Effect of gear design on the power transmission unit of a small-sized multipurpose agricultural utility vehicle

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Abstract. In this study, various gears were designed and evaluated to analyze the power transmission efficiency of a multipurpose agricultural utility vehicle. A computational simulation method was used to evaluate the effect of different models of power transmission systems before developing the vehicle. The 3D models of 15, 18, 21, 24, 27, and 30 teeth spur gears were generated using SM45C steel using commercial software. The power transmission efficiency was analyzed by varying the gear teeth number, face width of the gear teeth, and estimated torque values. The gear modules of 3.2, 2.7, and 2.2 mm were used to model the spur gear train using the 1:1 gear ratio. The power transmission efficiency of the proposed utility vehicle was simulated using 5, 10, and 15 Nm of torque. The simulated results of the 3.2 mm gear module with 30 teeth spur gear showed better performance with maximum power loss compared to other gears. The maximum power transmission efficiency was recorded to be 99.94% when adjusted for 15 Nm torque. The designed gears with 25 mm and 15 mm face width achieved 99.90% and 99.92% transmission efficiency, respectively. It was observed that gears with smaller face width achieved better efficiency with minimal power loss. The simulation results presented in this study is suitable to design and develop a utility vehicle for multipurpose agricultural use.

1. Introduction

A multipurpose agricultural utility vehicle is primarily used as the main equipment for performing various field operations. Thus, their demand is increasing globally. Generally, agricultural tractors are used as utility vehicles for performing various activities in large agricultural fields [1]. Nevertheless, it is quite challenging to accomplish agricultural activities in a small field, such as an orchard, due to the increase in agricultural management costs and the aging of agriculture. Presently, the development of a low-powered and economical multipurpose utility vehicle is a major requirement in agriculture because bulky machines are dangerous to work with, especially in mountainous areas, as they can cause serious injury to the operators and labourers. Small-sized electric tracked vehicles offer the best solutions to reduce the reliance on heavy machines. Tracked vehicles are widely used in agriculture fields owing to their excellent dynamic performance under complicated driving conditions. Furthermore, electric
tracked vehicles have garnered attention because of their high transmission efficiency, driving performance, and easy maintenance [2].

The power transmission of an agricultural utility vehicle is considered the most significant issue in determining working efficiency. The multipurpose small-sized utility vehicle was designed as a track-driven electric vehicle. A single gear train demonstrated the proposed vehicle to achieve high power transmission efficiency with minimum power loss. In the transmission system, gears and sprockets play a vital role as they are used as the primary transmission devices to deliver the prescribed power [3]. Gears are designed using various parameters based on their applications and service requirements. The transmission system of the proposed vehicle comprises different gears, bearings, and shafts along with the hydraulic pressure reducer. Spur gears are considered the core component for the transmission of power. The design of spur gear pairs is easy to manufacture [4], and numerous studies have been conducted on single and multistage gear trains [5–9] as a dominant part in power transmission systems in agricultural machinery. Considering the appropriate rotational speed and torque, various types of electric motors are perfectly adapted with electric vehicles [10] where the gearbox is played an essential role in power transmission. The design and development of an agricultural utility vehicle can be improved by selecting the optimal scheme for power transmission [11]. The modelling and simulation of the gear system were performed using various software to improve the efficiency of the transmission system and reduce the time required for development and improvement [12].

To summarize, a track driven electric utility vehicle is proposed for multipurpose agricultural use, and the overall efficiency and power loss of the power transmission system of the proposed vehicle were analyzed for various spur gears via simulation. In other words, this study aims to verify the effect of gear modules by changing the number of teeth and face width of the designed spur gear.

2. Materials and methods

2.1. Working procedure of the proposed multipurpose agricultural utility vehicle

A small-sized multipurpose agricultural utility vehicle was used for analyzing the power transmission system. The specifications of the vehicle are shown in Table 1.

| Item                                      | Specification         |
|-------------------------------------------|-----------------------|
| Utility vehicle size (length × width × height) (mm) | 948 × 970 × 899       |
| Empty vehicle weight (kg)                 | 544.6                 |
| Battery capacity (V)                      | 24                    |
| Motor power, W @ rpm                      | 1000 @ 3400           |
| Sprocket diameter (mm)                    | 7                     |
| Idler wheel diameter (mm)                 | 20                    |
| Distance between the sprocket and front road wheel (mm) | 237.5                |

Agricultural machinery, such as sprayer, mower, crusher, and branch pruner, can be attached to the main body of the proposed vehicle using the three-point hitch for performing the particular activity. The two tracked wheels bear the whole load of the vehicle. To drive the vehicle, a manual driving system was positioned in the middle of the vehicle mainframe. Figure 1 shows the major applications of the agricultural utility vehicle.
Figure 1. Various applications of agricultural utility vehicles.

2.2. **Modeling of the power transmission system**

The proposed vehicle was designed based on the direct gear-to-gear drive power transmission system. Figure 2 (left) shows the schematic of the power transmission system of the proposed vehicle. The vehicle was powered by two batteries (Model: Longest 12165) that distributed the required power to two different motors. The speed of the vehicle was controlled using the motor controller. The battery-powered DC motors transferred the torque produced via the shaft, and the drive sprocket received the output power from the driving gear through the gear assembly. The sprocket delivered the power to the wheels via track belts that were engaged with the sprockets (Figure 2 (right)).

