*Int. J. Adv. Res. Sci. Technol. Volume 15, Issue 5, 2026, pp.1974-1985.*

IJARST

International Journal of Advanced Research in Science and Technology

https://doi.org/10.62226/ijarst20262693

ISSN 2319 – 1783 (Print)

ISSN 2320 – 1126 (Online)

# Design and Development of a Custom Gearbox for an All-Terrain Vehicle (ATV)

***Aditya Bhardwaj*[1], Farhad Danish[2], Naeem Choudhary[3] and Habib Ur Rehman[4]***

*[1,2,3]Department of Mechanical and Automation Engineering, G. B. Pant Government Engineering College, New Delhi, India*

*[4]Department of Mechanical Engineering, IISc Bengaluru, India*

*addy2001bhardwaj@gmail.com*

**ARTICLE INFO**

***Article history:***

Received 20 May 2026
Accepted 25 May 2026
Available online 29 May 2026

***Keywords:***

*All-Terrain Vehicle, Custom Gearbox, Power Transmission, CAD Simulation, Mechanical Design.*

***Indexed in:***

doi Crossref

INDEX COPERNICUS INTERNATIONAL

Google scholar

*and in major libraries*

**ABSTRACT**

Transmission system contributes decisively to the performance, durability and off-road capacity of an All-Terrain Vehicle (ATV). This paper introduces the design and construction of a lightweight, small, and high power geared two stage gearbox specifically designed to be used in ATV. Traditional OEM gearboxes are primarily oversized, weighty, and have fixed gear ratios which do not match dynamic operation of the ATVs. To overcome these shortcomings, it designs an in-house gearbox that has optimized gear ratios, lower mass and higher packaging efficiency. The suggested gearbox is combined with Polaris P90 Continuously Variable Transmission (CVT) and is propelled with the help of a Briggs and Stratton 305cc engine. The selection of gears ratio is conducted on the basis of the requirements on wheel speed and the tractive forces and the rolling and the grade resistances are taken into consideration in worst-case conditions of the terrain. Two stage spur gear design is used to obtain the total reduction ratio of 10:1 to ensure high efficiency and simplicity in manufacturing. AGMA standards are applied to determine bending and contact stresses by doing gear design and strength testing. The shaft is also performed based on ASME and safe operation under the shock loading conditions. The casing of the gearbox is engineered out of Aluminum 6061-T6 that helps reduce the weight without compromising the structural integrity. Finite element analysis is performed to ensure that the analytical findings are verified, that stresses and deformations are not beyond acceptable levels.



## 1. Introduction:

All-Terrain Vehicles (ATVs) are special-purpose off-road vehicles aimed to be used in very challenging environment conditions like mud, gravel, sand, steep slopes, and average surfaces. In contrast to typical on-road vehicles, ATVs must provide good torque at lower speeds, have good traction, and be able to maintain constant shock loads whilst being reliable and safe to the driver. The demands result in the drivetrain and especially the gearbox being one of the most sensitive subsystems that impact the overall performance of the vehicle.

The gearbox is an engine driven mechanical multiplier of torque, which transforms engine power into valuable tractive effort at the wheels. It directly influences the important parameters of the vehicle performance including acceleration, gradeability, maximum speed, the efficiency of the driveline, and the use of fuel. In off-road conditions, where the action of the rolling resistance and gradient forces is considerably greater than those in paved roads, the gearbox should be durable, relatively small, and the transmitter of high torque.[1]

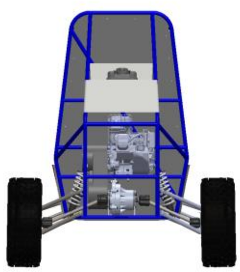

**Fig.1.** Rear view of ATV designed for SAE Baja

[1] ASM International. (2018). *ASM handbook, volume 1: Properties and selection—Irons, steels, and high-performance alloys*. ASM International.

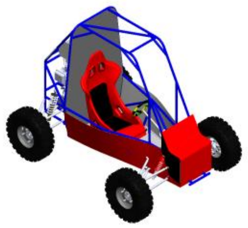

**Fig.2.** Isometric view of ATV designed for SAE Baja

OEM gearboxes sold commercially are mostly geared towards motorcycles or utility vehicles of a general purpose. Consequently, they tend to be excessively robust, excessive in weight and have fixed gear ratios unsuited to the precise operational envelope of ATVs. Their heavy packaging and complicated internal systems make them difficult to integrate into the small chassis size of a BAJA SAE-style ATV, as well.

In these limitations, this paper concentrates on development and design of a custom gear box that is specific to the ATVs usage. The design focuses on the best gear ratio choice, minimization of weight, high efficiency, simple production and adhering to the requirements of BAJA SAE designed and safety standards. The proposed gearbox is designed in a systematic engineering process that comprises of analysis of vehicle dynamics, analytical design, material selection and numerical verification.[2]

**Table.1.** Typical Performance Requirements of an ATV Transmission System

| **Parameter** | **Requirement** |
|---|---|
| Operating terrain | Off-road (mud, sand, gravel, slopes) |
| Required torque | High at low vehicle speeds |
| Gradeability | ≥ 35° |
| Gearbox efficiency | ≥ 90% |
| Weight constraint | Minimal for improved acceleration |
| Durability | Endurance event compliant |
| Packaging | Compact, chassis-compatible |

**Table.2.** Limitations of OEM Gearboxes for ATV Applications

| **Aspect** | **OEM Gearbox Limitation** |
|---|---|
| Weight | Excessively heavy |
| Gear ratios | Not optimized for off-road use |
| Packaging | Bulky and difficult to integrate |
| Maintenance | Complex internal mechanisms |
| Customization | Limited or unavailable |

[2] ASM International. (2018). *ASM handbook, volume 2: Properties and selection—Nonferrous alloys and special-purpose materials*. ASM International.

It is then possible to accurately fine-tune the performance characteristics, enhance the efficiency of the driveline, and increase the competitiveness of the vehicle when a custom gearbox is developed. In this study, an elaborate design plan of such a gearbox is provided and this is a key contribution to effective and reliable ATV drivetrain.

