficiency of the second gear (second) as a percentage. This calculation is used to determine the overall efficiency of the system through the power transmission efficiency at each stage. It

aids in optimizing the performance of the entire system and helps in identifying and improving any inefficient areas.

$$\eta_{2s} = \frac{(\eta_1)}{(\eta_2)} \tag{11}$$

where η_{2s} is the power transmission efficiency of prototype [%], η_1 is the first power transmission efficiency [%], and η_2 is the second power transmission efficiency [%].

The results of the power transmission efficiency test of the prototype 2-speed transmission are as follows: The efficiency of the first gear was 94.13% and that of the second gear was 94.34%. The average power transmission efficiency of the first and second gears was 94.24%. The power transmission efficiency evaluation results are summarized in Table 9 and presented in Figure 18.

Table 9. Power transmission efficiency.

Test Mode	Input Torque (T_i) [Nm]	Output Torque (T_o) [Nm]	Input Speed (ω_i) [rpm]	Output Speed (ω_o) [rpm]	Stepped Transmission Efficiency [%]	Prototype Transmission Efficiency [%] (1st + 2nd)/2
First	−117.64	625	1995.2	199.5	94.13	94.24
Second	−117.64	622.6	1996.2	199.9	94.34	

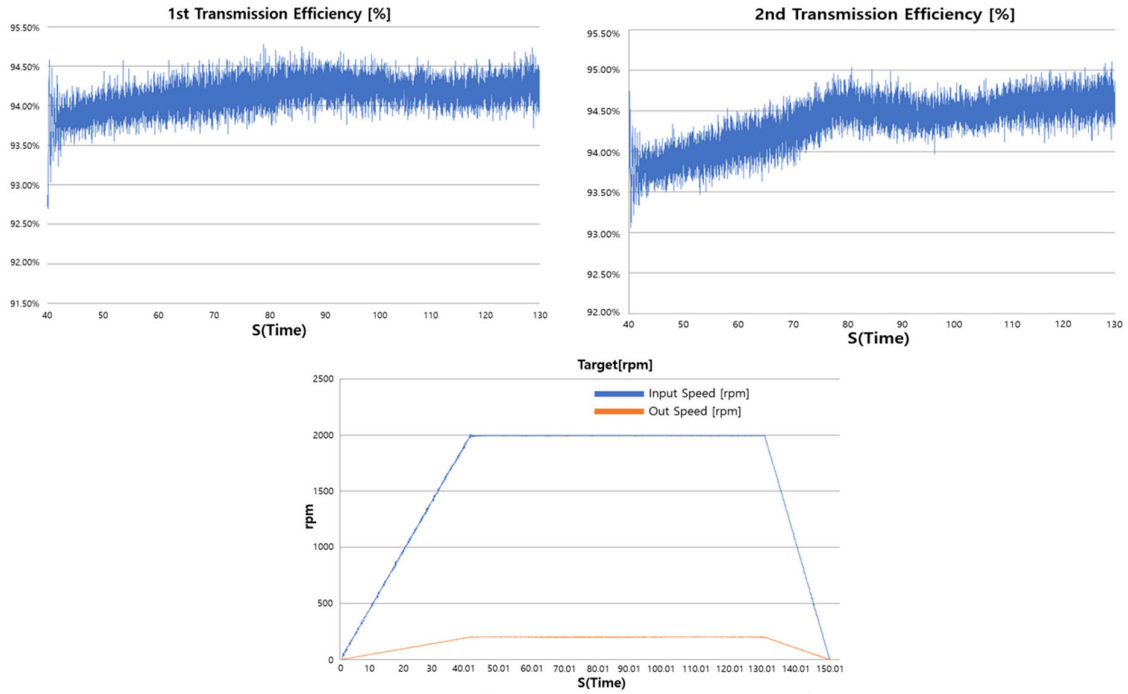


Figure 18. Graph of power transmission efficiency.