![Diagram of the power transmission system](image)

Figure 2. Schematic of the track and wheels of the vehicle (left). (1) Sprocket; (2) front road wheel; (3) joint bar; (4) fixing shaft; (5) rear road wheel; (6) support; (7) track belt; (8) driving direction; (9) utility vehicle body. Vehicle powertrain schematic (right).

The shaft and the spur gears were modelled using the KISSsoft drivetrain software 2017 (KISSsoft AG, Bubikon, Schwyz, Switzerland). The shaft length and diameter were 165 and 20 mm, respectively. The spur gears were designed with 15, 18, 21, 24, 27, and 30 number of teeth (T) for two face widths of 15 mm and 25 mm. Two case studies were investigated for predicting the working performance of the proposed vehicle. The efficiency of the transmission system was evaluated based on the number of teeth and face width of the gear. The gear ratio was selected as 1:1 for the primary test to achieve high efficiency from the proposed gear mechanism. The specifications of the shaft and gear are shown in Table 2.
Table 2. Shaft and gear specifications.

| Item                                      | Specification                      |
|-------------------------------------------|------------------------------------|
| Gear type                                 | Spur gear                          |
| Gear module (mm)                          | 3.2, 2.7, and 2.2                  |
| Gear teeth (T)                            | 15, 18, 21, 24, 27, and 30         |
| Gear material                             | SM45C                              |
| Tensile strength (MPa)                    | 640                                |
| Elastic modulus (GPa)                     | 207                                |
| Yield Strength (MPa)                      | 370                                |
| Gear ratio                                | 1:1                                |
| Poisson’s ratio                           | 0.3                                |
| Face width (mm)                           | 15 and 25                          |
| Shaft length and diameter (mm)            | 165 and 20                         |

The designed shaft and gears were simulated for monitoring the effect of using different gear sizes. The isometric views of the shaft pair constraint and the shaft and bearing model are shown in Figure 3.

![Isometric view of shaft pair constraint](image1)

![Model of the shaft and bearing](image2)

**Figure 3.** Model of gear and shaft pair constraint. (a) Shaft kinematic; (b) shaft with bearing and coupling.

2.3. *Simulation procedure of the power transmission system*

The gearbox was designed to control the overall efficiency and power loss of the proposed transmission system. The driven gear, driver gear, and gearbox were designed using SM45C. The efficiency of the gearbox was calculated using a computational simulation technique. The housing wall thickness of the gearbox was assumed to be 5 mm, and the thermal conductivity was recorded to be 50 w/m K. The transmission model of the main gear trains and gearbox model for the power transmission unit of the vehicle is shown in Figure 4 (a)–(b). In the power transmission model, Couplings were used to show the input and output powers in the entire power transmission model. The torque was transferred to the input shaft, and after transmitting the power was moved to the output shaft (Figure 4a). In this process, some power was lost due to internal parameter effects, such as churning, windage, sliding friction, and rolling friction loss. The simulation process was conducted for torque values of 5, 10, and 15 Nm.
3. Result and discussion

3.1. Effect of teeth number

The 3D surface map shows the effect of teeth number in the gear module of 3.2, 2.7, and 2.2 mm (Figure 5). The maps represent the overall efficiency and power loss based on the gear size and teeth number for estimated torques values of 5, 10, and 15 Nm. The minimum teeth number used in this experiment was 15, whereas the maximum teeth number was 30.

![Figure 5. Overall efficiency and power loss maps of the 3.2 mm (a)–(b), 2.7 mm (b)–(c), and 2.2 mm (c)–(d) spur gear module.](image)
The 3.2 mm gear module achieved the highest transmission efficiency of 99.94% for the highest teeth number (Figure 5 (a)–(b)). By contrast, the lowest transmission efficiency was 99.85% for the lowest teeth number. Approximately 9% of excess loss occurred due to the difference in teeth number. Contrariwise, the simulated results showed a maximum power loss of 0.032 kW for the 30 teeth gear, whereas the minimum power loss was achieved by the 15 teeth gear. A similar trend was observed for the 2.7 mm gear module (Figure 5 (c)–(d)). The maximum and minimum transmission efficiencies achieved were 99.93% and 99.89% when the power losses were 0.058 kW and 0.04 kW, respectively.

Likewise, in the simulation of the 2.2 mm gear module, the maximum and minimum transmission efficiencies were recorded to be 99.88% and 99.78%, and the overall maximum and minimum power losses were 0.087 kW and 0.07 kW. The simulation results prove that overall efficiency and power loss are inversely related. Although gears with higher teeth number enabled high transmission efficiency, it increased power loss too. In the simulation, it was observed that the torque value affected the overall performance of the power transmission system. A high torque value induced maximum efficiency with high power loss. However, the results seldom showed a different behaviour owing to the change in internal loss producing factors of the entire transmission system.