## 2. Need for a Custom Gearbox

The All-Terrain Vehicle drivetrain should be designed in a way that it can withstand the extreme off-road environmental factors and provide a reliable and efficient channel of power delivery. Contrary to the regular cars, the ATVs regularly face a high rolling resistance, impact loads, and steep slopes. The conditions require a lightweight transmission system, which is small in size and able to produce high torque with low speeds. Nevertheless, commercially available OEM gearboxes are not usually up to these special needs and a bespoke gearbox design is necessary.[3]

### 2.1 OEM Gearboxes limitations

The main application of OEM gearboxes is on the motorcycles or general-purpose utility vehicles that use relatively similar terrains. This also leads to overdesigning of such gearboxes when it comes to strength and therefore, adding needless weight to the car. Mass is negatively impacting acceleration, fuel efficiency, and vehicle maneuverability in general, which are important performance parameters in competitive ATV use.

Moreover, OEM gearboxes usually have fixed gear ratios that are not optimized to different torque and speed requirements realized when operating in the off-road. Such gears can either bring down top speeds or create a loss of torque during sharp climbs which are not safe. Also, the large size and complicated internal design of OEM gearboxes provide packaging space limitations in the small ATV chassis and present a greater maintenance challenge in the endurance events.

**Table.3.** Comparison of OEM Gearboxes and ATV-Specific Requirements

| **Parameter** | **OEM Gearbox** | **ATV Requirement** |
|---|---|---|
| Weight | High | Low |
| Gear ratio flexibility | Fixed | Optimized / Custom |
| Packaging | Bulky | Compact |
| Maintenance | Complex | Simple |
| Off-road suitability | Limited | High |

### 2.2 Performance Requirements

An ATV-specific gearbox allows extensive fine-tuning of gear ratios to achieve ATV-specific performance goals. It must have high torque multiplication to have high gradeability on steep and irregular terrain. Simultaneously, the gearbox should restrict the maximum vehicle speed to provide the safety of drivers and compliance with regulations. Optimized gear ratios are also beneficial to

[3] BAJA SAE India. (2023). *BAJA SAE India rulebook*. Society of Automotive Engineers India.

acceleration and drive-line economy, and they minimize the losses of power throughout the transmission.[4]

Also, a special gearbox enables the designer to choose appropriate materials, production process, and casing geometry, which contribute to a trade-off between strength, mass, and longevity. Such customization is essential to fulfilling the design requirements of BAJA SAE, and providing dependable operations during endurance and dynamic operations.

**Table 4:** Key Performance Targets for the Custom ATV Gearbox

| Performance Parameter | Design Target |
|---|---|
| Gradeability | ≥ 35° |
| Gearbox efficiency | ≥ 95% |
| Weight reduction | ≥ 20% vs OEM |
| Maximum vehicle speed | Controlled (≤ 60 km/h) |
| Durability | Endurance event compliant |

The shortcomings of OEM gearboxes and the high-performance requirements are obvious reasons why the creation of custom-designed gearbox that would specifically fit the requirements of the ATV gearboxes was produced.[5]

### 3. Design Objectives

The main objective of the study is to create and develop an individual gearbox that meets the high functional, structural, and regulatory standards of the All-Terrain Vehicle that has to work under severe off-road conditions. The gearbox is supposed to provide high torque at low speed and be compact, lightweight and reliable. To this end, a set of well-defined design objectives are put in place; these objectives form the basis in the whole development cycle that starts by selecting a concept to be developed through to validation.

The initial goal is to come up with a small and lightweight gear box which can be easily fitted in the small area of packaging that is found in an ATV chassis. The weight minimization is paramount since it directly affects the acceleration of the vehicles, fuel consumption, and maneuverability. Simultaneously, the gearbox should be strong enough in terms of its structure to endure shock loads, vibrations, and constant changes in torques that are characteristic of off-road conditions.

The second is to calculate the best gear ratios depending on the dynamics of the vehicles and the set performance targets including the top speed, acceleration and gradeability. Gear ratios are chosen to make sure that they have good multiplication of top speed in steep grades and at the same time do not have too high a top speed, thus providing better drivability and handling safety. The achievability of this goal will highly consider the engine characteristics, CVT behaviour, tyre dimensions, and the resistance forces of the terrain.[6]

The third task is to conduct analytical stress analysis of gears, shafts, and bearings in details in accordance with the accepted mechanical design criteria, including AGMA and ASME. These tests are performed to assure that every element performs within permissible stress levels of worst-case loading conditions such as shock and endurance loads.

The last aim is to prove the analytical design by the method of the finite element analysis (FEA). Numerical stress analysis is performed to determine the distribution of stress, deformation, and integrity of the gearing box components hence proving reliability and safety of the proposed design.[7]

**Table.5.** Summary of Design Objectives and Evaluation Criteria

| Objective | Description | Evaluation Method |
|---|---|---|
| Compact and lightweight design | Minimize mass and volume | CAD modeling, mass estimation |
| Optimal gear ratio selection | Achieve torque-speed balance | Vehicle dynamics calculations |
| Structural safety | Ensure stress within limits | AGMA & ASME analytical methods |
| Design validation | Verify stresses and deformation | Finite Element Analysis (FEA) |

All these aims are to make the developed gearbox meet performance requirements, durability requirements and regulatory requirements to be used in the competitive use of ATVs.[8]

### 4. Design Inputs and Methodology

The ATV gearbox design has been developed using a structured approach to mechanism, which combines the requirements of the vehicle performance, the nature of the powertrain, the mathematical calculations as well as numerical modelling. The correct definition of the design inputs will be required to make sure that the gearbox is designed to perform in accordance with the functional requirements without disturbing the reliability in off-road operating conditions.

#### 4.1 Vehicle and Powertrain Specifications

It has a gearbox that is intended to be used with a Briggs and Stratton 305 cc engine and a Polaris P90 Continuously Variable Transmission (CVT). These are highly adopted components in the ATVs that are compliant with the BAJA SAE standards because of their stability and performance. The engine provides maximum power output of 10 HP and peak torque of 28 Nm at 3800 RPM, and this is the maximum range of torque input to the gearbox.

[4] Bhandari, V. B. (2010). *Design of machine elements* (3rd ed.). Tata McGraw-Hill.

[5] Briggs & Stratton. (2022). *305 cc engine technical specifications*. Briggs & Stratton Corporation.

[6] Budynas, R. G. (2013). *Advanced strength and applied stress analysis* (2nd ed.). McGraw-Hill Education.

[7] Budynas, R. G., & Nisbett, J. K. (2015). *Shigley's mechanical engineering design* (10th ed.). McGraw-Hill Education.

[8] Cook, R. D. (2007). *Concepts and applications of finite element analysis* (4th ed.). John Wiley & Sons.

