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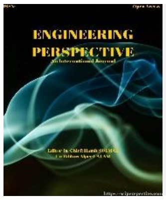

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Tractor Transmission Gear Ratio Optimization

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ABSTRACT

This study investigates the optimization of gear ratios for a 2-speed transmission, with a focus on enhancing performance and efficiency in diverse operating conditions. Specifically, the research addresses the need for two distinct gears: one optimized for field use and the other for road use. The goal is to improve the versatility and functionality of the transmission system, ensuring that it meets the demands of both rugged terrains and smooth highways. To achieve this, the study employed the company's lifetime test simulation to fine-tune the gear ratios, optimizing them for the most effective power delivery. A significant aspect of the research is the exploration of the transition from a traditional combustion engine tractor, which typically requires multiple gear ratios, to an electric motor setup with only two gears. This transition is made feasible by the electric motor's ability to deliver high torque across a broad RPM range, thereby enhancing performance while reducing the complexity of gear selection. The results of this optimization process show marked improvements in both the transmission's efficiency and its adaptability, making it highly suitable for a range of applications. This research offers valuable insights into the future of transmission design, particularly in the fields of agriculture and transportation, where there is a growing need for systems that are both efficient and versatile.

Keywords: Electrified Powertrain; Gear Ratio Optimization; Tractor Gearbox Design

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1. Introduction

The worldwide growing demand for food is pushing the agricultural field towards new innovative solutions to increase the efficiency and productivity of cultivations [1]. The automotive industry is currently experiencing a profound transformation towards sustainable mobility solutions, driven by the urgent need to curb carbon emissions and enhance energy efficiency. Just looking at the production of greenhouse gases (GHG), agricultural activities are responsible for almost 30% of the overall CO2 production, with a possible increase following the growing demand for more food to sustain the population growth [2,3]. The significant impact of emissions from agricultural machinery has necessitated the gradual implementation of increasingly stringent transnational regulations on pollutant emissions [4]. These directives restrict the permissible levels of pollutants in exhaust gases. To comply with these regulations, contemporary diesel engine manufacturers have adopted various methods, including different types of filters, catalytic systems, and recirculation strategies, to minimize pollutants in the exhaust stream [5,6]. In this evolving landscape, transmission technologies emerge as crucial elements in optimizing vehicle performance and fuel economy across diverse operational contexts.

This study explores into the process of optimizing gear ratios for tractor transmissions, specifically addressing the transition from conventional combustion engines to electric motors.

Dual-mode tractor transmissions, tailored with gears for both field and road applications, necessitate meticulous optimization to meet optimal performance criteria such as tractor wheel torque and vehicle speed. The primary objective is to strike a harmonious balance between power delivery and fuel consumption, ensuring seamless adaptation to varying terrains and driving scenarios. By leveraging advanced optimization techniques and utilizing the Jenkins lifetime test cycle, engineers can fine-tune gear ratios to match or surpass the performance of internal combustion engine tractors, all within a two-speed gearbox integrated into the electric tractor.

An essential aspect of this study is the shift from combustion engine tractors, which typically feature a multitude of gear ratios, to electric motors equipped with simplified two-gear transmissions. This transition is made feasible by the electric motor's distinctive capability to deliver high torques across a broad RPM range. The resulting benefits, reduced complexity in gear selection, and enabling the transmission to navigate rugged terrains and highway conditions effortlessly.

The outcomes of this research significantly contribute to the advancement of transmission design, particularly in agricultural and transportation applications. This study shows an alternative way of gear ratio optimization for tractor transmission technologies. The streamlined and efficient transmission solutions developed through this research not only enhance vehicle performance but also align with sustainability goals, ushering in a new era of innovative and eco-friendly mobility solutions for the agricultural and transportation sectors.