### 3.2. Effects of gear face width

The overall efficiency and power loss for different spur gear sizes with different face widths are shown in Figure 6. The figure shows the effect of gear transmission performance for the face widths of 15 and 25 mm. When the face width was 15 mm, the overall efficiency was high with minimum power loss. By contrast, the 25 mm face width demonstrated comparatively low efficiency with high power loss. Throughout this study, the overall efficiency of the 3.2 mm gear module was recorded to be 99.90%, and 99.92% for the 25 mm and 15 mm face width, respectively. The difference in efficiency was 2% for the 10 mm difference in face width, which was due to low input power and improper meshing of gear teeth. Moreover, a maximum difference of 4% was observed for the 2.7 mm gear module for the 10 mm difference in face width. The maximum power loss was 0.056 kW for the 2.2 mm module gear with a 25 mm face width, whereas the minimum loss was observed for the 3.2 mm gear module with a 25 and 15 mm face width ($p \leq 0.05$).

![Graphs showing overall efficiency and power loss for different face widths](image)

**Figure 6.** Overall efficiency (left) and power loss (right) graphs for different face widths of the spur gear. The mean values shown in the graphs indicated with different letters are significantly different according to Tukey’s one-way comparisons ($p \leq 0.05$).

The simulation results showed an overall efficiency of 99.15%, 99.84%, and 99.85% for the 25 mm face width, and 99.92%, 99.88%, and 99.86% for the 15 mm face width, respectively, of the 3.2, 2.7, and 2.2 mm gear module. By contrast, the simulation results showed an overall power loss of 0.029, 0.049, and 0.056 kW, and 0.024, 0.041, and 0.050 kW for the 25 mm and 15 mm face width of the 3.3,
2.7, and 2.2 mm gear modules, respectively. The simulation results showed that big-sized gears with minimum face width achieved maximum transmission efficiency.

4. Conclusions
The software-based analysis of power transmission gears was performed to devise guidelines for the optimal design of the proposed multipurpose agricultural utility vehicle. A single gear train driveline was selected to analyze the effect of using different sizes of spur gears. The big-sized gear with minimal teeth numbers achieved better transmission efficiency. The efficiency of a gearbox depends on various factors. However, in the simulation, better efficiency led to high power loss as well. In the entire experiment, overall efficiency and power loss were influenced by torque. The high range of torque produced high power, part of which was lost during transmission. Multi-gear train models and simulation can be used for selecting better transmission systems. Nevertheless, field tests and validation are necessary for designing the power transmission system of an agricultural utility vehicle by considering equivalent torque, the torque required during various operations, and work conditions to improve the reliability of the transmission system.

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References
[1] Lee P U, Lee N G, Choi C H, Kim Y J 2018 Effects of working speeds of an agricultural tractor on a gear transmission. Proceedings of the ASABE Annual International Meeting 2018 (paper no. 180978) Michigan: St. Joseph
[2] Wang Z, Lv H, Zhou X, Chen Z, Yang Y 2018 Design and modelling of a test bench for dual-motor electric drive tracked vehicles based on a dynamic load emulation method Sensors. 18 1-20
[3] Lee Y S, Ali M, Islam M N, Rasool K, Jang B E, Kabir M S N, Kang T K, Chung S O 2020 Theoretical analysis of bending stresses to design a sprocket for transportation part of a Chinese cabbage collector J. Biosyst. Eng. 45 85-93
[4] Patil A 2017 Bending stress analysis of spur gear Int’l J. Res. App. Sci. Eng. Tech. 5 422-426
[5] Jung J W, Kim K P, Ji H C, Moon T S 2015 Design improvement of the driving bevel gear in transmissions of a tracked vehicle J. Korean Soc. Manuf. Process. Eng. 14 2 1-6 [In Korean]
[6] Heingtartner P, Mba D 2003 Determining power losses in the helical gear mesh; case study. Proceedings of the DETC’3 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference 2003 4 P965-70
[7] Johnson T T P, Kahraman A, Anderson N E, Chase D R 2008 An experimental investigation of spur gear efficiency J. Mech. Des. 15 6 062101-10
[8] Kuria J, Kihiu J 2011 Prediction of overall efficiency in multistage gear train Int’l. J. Mech., Aeros., Ind., Mech. Manufact. Eng. 5 2 50-56
[9] Zhao Y E, Zhang J W, Guan X Q 2009 Modeling and simulation of electronic differential system for an electric vehicle with two-motor-wheel drive. Proceedings of the EEE Intelligent Vehicles Symposium 2009 P1209-1214
[10] Lee P U, Chun S O, So J H, Nam Y S, Choi C H, Kim Y J 2016 Analysis of PTO gear pair using gear design program. Proceedings of the ASABE Annual International Meeting 2016 (Paper no. 162461087) Michigan: St. Joseph
[11] Im B G, Lee G H, Kim H R, Park Y J, Kim T W 2013 A summary of strength analysis of the main gearbox for helicopter. Proceedings of the Korean Society for Aeronautical and Space Sciences (spring conference) 2013 948-954
[12] Han H S, Lee J K 2004 Development of a web-based powertrain performance simulation system. *J. Korean Soc. Prec. Eng.* 21 2, 100-107 [In Korean]