The parameters that are taken into account in the vehicle level like the total mass, tyre radius and the highest vehicle speed are used to calculate the necessary multiplication of the torque and the reduction of the gears. The worst-case operating conditions are taken to be a fully loaded vehicle mass of 250 kg including the driver. The top speed of the vehicles is not more than 56 km/h so that the operation of the vehicles is safe and in accordance with the rules of competition.

**Table .6.** Vehicle and Powertrain Design Inputs

| Parameter | Value |
|---|---|
| Engine type | Briggs & Stratton |
| Engine displacement | 305 cc |
| Maximum power | 10 HP |
| Maximum torque | 28 Nm @ 3800 RPM |
| Vehicle mass (with driver) | 250 kg |
| CVT model | Polaris P90 |
| CVT ratio range | 3.9:1 (max) – 0.75:1 (min) |
| Tyre radius | 0.2794 m |
| Maximum vehicle speed | 56 km/h |

### 4.2 Gearbox Architecture

Two stage spur gear reduction gearbox is chosen to get the desired overall reduction ratio and yet compactness and high mechanical efficiency. Spur gears are also preferred because they are based on simple geometry, easy to manufacture, have large load carrying capacity, and no axial thrust making bearing and casing design easy.[9]

The overall ratio of the gearbox reduction is chosen at 10:1 to provide enough torque when operating in extreme terrain conditions. The reduction is done in two identical steps each with a reduction ratio of 3.16:1. Dividing the overall reduction between two phases allows gear size to be smaller, decreases the level of stress concentration, and enhances the distribution of loads among parts.

**Table .7.** Gearbox Architecture Parameters

| Parameter | Specification |
|---|---|
| Gear type | Spur gears |
| Number of stages | Two |
| Reduction ratio per stage | 3.16:1 |
| Total gearbox reduction ratio | 10:1 |
| Axial thrust | Negligible |
| Gearbox efficiency | High (>95%) |

The chosen gearbox design offers the best combination of strength, efficiency, manufacturability, and packaging and therefore is appropriate to off-road ATV use.

## 5. Calculations of Gear Ratio and Load

One of the most important steps in providing adequate tractive force to the ATV with extreme off-road conditions that does not exceed safe and controlled maximum speed is the choice of the right gearbox reduction ratio. The gear ratio is calculated depending on the needs of the vehicle speed, the dynamics of the wheels, the force of resistance, and the capacities of the powertrain.

### 5.1 Wheel Speed and total transmission ratio

The upper limit of the vehicle velocity is 56km/h or 15.56ms to be on the safe side and to comply with regulations. The angular velocity of the wheel is given as:

$$\omega = \frac{\mathrm{V}}{\mathrm{r}} = \frac{15.56}{0.2794} = 55.7\ \mathrm{rad/s}$$

The formula used, $\omega = \frac{V}{r}$, calculates the angular velocity ($\omega$) of an object moving in a circular path.

The corresponding speed of rotation of the wheel is:

$$\mathrm{N_w} = \frac{\omega \times 60}{2\pi} = 532\ \mathrm{RPM}$$

This formula calculates the rotational speed in revolutions per minute (RPM) from the angular velocity in radians per second ($\omega$).

#### 5.1.1. Calculation:

Given that already have:

$$\omega = 55.7\ \mathrm{rad/s}$$

Now, applying the formula:

$$N_w = \frac{55.7 \times 60}{2\pi}$$

Let's break it down:

$$N_w = \frac{3342}{6.2832} = 532\ \mathrm{RPM}$$

The total transmission ratio needed is: at the peak torque speed of an engine, which in this case is 3800 RPM.

$$\mathrm{i_{overall}} = \frac{\mathrm{N_{engine}}}{\mathrm{N_{wheel}}} = \frac{3800}{532} \approx 7.14$$

Here, it involves determination of the general transmission ratio required between engine speed and wheel speed at the maximum engine torque speed.

Gearbox reduction ratio required in consideration of the minimum CVT ratio of 0.75:1:

$$\mathrm{i_{gearbox}} = \frac{\mathrm{i_{overall}}}{\mathrm{i_{CVT(min)}}} = \frac{7.14}{0.75} \approx 10:1$$

In this calculation, determining the gearbox transmission ratio required when using a Continuously Variable Transmission (CVT) to achieve the overall desired transmission ratio.

### 5.2 Computations of a Tractive Force and Resistance

The maximum calculation of resistance forces is done at the worst-case gradient of 35 degrees in order to achieve consistent performance on steep terrains. The rolling resistance coefficient of 0.125 was used to determine rolling resistance:

#### 5.2.1. Rolling Resistance Force ($F_{rr}$):

Rolling resistance is the force, which opposes the rolling of a wheel or a tire over a surface. It is dependent on the weight of the vehicle and the rolling resistance coefficient.

The formula for rolling resistance is:

$$F_{rr} = C_{rr} \times m \times g$$

Where:

$C_{rr}$= Rolling resistance coefficient (given as 0.125)

[9] Dudley, D. W. (2012). *Handbook of practical gear design*. CRC Press.

$m$= Mass of the vehicle (given as 250 kg)

$g$= Acceleration due to gravity (9.81 m/s²)

### 5.2.2. Calculation:

$$F_{rr} = C_{rr} \times m \times g = 0.125 \times 250 \times 9.81 = 307 \text{ N}$$

This means the rolling resistance force is 307 N. It resists the vehicle's motion along the surface.

### 5.2.3. Grade Resistance Force ($F_{grade}$):

Grade resistance is the resistance force against motion at the time when the vehicle is on inclined plane (slope). It is determined by the weight of the vehicle, the force of gravity and the slope of the slope.

The formula for grade resistance is:

$$F_{grade} = m \times g \times \sin(\theta)$$

Where:

$m$= Mass of the vehicle (250 kg)

$g$= Acceleration due to gravity (9.81 m/s²)

$\theta$= Angle of the slope (given as 35°)

### 5.2.4. Calculation:

The Grade resistance is computed:

$$F_{grade} = m \times g \times \sin(35°) = 250 \times 9.81 \times \sin(35°) \approx 1406 \text{ N}$$

$$F_{grade} = 250 \times 9.81 \times \sin(35°) \approx 1406 \text{ N}$$

This implies that the grade resistance is 1406 N which is the extra force needed to overcome the slope inclination.

### 5.2.5. Total Tractive Force ($F_{total}$):

The total tractive force needed to overcome both rolling and grade resistance is the sum of the two forces.

$$F_{total} = F_{rr} + F_{grade}$$

### 5.2.6. Calculation:

The overall tractive force which is needed is thus:

$$F_{total} = F_{rr} + F_{grade} = 1713 \text{ N}$$

So, the overall tractive force required to move the vehicle on the slope is 1713 N.

