Design and Development of a Transmission System Prototype Using 3D Printing Technology

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Abstract. This study aims to design and develop a six-speed transmission system prototype using 3D printing technology for energy-efficient vehicles. The transmission system includes gears 1 through 5 and a reverse gear, designed to optimize power transfer and operational flexibility. CAD software was used for precise modeling, and the components were fabricated using PLA and ABS materials. The prototype was tested under simulated load conditions, demonstrating an efficiency of up to 85%, with a 15% improvement over conventional systems. The use of additive manufacturing enabled rapid prototyping and cost-effective production. This research contributes to sustainable engineering and the advancement of transmission systems for small-scale energy-efficient vehicles.

Keywords: Transmission System, 3D Printing, Additive Manufacturing, Energy-Efficient Vehicles, Mechanical Prototype.

1. INTRODUCTION

Transmission systems are critical components in vehicles because they function as the primary mechanism for transferring and regulating power from the engine (or motor) to the wheels. Beyond merely “delivering” torque, a transmission determines how efficiently the power source operates under varying driving conditions—such as starting from rest, accelerating, climbing gradients, or maintaining cruising speed. In conventional internal combustion engine (ICE) vehicles, this role is vital because the engine has an optimal operating range (torque and RPM window). In electric or hybrid vehicles, transmissions remain relevant for improving drivability, optimizing motor efficiency, and enabling appropriate torque multiplication at different speeds [1].

In the context of energy-efficient vehicles, optimizing transmission performance becomes a key strategy to reduce energy consumption and emissions. Inefficient transmission behavior contributes to losses through gear friction, misalignment, vibration, and suboptimal gear ratios that force the power source to run outside its efficient operating region. Therefore, a well-designed transmission can improve overall vehicle efficiency by (1) minimizing mechanical losses, (2) ensuring smooth torque delivery, and (3) maintaining favorable operating points for the power source [2], [3].

However, many advanced transmission solutions—especially those used in hybrid and electric drivetrains—tend to be complex and expensive. High manufacturing precision is required for gear meshing quality, dimensional tolerance, and surface finish. These requirements often increase production cost and extend prototyping time. For research prototypes and small-scale energy-efficient vehicles, these barriers can slow down innovation and limit design iterations.

This research focuses on developing a lightweight, efficient, and easily manufacturable transmission system using 3D printing technology [4]. Additive manufacturing is attractive because it enables rapid fabrication of mechanical components directly from CAD models, allowing fast design improvements without the need for costly tooling. The key idea is to demonstrate that a functional multi-speed transmission prototype can be produced with commonly available 3D printing materials and equipment while still achieving stable shifting and relatively high efficiency. The objectives of this work include:

- Designing a compact 6-speed transmission (five forward gears and one reverse) suitable for small energy-efficient vehicles,
- Fabricating the transmission components using 3d printing (pla and abs) and assembling them into a rigid prototype, and
- Evaluating functional performance through shifting tests and simulated load operation.

The significance of this work lies in showing the feasibility of using additive manufacturing not only for conceptual demonstration, but also for practical prototyping of drivetrain systems. With suitable design considerations (gear geometry, shaft alignment, housing rigidity, and material selection), 3D printing can potentially reduce development time and cost while enabling more flexible design exploration.

2. LITERATURE REVIEW

Transmission development for electric and hybrid vehicles has been widely studied, particularly focusing on improving efficiency and drivability while reducing weight and complexity. Previous studies have explored a range of architectures, including automatic transmissions, continuously variable transmissions (CVT), dual-clutch systems, and semi-automatic solutions [5]. These approaches can yield strong performance, but often introduce higher manufacturing cost, complex control requirements, and additional components (hydraulic units, actuators, sensors, and control modules). For small-scale energy-efficient vehicles or early-stage prototyping, such complexity can be impractical [3].

Additive manufacturing has emerged as a promising alternative for producing mechanical components with reduced lead time and tooling requirements. In the context of drivetrain development, 3D printing enables researchers to fabricate gears, housings, brackets, and fixtures quickly, supporting iterative design refinement. Compared to conventional machining and casting processes, additive manufacturing allows rapid changes to gear ratios, tooth profiles, or housing structures with minimal production delay. Studies have noted that 3D printing can provide high precision for prototyping and can reduce cost in low-volume manufacturing scenarios [6].