5. Conclusions

In this research, the developed 2-speed transmission for electric vehicles is coupled to the drive motor, forming a coaxial arrangement with the input shaft and the shifting shaft. The drive sun gear is directly connected to the motor, forming a single axis. Overall, the design allows for structural and energy-efficient use, and a 300 Nm class 2-speed electric vehicle transmission featuring efficient planetary gears and a wet multi-plate clutch was developed. To test and verify the performance of the developed 2-speed transmission, analyses of the transmission structure, gear ratio tests, torque capacity tests, and power transmission efficiency tests were conducted, yielding the following results:

(1) A 2-speed EV transmission consisting of a DIFF, an output shaft, a transfer driven gear, a planetary gear set, a multi-plate clutch, a transfer drive gear (carrier), a dog clutch, an OWC, and an input shaft was designed and fabricated.
(2) Each gear ratio was analyzed based on the gear specifications. The planetary gear ratio was calculated as 1.64:1 (first: second), output gear ratio as 2.76, final gear ratio as 4.53, and total gear ratio as 9.98:6.2 (first: second).
(3) Structural analysis of the 2-speed transmission was conducted using the ABAQUS program. The analysis of the case and clutch components showed that all parts had a safety factor of over 1.
(4) A gear ratio test was conducted and analyzed. The calculated result yielded a gear ratio of 1.61.
(5) A gear shift test was carried out, and the shifting time was analyzed. The calculated result yielded a shift time of 0.43 s.
(6) A Torque capacity test was conducted, and using the measurement program, it was confirmed that the Max Torque capacity reached 300 Nm.
(7) A power transmission efficiency test was carried out, and the transmission's baseline efficiency was calculated based on the results. A baseline efficiency of 94.24% was obtained for transmission. The baseline efficiency for first gear shift was 94.13%, while for the second gear shift it was calculated at 94.34%.

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References

1. Damert, M.; Baumgartner, R.J. Intra-sectoral differences in climate change strategies: Evidence from the global automotive industry. *Bus. Strategy Environ.* **2018**, *27*, 265–281. [CrossRef] [PubMed]
2. Borkhade, R.; Bhat, K.S.; Mahesha, G. Implementation of Sustainable Reforms in the Indian Automotive Industry: From Vehicle Emissions Perspective. *Cogent Eng.* **2022**, *9*, 2014024. [CrossRef]
3. Song, C.H.; Aaldering, L.J. Strategic intentions to the diffusion of electric mobility paradigm: The case of internal combustion engine vehicle. *J. Clean. Prod.* **2019**, *230*, 898–909. [CrossRef]
4. Kim, W.; Kim, D.; Lee, D.; Moon, I.; Lee, J. Analysis of Optimal Shift Pattern Based on Continuously Variable Transmission of Electric Vehicle for Improving Driving Distance. *Appl. Sci.* **2023**, *13*, 1190. [CrossRef]
5. Karki, A.; Phuyal, S.; Tuladhar, D.; Basnet, S.; Shrestha, B.P. Status of pure electric vehicle power train technology and future prospects. *Appl. Syst. Innov.* **2020**, *3*, 35. [CrossRef]
6. Cesare, P. Umberto Monarca, and Giuseppe Surdi. Electric vehicle evolution: Issues and policy implications. *Glob. Local Econ. Rev.* **2020**, *24*, 1.
7. Husain, I.; Ozpineci, B.; Islam, S.; Gurpinar, E.; Su, G.-J.; Yu, W.; Chowdhury, S.; Xue, L.; Rahman, D.; Sahu, R. Electric drive technology trends, challenges, and opportunities for future electric vehicles. *Proc. IEEE* **2021**, *109*, 1039–1059. [CrossRef]
8. Wellings, J.; Greenwood, D.; Coles, S.R. Understanding the Future Impacts of Electric Vehicles—An Analysis of Multiple Factors That Influence the Market. *Vehicles* **2021**, *3*, 851–871. [CrossRef]
9. Rajper, S.Z.; Albrecht, J. Prospects of electric vehicles in the developing countries: A literature review. *Sustainability* **2020**, *12*, 1906. [CrossRef]
10. Patil, L.N.; Khairnar, H.P. Investigation of Perceived Risk Encountered by Electric Vehicle Drivers in Distinct Contexts. *Appl. Eng. Lett.* **2021**, *6*, 69–79. [CrossRef]