The force that opposes the movement of the vehicle on a flat surface is the rolling resistance 307N.

1406 N This force is the extra force required to overcome the slope of the slope.

The sum of all the tractive forces is the force that the engine of the vehicle will need to supply to propel it up the slope taking into account the resistance of the slope as well as the rolling resistance.

### 5.3 Wheel Torque Requirement

Here, the calculation is of the torque needed at the wheel to overcome the sum total of the tractive force in order to move the vehicle. The formula used is:

$$T_w = F_{total} \times r$$

Where:

$T_w$ is the torque at the wheel, measured in Nm (Newton-meter)

$F_{total}$ is the total tractive force (calculated earlier as 1713 N).

$r$ is the radius of the wheel, given as 0.2794 meters.

### 5.3.1. Calculation:

The torque needed to move the wheel to counter the summation force is:

$$T_w = F_{total} \times r = 1713 \times 0.2794 \approx 478.5 \text{ Nm}$$

**Table.8.** Tractive Force and Torque Calculations

| **Parameter** | **Value** |
|---|---|
| Rolling resistance force | 307 N |
| Grade resistance force (35°) | 1406 N |
| Total tractive force | 1713 N |
| Required wheel torque | 478.5 Nm |

### 5.4 Design and available Torque

In this calculation, you are determining the output torque of the Continuously Variable Transmission (CVT) system. The formula used is:

$$T_{CVT,\,out} = T_{input} \times i_{CVT} \times \eta_{CVT}$$

Where:

$T_{CVT,\,out}$is the output torque from the CVT, measured in Nm (Newton-meters).

$T_{input}$is the input torque to the CVT, which is given as 28 Nm.

$i_{CVT}$is the CVT ratio (gear ratio), which is 3.9.

$\eta_{CVT}$is the efficiency of the CVT, which is given as 0.85 (85%).

The peak engine torque, CVT ratio and efficiency are used to determine the torque at the CVT output:

$$T_{CVT,out} = 28 \times 3.9 \times 0.85 \approx 92.8 \text{ Nm}$$

Including service factor,

$$T_{design} = 92.8 \times 1.5 = 139 \text{ Nm}$$

A service factor of 1.5 is used to cover shock loading and off-road effects giving a design torque of about 139 Nm on the gearbox input. The chosen ratio of the gearbox of 10:1 gives enough multiplication of the torque to cover the needs of the wheels and still be safe and reliable in the extreme conditions.[10]

## 6. Gear Design and AGMA Stress Analysis

The design of a gear train is the main factor that will determine the structural integrity and durability of the gearbox. EN24 alloy steel is chosen in this work as the material of gears because of its high tensile quality, extremely good fatigue resistance as well as its capability to undergo heat treatment. EN24 has these properties, which

[10] Hamrock, B. J., Schmid, S. R., & Jacobson, B. O. (2004). *Fundamentals of machine elements* (2nd ed.). McGraw-Hill.

render it good in off-road operations with shock loads and cyclic loads.

### 6.1 Gear Material Selection

EN24 (nickelchromolybdenum alloy steel) offers a good balance between strength and toughness, so gears can take both results of bend and surface contact stresses. The pinions are hardened on the surface to enhance wear capability and the gears are normalized to enhance toughness.

Torque on stage 1 is $T_1$,

$$T_1 = 139Nm$$

Torque on stage 2 is $T_2$,

$$T_2 = T_1 \times 3.16 = 139 \times 3.16 = 439\,\text{Nm}$$

**Table.9.** Mechanical Properties of EN24 Steel

| Property | Value |
|---|---|
| Ultimate tensile strength | 850–1000 MPa |
| Yield strength | 680 MPa |
| Allowable bending stress | 300 MPa |
| Allowable contact stress | 1100 MPa |
| Young's modulus | 210 GPa |

### 6.2 Gear Geometry and Constitution

The two-stage spur gear system is used to obtain the desired overall ratio reduction and at the same time, keep the size small and efficient. The two stages apply pressure angle of 20 degrees to facilitate transfer of power and sufficient strength of teeth.[11]

**Table.10.** Gear Geometry Parameters

| Parameter | Stage 1 | Stage 2 |
|---|---|---|
| Pinion teeth | 19 | 19 |
| Gear teeth | 60 | 60 |
| Module (mm) | 2 | 3 |
| Face width (mm) | 20 | 30 |
| Pitch diameter of pinion (mm) | 38 | 57 |
| Pitch diameter of gear (mm) | 120 | 180 |
| Reduction ratio | 3.16:1 | 3.16:1 |

### 6.3 AGMA Stress Analysis Bending

The gear tooth bending force is measured based on AGMA bending stress equation:

$$\sigma_b = \frac{F_t K_o K_v K_s}{bmY}$$

Where:

- $\sigma_b$ = bending stress
- $F_t$ = tangential load
- $K_o$ = overload factor
- $K_v$ = velocity factor
- $K_s$ = size factor
- b = face width
- m = module
- Y = Lewis form factor

The bending stresses calculated are about 162 MPa on the first stage and 198 MPa on stage two which is greatly lower than the allowable bending stress of EN24 material.

### 6.4 AGMA Contact Stress Analysis

The AGMA contact stress equation is used to assess contact stress:

$$\sigma_c = Z_e \sqrt{\frac{F_t K_o K_v}{b d_p}}$$

Where:

$$\sigma_c = contact\ (Hertz)\ stress$$

$$Z_e = \text{elastic coefficient}$$

- $F_t$ = tangential load
- $K_o$ = overload factor
- $K_v$ = velocity factor
- b = face width
- $d_p$ = pitch diameter

The obtained contact stresses of both stages are significantly lower than the allowable contact stress of 1100 Mpa, which will guarantee reasonable durability of the surfaces and pitting failure resistance.[12]

Stage-1:

$$F_t = \frac{2T}{d_p} = \frac{(2 \times 139000)}{38} = 7316\,\text{N}$$

$$\sigma_{b1} \approx 162\text{MPa} < 300\text{MPa}$$

Stage-2:

$$F_t = \frac{2T}{d_p} = \frac{(2 \times 439000)}{57} = 15403\,N$$

$$\sigma_{b2} \approx 198\text{MPa} < 300\text{ MPa}$$

Safe in bending

AGMA Contact Stress Analysis

$$\sigma_c = Z_e \sqrt{\frac{F_t \times K_o \times K_v}{b \times d_p}}$$

Elastic coefficient for steel: $Z_e = 191\ \text{MPa}^{0.5}$

Stage-1:

$\sigma_{c1} \approx 640$ MPa

Stage-2:

$\sigma_{c2} \approx 780$ MPa

Below allowable contact stress

AGMA standards are used to evaluate bending and contact stresses. The calculated bending stresses for both gear stages are below 200 MPa, which is well within the

---

[11] Harris, T. A., & Kotzalas, M. N. (2006). *Rolling bearing analysis* (5th ed.). CRC Press.