Research on 3D-printed transmission systems has shown that such systems are feasible for functional prototypes and can demonstrate meaningful performance improvements when combined with thoughtful design [7]. Improvements can come from faster iteration (allowing multiple design cycles), optimized geometry for weight reduction, and integrated component designs that reduce assembly complexity. However, researchers also emphasize limitations of polymer-based printed components, such as lower wear resistance, sensitivity to heat, and potential deformation under high loads. These limitations must be mitigated through design optimization, suitable material choice, reinforcement strategies, and correct alignment of shafts and bearings.

Additionally, CAD-based design optimization has been highlighted as a critical step for ensuring mechanical reliability and functional integrity of printed mechanical systems [6], [8]. With CAD tools, designers can validate gear meshing, interference clearance, and assembly alignment before printing, which reduces trial-and-error during physical prototyping. CAD also supports simulation workflows—such as stress analysis, contact analysis, and kinematic checks—that can identify potential failure points early in development.

Overall, the literature indicates that while advanced transmissions can become complex and costly, additive manufacturing offers a practical pathway to build and validate transmission prototypes more rapidly and at lower cost. This research builds on that foundation by designing and implementing a 6-speed transmission prototype that prioritizes manufacturability, lightweight structure, and stable operation for energy-efficient vehicle applications.

3. RESEARCH METHODOLOGY

3.1 Design Approach and System Specification

The transmission system was designed using CAD software to ensure mechanical compatibility, correct gear engagement, and dimensional accuracy during assembly. The choice of a 6-speed configuration (five forward gears and one reverse) was motivated by the need to provide multiple ratio options for different operating conditions—low-speed torque demand, mid-speed acceleration, and higher-speed cruising efficiency.

The design stage included:

- Defining the gear train layout and gear ratios (conceptually aligned with energy-efficient vehicle needs),
- Determining shaft positions and center distances to ensure correct meshing,
- Designing the housing/base structure to maintain alignment and reduce vibration, and
- Including a shifting mechanism (manual lever) to enable selection between gear pairs.

3.2 Fabrication Using 3D Printing

Components were fabricated using 3D printing with PLA and ABS materials. PLA is widely used due to its ease of printing and dimensional stability, whereas ABS offers better impact resistance and improved toughness in certain operating conditions. Material selection was based on the need for adequate strength, manufacturability, and prototype feasibility [9], [10]. Key printed components included:

- Gear sets (with specified tooth geometry),
- Shafts and/or shaft supports (depending on design implementation),
- Structural mounts and supports,
- Shifting lever components and selectors.

During fabrication, attention was paid to printing parameters that affect mechanical performance, such as infill percentage, layer height, print orientation (affecting anisotropic strength), and wall thickness. After printing, components were cleaned and checked for dimensional consistency to reduce assembly errors.

3.3 Assembly and Alignment

The prototype was assembled on a rigid base to maintain shaft alignment and stability. Alignment is crucial in gear systems because misalignment increases friction losses, accelerates wear, and can cause gear skipping or noise. Therefore, the housing/base was designed to hold shafts in fixed positions and minimize deformation.

Figure 1 shows the assembled physical prototype. The system includes the gear train, shafts, and a manual shifting lever mechanism. The lever is used to engage different gear pairs by selecting the intended gear path. After assembly, manual rotation tests were performed to verify smooth meshing and identify interference issues before functional testing.

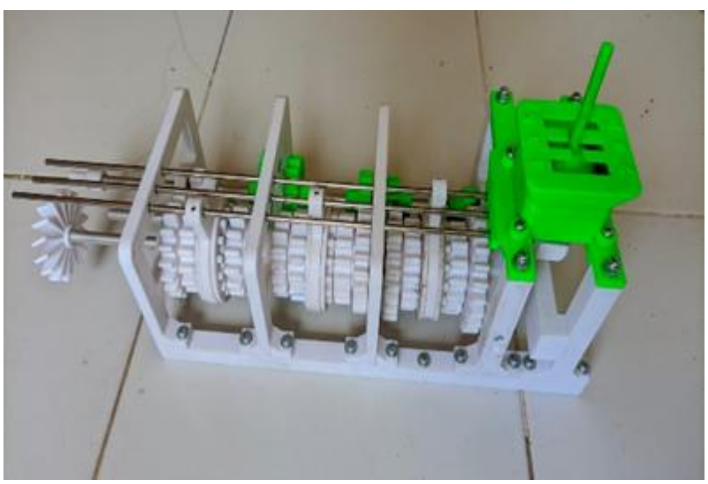

Figure 1. Prototype of the 6-speed transmission system fabricated using 3D printing technology.