2. Project scope

Agricultural tractors, as typical representatives of off-road vehicles (ORVs), differ from road vehicles in that they have a short working season, long centralized operation time, and heavy working load. Therefore, the power performance and reliability of tractors are the key issues of concern. The power take-off driveline is an important part of a wheeled tractor, which provides rotating power for field machines [7]. As a starting input, internal combustion engine tractor Jenkins cycle is used which shows different tractor speed and corresponding wheel torques for a specific tire option for different gear selection with corresponding time intervals. Jenkins cycle is a unique accelerated bench test which simulates 10 years of lifetime of a tractor. Thus, electric tractor dual mode gearbox needs to deliver almost same or better performance. Here below, it may be seen an example of tractor gearbox bench testing in Figure 1.

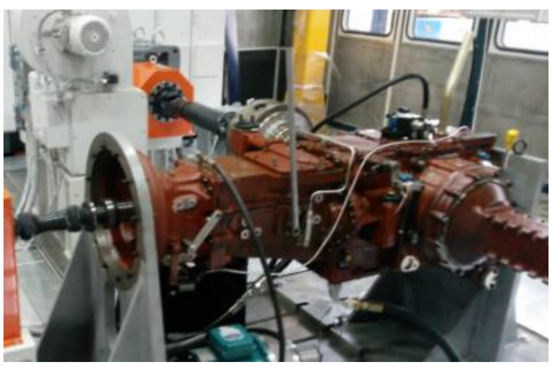

Figure 1. Sample gearbox bench testing

For electric tractor dual mode gearbox input from electric motor is crucial and there must be an engine torque/rpm efficiency map to optimize the gear ratios beside tire radius index. Here below in Table 1 summarized sample electric motor inputs.

Table 1. Sample electric motor technical specification.

Engine Max Power (kW)	50
Engine Speed @Max Power (rpm)	3500
Engine Max. Torque (Nm)	180
Engine Speed @Max Torque (rpm)	460
Tire Index Rear (mm)	750

2.1. Dual-mode gearbox ratio inputs

Modern conventional tractors feature intricate gearboxes to provide operators with the widest possible range of working speeds such as up to 24 shifts or more. This complexity is necessary because the rotational speed of the internal combustion engine (ICE) must be appropriately adjusted to meet the specific requirements of each field task, ICE needs to be run at specific range of rpm for its efficiency restrictions [8,9,10]. However, the advent of electric motors has introduced a paradigm shift, leveraging their ability to deliver high torque across a wide RPM range efficiently. This efficiency allows us to achieve the same performance objectives with just two gears, simplifying the transmission system significantly.

In vehicles such as tractors, where wheel torques are very high, a gearbox and axle gears are still required to increase the torques of the electric motor. Alternatively, solutions such as hub motors directly attached to the wheel can be considered. However, this approach has significant disadvantages, especially when working in design-constrained areas, as it tends to be large and very costly. Therefore, a simplified gearbox is highly advantageous due to its low cost and small design volume. Agricultural machinery must be robust enough to endure heavy workloads while remaining cost-effective [11].

The goal is to replicate or even surpass the wheel torque and tractor speeds achieved by internal combustion engine tractors using a dual-mode transmission with two gears—one for road use and the other for field applications. This transition not only enhances performance but also simplifies operation for farmers, eliminating the need for many manual control systems. The critical aspect lies in finding gear ratio optimizations that align with the motor torque RPM efficiency curve-which is shown as a sample in Figure 2, achieved through rigorous testing using the Jenkins cycle for internal combustion engines.