11. Sahoo, B.; Routray, S.K.; Rout, P.K. Advanced Speed-and-current control approach for dynamic electric car modelling. *IET Electr. Syst. Transp.* **2021**, *11*, 200–217. [CrossRef]
12. Mantriota, G.; Reina, G. Dual-Motor Planetary Transmission to Improve Efficiency in Electric Vehicles. *Machines* **2021**, *9*, 58. [CrossRef]
13. Machado, F.A.; Kollmeyer, P.; Barroso, D.G.; Emadi, A. Multi-Speed Gearboxes for Battery Electric Vehicles: Current Status and Future Trends. *IEEE Open J. Veh. Technol.* **2021**, *2*, 419–435. [CrossRef]
14. Tseng, C.-Y.; Yu, C.-H. Advanced shifting control of synchronizer mechanisms for clutchless automatic manual transmission in an electric vehicle. *Mech. Mach. Theory* **2015**, *84*, 37–56. [CrossRef]
15. Kim, S.; Choi, S.B. Cooperative control of drive motor and clutch for gear shift of hybrid electric vehicles with dual-clutch transmission. *IEEE/ASME Trans. Mechatron.* **2020**, *25*, 1578–1588. [CrossRef]
16. Wei, C.; Hofman, T.; Caarls, E.I. Co-Design of CVT-Based Electric Vehicles. *Energies* **2021**, *14*, 1825. [CrossRef]
17. Zhu, B.; Zhang, N.; Walker, P.; Zhan, W.; Zhou, X.; Ruan, J. Two-speed DCT electric powertrain shifting control and rig testing. *Adv. Mech. Eng.* **2013**, *5*, 323917. [CrossRef]
18. Gao, B.; Liang, Q.; Xiang, Y.; Guo, L.; Chen, H. Gear ratio optimization and shift control of 2-speed I-AMT in electric vehicle. *Mech. Syst. Signal Process.* **2015**, *50*, 615–631. [CrossRef]
19. Tian, Y.; Ruan, J.; Zhang, N.; Wu, J.; Walker, P. Modelling and control of a novel two-speed transmission for electric vehicles. *Mech. Mach. Theory* **2018**, *127*, 13–32. [CrossRef]
20. Walker, P.; Zhu, B.; Zhang, N. Powertrain dynamics and control of a two speed dual clutch transmission for electric vehicles. *Mech. Syst. Signal Process.* **2017**, *85*, 1–15. [CrossRef]
21. Available online: https://www.greencarcongress.com/2014/11/20141110-gkn.html (accessed on 10 November 2014).
22. Zhang, Y.; Du, J.; Mao, J.; Xu, M. Dynamic Analysis of High-Speed Helical Gear Transmission in Pure Electric Vehicle Gearbox. *Shock Vib.* **2020**, *2020*, 6639372. [CrossRef]
23. Gassmann, T.; Gueth, D.; Haupt, J. Seamless-shift Two-speed Transmission with Torque Vectoring Functionality. *ATZ Worldw.* **2017**, *119*, 46–49. [CrossRef]
24. Shin, J.W.; Jung, H.Y.; Oh, S.H. A study on 2-speed transmission of electric vehicle by using inventogram. *J. Mech. Sci. Technol.* **2017**, *31*, 2543–2548. [CrossRef]
25. Han, J.-O.; Shin, J.-W.; Kim, J.-C.; Oh, S.-H. Design 2-speed transmission for compact electric vehicle using dual brake system. *Appl. Sci.* **2019**, *9*, 1793. [CrossRef]
26. *JGMA 6101—02*; Calculation of Bending Strength for Spur and Helical Gears. 2007.
27. *JGMA 6102—02*; Calculation of Surface Durability (Pitting Resistance) for Spur and Helical Gears. 2009.
28. Han, J.-O.; Jeong, W.-H.; Lee, J.-S.; Oh, S.-H. The Structure and Optimal Gear Tooth Profile Design of Two-Speed Transmission for Electric Vehicles. *Energies* **2021**, *14*, 3736. [CrossRef]
29. Stanojević, M.; Tomović, R.; Ivanović, L.; Stojanović, B. Critical Analysis of Design of Ravigneaux Planetary Gear Trains. *Appl. Eng. Lett.* **2022**, *7*, 32–44. [CrossRef]
30. Available online: https://www.electrive.com/2019/07/17/zf-presents-two-speed-transmission-for-electric-cars/ (accessed on 18 July 2019).

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