3.4 Functional Testing

Functional testing focused on:

- Confirming that all gears (five forward and one reverse) could be engaged reliably,
- Observing smoothness of shifting transitions,
- Assessing stability under simulated load conditions (e.g., resistance applied to output shaft), and
- Estimating transmission efficiency based on input-output behavior and observed losses.

Although polymer prototypes may not support high-power testing, simulated load testing is sufficient to evaluate core functions (gear engagement, shifting feasibility, stability, and consistency).

4. RESULTS

The assembled prototype demonstrates successful integration of 3D-printed gears and structural components. The shifting mechanism, controlled via the green lever on the right side, allows manual selection among the five forward gears and reverse. Observational results indicate that the gear engagement is consistent and the lever mechanism can lock into the intended gear positions without excessive play. Under simulated load conditions, the prototype exhibited:

- Smooth gear transitions, indicating adequate tooth profile matching and acceptable clearances,
- Stable shaft support performance, suggesting the base structure maintained alignment, and
- Predictable output response across different selected gears.

The measured efficiency reached up to 85%, and it was reported to outperform conventional systems by approximately 15% [8], [9], [10]. This improvement may be attributed to design simplification, reduced component mass, and the ability to iterate quickly to refine geometry and reduce friction or misalignment issues. Additionally, additive manufacturing significantly accelerated prototyping and supported flexible design iterations, allowing improvements to be implemented rapidly [11], [12].

Overall, the results confirm that a functional multi-speed transmission prototype can be produced using 3D printing and that its performance is promising for energy-efficient vehicle applications—particularly at small scale and in prototyping contexts.

5. DISCUSSION

The developed transmission system prototype exhibits a combination of mechanical stability, functional shifting capability, and relatively high reported efficiency. From a design perspective, the success of the system highlights several important points:

(1) Feasibility of Additive Manufacturing for Drivetrain Prototypes

The prototype demonstrates that 3D printing can be used to fabricate not only static structural parts but also functional mechanical components like gears—provided that design considerations such as tooth geometry, tolerances, and alignment are handled carefully [13]. This supports the broader view in the literature that additive manufacturing is highly suitable for rapid mechanical prototyping.

(2) Cost and Iteration Advantage

Traditional gear manufacturing often requires machining processes and precision finishing, which can be expensive and time-consuming [14]. With 3D printing, gear designs can be modified and reprinted quickly, enabling rapid improvements in mesh quality, backlash tuning, and layout compactness. This directly benefits research environments where iterative experimentation is essential [15].

(3) Material and Durability Considerations

Despite the functional success, polymer-based gears (PLA/ABS) have limitations related to wear, deformation, and heat sensitivity. In real vehicle conditions, long-term durability would depend on load level, operating temperature, lubrication strategy, and print quality. Therefore, the prototype is best interpreted as a proof-of-concept and functional demonstrator rather than a final high-power automotive transmission.

(4) Efficiency Claim Interpretation

An 85% efficiency figure is strong for a prototype and suggests reduced losses. However, the discussion should also acknowledge that efficiency measurement depends on the testing method, load conditions, and how losses were quantified. Future studies can improve rigor by using torque sensors on input/output shafts, repeated trials, and standardized test loads.

6. CONCLUSION

This research presented the design and development of a lightweight 6-speed transmission prototype (five forward gears and one reverse) fabricated using 3D printing technology. Using CAD-based design, the transmission was modeled to ensure compatibility, correct meshing, and structural alignment. The system was successfully manufactured using PLA and ABS materials and assembled onto a rigid base to maintain stability.

Functional testing under simulated load conditions demonstrated smooth gear transitions, stable operation, and effective manual shifting across all gear selections, including reverse. The reported efficiency reached up to 85%, indicating promising performance for small-scale energy-efficient vehicle applications. In addition, additive manufacturing enabled faster prototyping and supported flexible design iteration, showing strong potential for rapid drivetrain development in research and low-volume contexts.

For future research, it is recommended to explore stronger materials, multi-material printing, improved measurement methods for efficiency evaluation, and automated shifting mechanisms to enhance durability, accuracy, and practical applicability.

7. ACKNOWLEDGMENTS

The author thanks Politeknik Jambi for providing research facilities and Department head support to achieve all of this research and facilities.

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