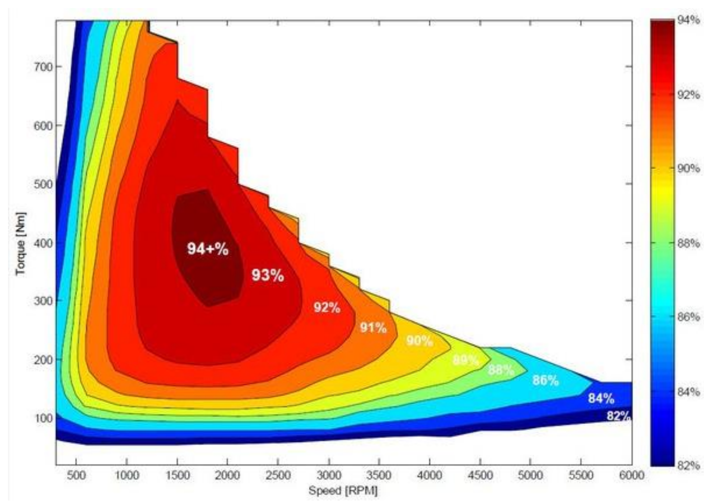

Figure. 2. Sample electric motor efficiency map

This study delves into the optimization of gear ratios for dual-mode tractor transmissions, with a focus on the seamless transition from complex combustion engine systems to streamlined electric motor-driven solutions. By leveraging the unique capabilities of electric motors, it is aimed to revolutionize tractor transmission design, making it more efficient, user-friendly, and aligned with modern agricultural practices.

2.2. Jenkins cycle

Tractor driveline should be provided worldwide in the fields of agriculture and construction to different end-users. Therefore, the conditions of application and the loads (e.g. due to soil characteristics) vary considerably from customer to customer [12].

Türk Traktör use a specific cycle to simulate tractor life in the field. The Jenkins cycle is an accelerated powertrain system bench test. Developed through company know-how, this cycle is applied to the powertrain system under test with a specified number of repetitions to ensure that the tractor meets the company's designated lifespan criteria. In this cycle, different gears are simulated with specific durations to mimic the farmer's tractor usage, and the tractor's lifespan is simulated in an accelerated manner with a certain correlation.

During this test, tractor speeds and corresponding wheel torques are applied to the powertrain system at specific time intervals, and it is expected to pass the test. This determines whether the powertrain system's performance under these conditions is suitable and whether tractor can perform the relevant tasks in field conditions without failure. If there is need for improvement, this test is used to identify it.

3. Gear ratio optimization approach

When determining the gear ratios for the 2-speed electric tractor, the approach was centered on achieving performance levels that matched or exceeded those of its equivalent internal combustion engine counterpart. Specifically, it is aimed to ensure that key performance criteria, such as wheel torque and tractor speeds, were either on par with or surpassing those of the internal combustion engine tractor.

For the first gear, designed for field mode and operating within the speed range of 0-16 kph, the objective was to provide wheel torques that were comparable to the internal combustion engine tractor's performance in similar conditions. This was essential to ensure optimal functionality during field operations, where high torque at lower speeds is often required. For the second gear optimized for road mode and operating at speeds below 40 kph. For those 2-gears, the goal was to maintain suitable wheel torques while covering or even exceeding the performance of an equivalent 100 hp internal combustion engine tractor. This required careful consideration of the gear ratios to ensure gearbox robustness, and not inputting much more power that exceeded up to design limit of the complete tractor driveline.

To achieve these objectives, several factors were considered. Firstly, it is implemented a torque limit to ensure that the electric motor's output did not exceed 100 hp. This limit was crucial in maintaining the desired performance levels while preventing excessive strain on the driveline. Additionally, a RPM limit of 7000 RPM was set to avoid overworking the electric motor and to ensure its longevity. This RPM limit was chosen based on the motor's optimal operating range and to prevent any potential overheating or mechanical stress.

The process of determining the optimal gear ratios involved translating the torque and RPM values obtained from the electric motor's performance graph into a comprehensive table. Electric motor matching data points for rpm and torque on the continuous performance curve are a crucial input for gear ratio optimization. This table served as input data for an optimization calculator, which was then used to calculate all tractor speeds and corresponding wheel torques through various gear cycles. Furthermore, to visualize and compare the performance of the 2-speed gearbox with its internal combustion engine counterpart, graphical representations were created. These visualizations provided valuable insights into how the electric motor's torque and RPM values translated into actual tractor speeds and wheel torques, allowing us to assess whether the selected gear ratios met the performance criteria.

By iteratively refining and testing different gear ratios within the optimization calculator, it may be determined the most suitable gear ratios that not only met but exceeded the performance expectations set by the equivalent internal combustion engine tractor. This meticulous approach ensured that the 2-speed electric tractor could deliver optimal performance across different operating conditions, making it a viable and efficient alternative in agricultural settings. Simple flow chart of the approach summed up as in Figure 3.