[12] ISO. (2006). *Calculation of load capacity of spur and helical gears* (ISO 6336). International Organization for Standardization.

allowable bending stress of EN24 material. Similarly, the contact stresses are significantly lower than the allowable contact stress, ensuring safe operation.

**Table.11.** Summary of AGMA Stress Results

| Parameter | Stage 1 | Stage 2 | Allowable |
|---|---|---|---|
| Bending stress (MPa) | 162 | 198 | 300 |
| Contact stress (MPa) | < 700 | < 800 | 1100 |
| Design safety | Safe | Safe | — |

The analytical findings using AGMA prove that the gears designed are safe to operate in the maximum load condition with enough safety margin.

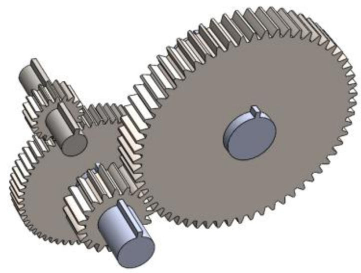

**Fig.3.** Layout of Gears

## 7. Shaft and Bearing Design

The gearbox also contains shafts and bearings as important parts that ensure that torque and gears are relayed without creating any power losses and alignment. These components are combined torsional, bending, and shock-loaded in the case of off-road ATV use. As such, their design should be such that they are sufficiently strong, stiff, and fatigue life in extreme operating conditions.[13]

### 7.1 Shaft Design

The gears box shafts are developed based on the ASME code of transmission shafts: it takes into consideration the joint effects of torsion and bending. The shafts are chosen on EN24 alloy steel because it has high yield strength and is considered to be fatigue resistant. The shock and fatigue factors are included to consider dynamic loading conditions that are normally experienced when off-road operation is in use.[14]

The shaft diameter is calculated by the equation of ASME shaft design:

$$d = \sqrt[3]{\left(\frac{16}{\pi \times \tau_{allow}}\right) \times \sqrt[2]{(K_t \times T)^2 + (K_b \times M)^2}}$$

**Where:**

- d = shaft diameter
- $\tau_{allow}$ = allowable shear stress
- T = torque
- M = bending moment
- $K_t$ = torsional shock and fatigue factor
- $K_b$ = bending shock and fatigue factor

Assumptions:

Allowable shear stress for EN24 = 100MPa

Shock Factors: $K_t = 1.5$ and $K_b = 1.5$

Depending on the calculated levels of torque in the various stages of the gearbox, the input, intermediate, and output shafts are fabricated with successive enlargement of diameter to comfortably pass on to the successive stages of the gearbox, the higher torques.

**Table.12.** Shaft Design Parameters

| Shaft | Transmitted Torque (Nm) | Selected Diameter (mm) |
|---|---|---|
| Input shaft | 139 | 20 |
| Intermediate shaft | 439 | 30 |
| Output shaft | 1390 | 40 |

The chosen shaft sizes have large margins in regard to yielding and undue deformation and they are small and may be easily produced.

### 7.2 Bearing Selection and Life Estimation

Deep groove ball bearings have been chosen in all shaft supports because they are capable of supporting high radial loads, medium speeds, and they can be installed easily. Deep groove ball bearings would be a good solution since spur gears are employed and hence, axial forces are insignificant.[15]

Bearing type: Deep Groove ball bearing

Equivalent dynamic load: $P = X \times F_r + Y \times F_a$

For Spur gears, $F_a = 0$

Bearing Life ($L_{10}$) = $L_{10} = (C / P)^3 \times 10^6$ revolutions

$L_{10} > 10^9$ revolutions for current bearing hence it can endure.

The evaluation of bearing life is determined with the use of L10 life equation on the basis of equivalent dynamic load. It's calculated bearing life is greater than $10^9$ revolutions, and this value meets and surpasses the endurance requirements given by BAJA SAE competitions.

**Table.13.** Bearing Design Considerations

| Parameter | Value |
|---|---|
| Bearing type | Deep groove ball bearing |
| Axial load | Negligible |
| Dominant load | Radial |
| Calculated L10 life | > $10^9$ revolutions |
| BAJA SAE requirement | Endurance compliant |

The shaft and bearing system will provide consistent service delivery through required tight off-road tasks, low vibration, and torque delivery.

[13] Juvinall, R. C., & Marshek, K. M. (2011). *Fundamentals of machine component design* (5th ed.). John Wiley & Sons.
[14] Lalanne, C. (2014). *Mechanical vibration and shock analysis*. John Wiley & Sons.

[15] Litvin, F. L., & Fuentes, A. (2004). Gear geometry and applied theory. Cambridge University Press.

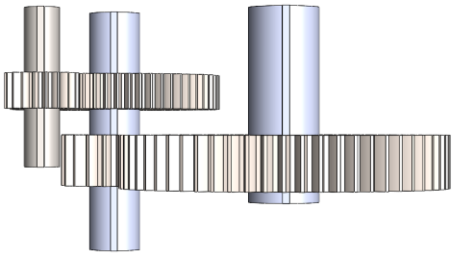

**Fig.4.** Input, Intermediate, Output Shafts and gears

## 8. Gearbox Casing Design

The gearbox casing is the main structural enclosure of all the rotating components, which is essential in ensuring that the shaft remains in its course, bearing loads, and the internal parts are not exposed to external factors like dust, mud, and water. In off-road ATV uses, the casing needs to be sufficiently stiff and strong and also minimize the weight of the entire system.[16]

### 8.1 Material Selection

The choice of the aluminum 6061-T6 to be used as the gearbox casing is based on the fact that the material has high strength to weight ratio, high corrosion resistance, and it has high machinability. These characteristics render it appropriate in light automotive and off-road purposes where the structural integrity and reduction in weight are all considered. Aluminum 6061-T6 is also thermal conductive and this can be used to facilitate heat removal in case of long working hours.[17]

**Table.14.** Mechanical Properties of Aluminum 6061-T6

| Property | Value |
|---|---|
| Density | 2700 kg/m³ |
| Young's modulus | 69 GPa |
| Yield strength | 275 MPa |
| Ultimate tensile strength | 310 MPa |
| Poisson's ratio | 0.33 |

### 8.2 Casing Geometry and Wall Thickness

The casing geometry is made to be small and symmetrical so that the load is evenly distributed and is easy to manufacture. An empirical design relation that is usually used in the design of gearbox casings is used to determine the wall thickness:

$$t = 0.03a + 5$$

### 8.3 Ribbing and Assembly Structural considerations

To enhance the stiffness of the casing, structural ribs are added to the outside casing surfaces to minimize focal deformation under load. The ribs are so arranged to avoid bearing seats and mounting points to assure accurate shaft alignment in operation. The casing is constructed in the form of a split housing so that it can be easily assembled, inspected and maintained.[18]

The casing is sealed with a silicone sheet gasket with the aim of providing effective sealing and preventing the leaking of lubricants under different temperature environments.