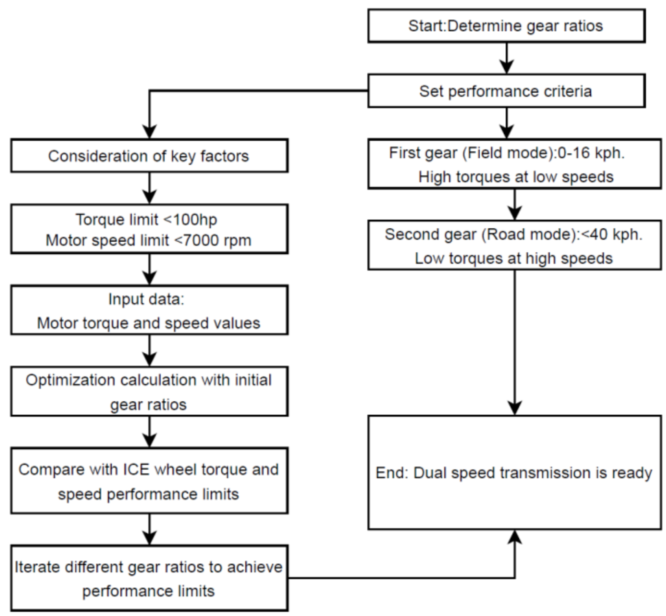

Figure. 3. Gear ratio optimization flow chart

4. Gear ratio optimization results

It is delved into the analysis of results derived from the Jenkins cycle data, using the performance metrics of a 100 hp internal combustion engine tractor as the baseline reference for wheel torque and tractor speed data. In Figure 4 it may be found the gear ratio optimization graphics. In the graphics the blue curve represents the wheel torque and tractor speeds observed for the internal combustion engine tractor at the specific gear under examination within the Jenkins cycle. This curve is meticulously constructed by connecting the data points of wheel torque and tractor speeds obtained during the comprehensive testing conducted in the Jenkins cycle.

On the other hand, the green lines depicted in the analysis signify the wheel torque and tractor speeds achieved utilizing the torque and RPM values derived from the electric motor of the tractor. These values are meticulously calculated based on the continuously attained gear ratio. As illustrated in the analysis, the optimized gear ratios culminate in the green lines being consistently positioned above or slightly surpassing the blue curve, signifying an equivalent or slightly enhanced performance compared to the internal combustion engine tractor.

It's imperative to note that each of the two gear ratios serves a distinct purpose within the operational spectrum of the tractor. The first gear, covering tractor speeds ranging from 0-16 kph, is tailored to match or exceed the wheel torques necessary for efficient field operations, aligning with the demands of agricultural tasks. On the other hand, the second gear, designed for speeds between 16-40 kph, is optimized to deliver suitable wheel torques for road usage, ensuring smooth and efficient performance during transportation activities.

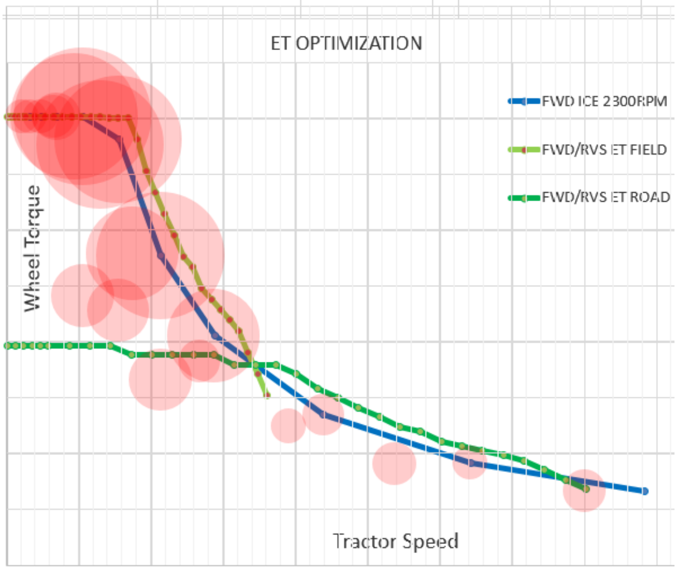

Figure. 4. Gear ratio optimization results

Furthermore, the red circles strategically marked in the analysis delineate the specific tractor speeds and corresponding wheel torques where farmers are anticipated to utilize the tractor more frequently. This data not only aids in understanding the operational preferences but also provides crucial insights into the range of operational conditions where this powertrain system will be extensively utilized.