**Table.15.** Gearbox Casing Design Parameters

| Parameter | Specification |
|---|---|
| Material | Aluminum 6061-T6 |
| Wall thickness | ~8 mm |
| Casing type | Split housing |
| Ribbing | External stiffening ribs |
| Sealing method | Silicone sheet gasket |

The casing geometry has been very successful in reducing weight without compromising structural integrity so that the gearboxes can be reliable even in extreme off-road environments.

Gasket Selection: Sheet Gaskets are used to secure the two parts of the gearbox together to avoid spillage of gearbox oil. In Sheet gasket the material used is Silicon. Silicon gaskets are flexible and perform the best even in high and low temperatures. It offers low toxicity as well as low odor.

Differential Selection: The Torsen differential is capable of directing a greater percentage of torque through one wheel depending on the ratios of the gears. This removes the power limitation that open differentials suffer because the amount of torque available is not being limited by the amount traction in either wheel. Its lockup characteristics is very dynamic. It can go from zero lock to directly full lock condition. It is easier to drive. It has low maintenance. It is less noisy as compared to other differentials.

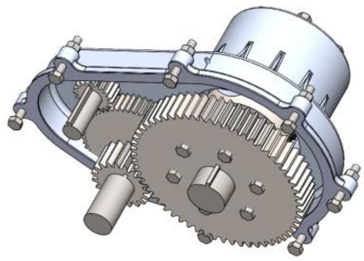

**Fig.5.** Gearbox Casing, Differential, Gasket

## 9. Finite Element Analysis

The analytical design of the gearbox is confirmed by carrying out Finite Element Analysis (FEA) to verify the structural integrity of the gearbox when carrying out under the maximum loading conditions. Numerical simulations can give a picture of the distributions of stresses, behavior of deformation and areas of critical behaviors that might not be clearly reflected by analytical techniques. In this work, FEA is conducted on the gears, shafts and gearbox casing with the help of the relevant material models and realistic boundary conditions.[19]

[16] Maitra, G. M. (2008). *Handbook of gear design* (2nd ed.). Tata McGraw-Hill.
[17] Niemann, G., Winter, H., & Höhn, B. R. (2019). *Machine elements: Design and calculation in mechanical engineering*. Springer.
[18] Norton, R. L. (2013). *Machine design: An integrated approach* (5th ed.). Pearson Education.
[19] Polaris Industries. (2021). *P90 CVT technical specifications and service manual*. Polaris Inc.

### 9.1 Analysis Boundary Conditions and Methodology

CAD software is used to produce three-dimensional solid models of the gearbox components which are then imported into a finite element solver in order to receive a static structural analysis. The gears and the shafts are of material properties that are attributed to EN24 alloy steel and the casing of the gearbox is made of Aluminum 6061-T6.

In the case of gear analysis, second-stage gear is the most critical gear (high transmitted torque) that is chosen. The pinion is applied with a torque of 439 Nm and the mating gear is fixed at the shaft. Frictionless contact is established between surfaces of gear teeth to model the perfect meshing.[20]

The analysis of the shaft is carried out by attachment of the bearing seats with cylindrical supporting fixing and loading the design torque at the gear mounting point. In the case of casing analysis, radial bearing reaction forces are imposed at the bearing locations and mounting points are completely constrained, to have them represent an attachment to the chassis.[21]

### 9.2 Results and Validation

The obtained FEA results show that the greatest von Mises stress that was built up in the gear teeth is significantly lower than the stress limits that were estimated by AGMA analysis. Equally, the stresses on the shafts are well within a safe range which ensures sufficient resistance to torsional and bending forces. The gearbox casing has the highest deformation of less than 0.02 mm which gives the gearbox a correct bearing alignment and smooth meshing of gears.

Analyses Performed:

1. Gear tooth bending stress
2. Shaft torsional stress

Boundary Conditions:

Applied torque at input shaft

Fixed bearing locations

Material properties of EN24

Material Used for gears and shaft is EN24.

**Table.16.** EN 24 Material Properties

| Properties | Value |
|---|---|
| Density | 7850 kg/m$^3$ |
| Young's Modulus | 210GPa |
| Poisson's Ratio | 0.3 |
| Yield Strength | 680MPa |
| Ultimate Tensile Strength | 850MPa |
| Allowable Bending Stress | 300MPa |
| Allowable Contact Stress | 1100MPa |

Gear tooth Bending Stress simulation to validate AGMA bending stress

As all the gears used are of same material, we will be taking the most critical gear that is Stage 2 gear.

Torque applied = 439 Nm

Tangential Force = $F_t = \frac{2T}{d_p} = \frac{(2 \times 439000)}{180} = 4878$ N

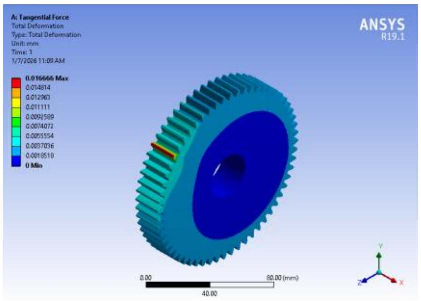


**Fig.6.** Deformation Analysis on Gear tooth

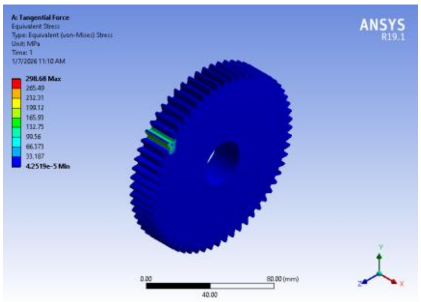


**Fig.7.** Stress Analysis on Gear tooth

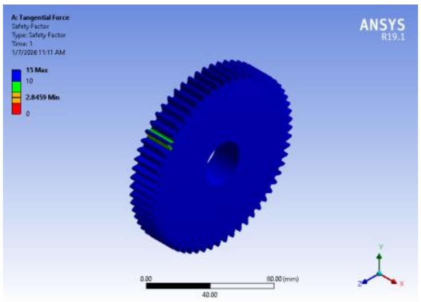


**Fig.8.** Factor of Safety of Gear tooth

### Gear Contact Mesh Pair Simulation

To determine AGMA contact stress between gears pinion and gear is selected. Geometry contact are set to be frictionless. Behavior is asymmetric and formulation is Augmented Lagrange. Gear is fixed and torque of 439 Nm is applied.

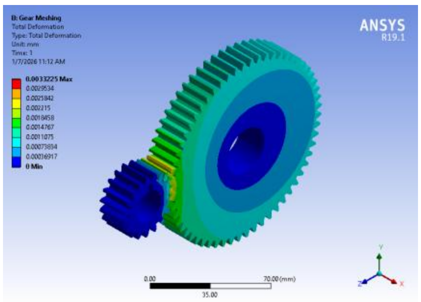


**Fig.9.** Deformation Analysis on gear contact pair

[20] Rao, J. S. (2011). *History of rotating machinery dynamics*. Springer.
[21] Rao, S. S. (2017). *The finite element method in engineering* (6th ed.). Butterworth-Heinemann.

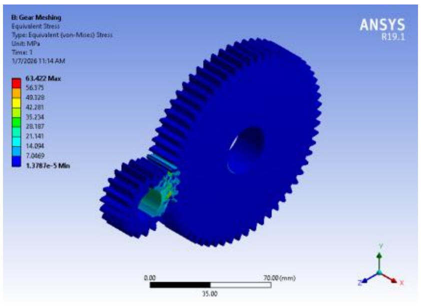


**Fig.10.** Stress Analysis on gear contact pair

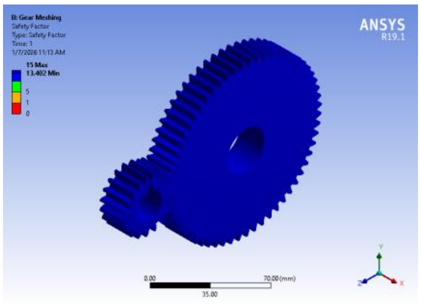


**Fig.11.** Factor of Safety of gear contact pair

For the shaft design analysis, we will check the gear seat as well as the bearing seat. We will fix the bearing seat by applying cylindrical support and apply torque on gear seat of 439Nm.

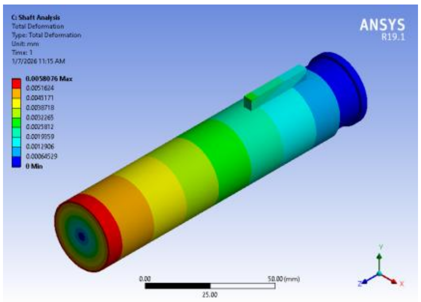


**Fig.12.** Deformation Analysis of the shaft

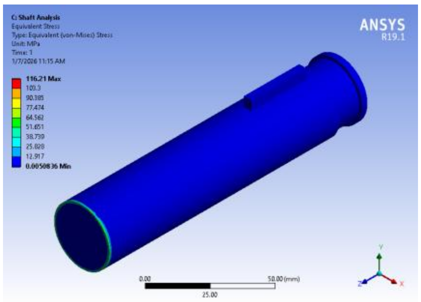


**Fig.13.** Stress Analysis of the shaft

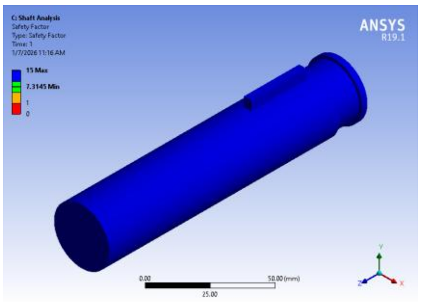


**Fig.14.** Factor of Safety of the shaft

*Gearbox Casing Analysis:*

To ensure bearing alignment and deformation it is needed to be done. Bearing will provide reaction forces which is equal to

$$F_r = 1.5 \times F_t = 7300 \text{ N}$$

This load is applied radially and bolting points are to be fixed.

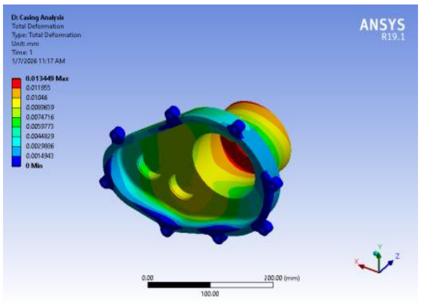


**Fig.15.** Deformation Analysis of the casing

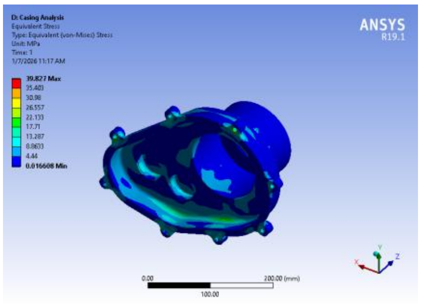


**Fig.16.** Stress Analysis of the casing

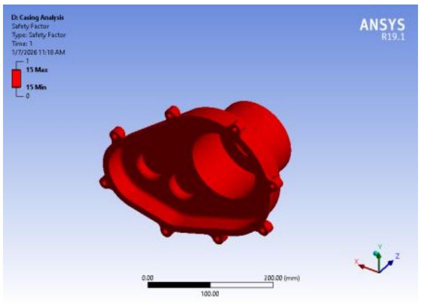


**Fig.17.** Factor of Safety of the casing

**Table.17.** Summary of FEA Results

| Component | Maximum Stress | Allowable Limit | Maximum Deformation |
|---|---|---|---|
| Gear tooth (Stage 2) | < 300 MPa | 300 MPa | Negligible |
| Shaft | < Yield strength | Material limit | Minimal |
| Gearbox casing | — | — | < 0.02 mm |

Close correspondence between analytical and numerical values confirms the design process and safety of the structure of the gearbox under the worst operating conditions.