Through this meticulous analysis and data interpretation, it can be derived the optimal gear ratios for the electric tractor, ensuring that its performance matches or exceeds that of its internal combustion engine counterpart across a diverse range of operational scenarios. This detailed analysis serves as the cornerstone for transitioning into the detailed design phase of the gearbox, where all gear pairs will be meticulously designed and calibrated based on the established performance benchmarks.

Indeed, the study yields another significant benefit in terms of analyzing the torque and RPM ranges where the tractor will operate more frequently throughout its entire lifespan, using both the Jenkins cycle data and the determined gear ratios. This analysis allows us to trace backward and visualize the operational patterns of the electric motor, providing valuable insights into the torque and RPM ranges that will be most encountered during its lifetime. In Figure 5 it may found the electric motor torque and rpm usage density.

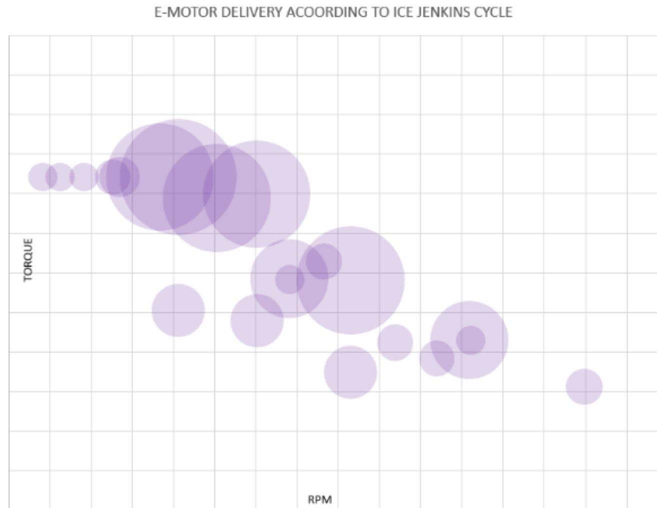

Figure. 5. Electric motor torque rpm usage density

This analysis not only aids in optimizing the performance of the tractor but also provides crucial information for motor manufacturers to assess whether their motors can withstand the operational demands anticipated during the tractor's lifespan. By aligning the motor's capabilities with the anticipated torque and RPM requirements, motor manufacturers can ensure the durability and reliability of their motors in real-world agricultural applications.

5. Conclusions

In conclusion, this study focused on optimizing gear ratios for a 2-speed electric tractor, with a particular emphasis on leveraging Jenkins cycle data and analyzing torque and RPM ranges. Through advanced optimization techniques and simulation-based approaches, it is successfully determined gear ratios that matched or exceeded the performance of equivalent internal combustion engine tractors across various operating conditions.

The transition from traditional combustion engines to electric motors presented a paradigm shift which is also force OEMs to find a new way to achieve emissions limits prescribed by the current regulations in force [13,14,15], allowing us to streamline the transmission system with just two gears while maintaining or enhancing performance criteria such as wheel torque and tractor speeds. This transition not only improved efficiency but also simplified operation and reduced complexity for farmers.

Furthermore, the analysis using Jenkins cycle data and backward-looking torque and RPM range analysis provided valuable insights into the tractor's operational dynamics throughout its lifespan. This information is crucial for optimizing tractor performance and ensuring the durability and reliability of electric motors in agricultural applications.

Overall, this research contributes to the advancement of transmission design for electric tractors, making them more efficient, versatile, and suitable for modern agricultural practices. It also underscores the importance of leveraging simulation data and advanced optimization techniques in optimizing gear ratios and enhancing overall tractor performance.

Acknowledgment

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Müjdat Ersarı: Conceptualization Formal analysis,Investigation, Methodology, Writing - original draft
Murat Gündoğdu: Conceptualization, Supervision.

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