**9.3. Explanation**

FEA (Finite Element Analysis): The plot in color depicts the stress deformation of the gearbox casing during the process of loading. FEA is a computerized method of estimating the way objects react to the external forces, vibration, heat, and other physical influences. It assists the engineers in determining the deformation of a component such as the gearbox casing when in various circumstances.

Color Scale: The color scale on the right is the total deformation (in millimeters, mm). This is because the colors are blue (low deformation) to red (high deformation). This shows the places of the casing that are experiencing the greatest deformation as a result of forces or the pressures exerted.

Deformation Concentration: Red and orange areas depict the area where most deformation takes place, probably because of the concentration of high stress or force in those areas. The blue and green areas show the location of the casing where there is less or no deformation implying that these are less stressed or more structural.

Purpose: This analysis is aimed at making sure that the gearbox casing is not overloaded by the forces of operation that would cause it to deform to the extent that it would impair the functioning of the casing or its own survival.

This plot plays a significant role in getting knowledge of the structural integrity of the gear box casing and how it can be reinforced or how the design can be changed.

### 9.4. Finite Element Analysis Validation

Results:

Max gear tooth stress < AGMA values

Shaft stress < yield limit

Casing deformation < 0.02 mm

Numerical results validate analytical design.

Finite element analysis is conducted to validate the analytical design. Static structural analysis is performed on gears, shafts, and casing under maximum torque conditions. The results show that stresses and deformations are within allowable limits, confirming the safety of the proposed design.

## 10. Results and Discussion

The combination of the analytical calculations and finite element simulations indicate that the offered custom gearbox design meets all the functional, structural and performance requirements of the All-Terrain Vehicle to be used under harsh off-road conditions. Analytical design, combined with numerical validation, provides reliability, safety, and robustness of the gearbox in the case of maximum loading.[22] The two-stage spur gear design chosen manages to reach the intended overall reduction ratio of 10:1, sufficient enough to allow sufficient multiplication of torque to meet steep gradient and high rolling resistance gradient requirements. AGMA standards of design of analytical gear design assures us that both the bending and the contact stresses of the first and the second gear stage of the design are not beyond reasonable limits with EN24 alloy steel. This means that it has adequate resistance to both cyclic and shock loading tooth bending failure and surface pitting. The Finite Element Analysis also confirms these results as it is precise in the distribution of stress and deformation in gears, shafts, and casing of the gearbox. The fact that AGMA-based analytical stresses are very close to those obtained with FEA is an indication that the design assumptions and calculation methodology are correct. The ultimate casing deformation is restricted to a level less than 0.02 mm which ensures accurate bearing centering and the flawless mesh of the gears as they are running.[23]

The endurance and reliability requirements are also satisfied with the design of the shaft and bearing. The calculated bearing life is much higher than those of BAJA SAE endurance standards, which is good to be operated under varying load conditions at a long period of time. The material used in the gearbox casing; Aluminum 6061-T6, is helpful in reducing the overall weight of the vehicle by a significant percentage and thus enhancing the overall weight bearing capacity and performance of the vehicle in terms of acceleration and maneuverability. The incorporation of the custom gearbox in conjunction with Polaris P90 CVT improves driving characteristics, as one can have an indefinite variation of ratios, which allows the engine to operate within the recommended optimal torque range in various settings. The combination enhances throttle response, gradeability and control, and the drivetrain is very versatile to dynamic off-road conditions.

**Table.18.** Summary of Key Results

| Parameter | Result | Design Requirement |
|---|---|---|
| Total gearbox ratio | 10:1 | ≥ Required |
| Gear stresses | Within limits | Safe |
| Casing deformation | < 0.02 mm | Acceptable |
| Bearing life | > $10^9$ revolutions | Endurance compliant |
| Drivetrain efficiency | High | Optimized |

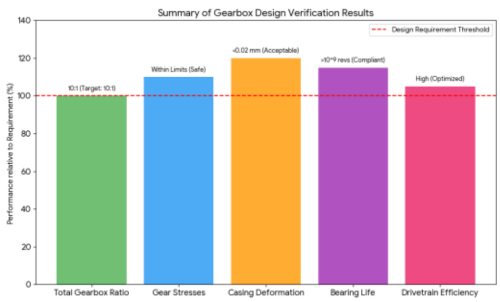


**Fig.18.**Gearbox design verification results

All in all, this analysis shows that the proposed design of the gearbox is structurally sound, efficient, and suitable to be used in competition and endurance-oriented ATV applications.[24]

## 11. Conclusion

The paper has managed to outline the entire design and development of a custom gearbox that is specifically designed to be used in an All-Terrain Vehicle application. It is realized that the traditional OEM gearboxes have their shortcomings with regard to weight, size and that they have

[22] SAE International. (2020). *Manual transmission and driveline systems*. SAE International.

[23] Shigley, J. E., Mischke, C. R., & Budynas, R. G. (2011). *Mechanical engineering design* (9th ed.). McGraw-Hill.

[24] Singh, R. (2016). *Applied mechanics and strength of materials*. McGraw-Hill Education.

the incorrect gear ratios to suit harsh off-road use, a special two-stage spur gear transmission has been designed to accommodate the high-performance and robustness demanded by off-road work. The systematic design approach is taken with the identification of the vehicle performance requirements like maximum speed, demand in torque and gradeability. Through these inputs, a desired gearbox reduction ratio of 10:1 is chosen and achieved by the use of a small two-stage spur gear. Analytical computations using standard AGMA and ASME standards assure that, under worst-case loading and shock conditions, gear bending stresses, contact stresses, shaft stresses, and bearing loads are all well within limit.[25] The choice of the material is also important in order to have the balance between strength and weight. Gears and shafts are made of EN24 alloy steel to provide high fatigue strength and reliability whereas the gearbox casing is made of Aluminum 6061-T6 to reduce mass without affecting structural stiffness. Gears, shafts, casing are subjected to a finite element analysis to confirm the analytical design, and the results showed that there was very little deformation and stress was less than the yield limit of material.[26] Combining the custom gearbox with Polaris P90 Continuously Variable Transmission will improve the drives as they will allow the efficient torque delivery in different environments and conditions of operation. All in all, the proposed gearbox has better performance, durability, and efficiency and is very applicable in the competitive and endurance-based ATV settings. The design approach offered in this work offers a credible model upon which the lightweight and application-specific off-road transmission systems can be developed in the future.[27]

## 12. Funding

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

## 13. Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

## 14. Author Contributions

All the authors contributed to the study conception and design. Material preparation, data collection, analysis was performed by Aditya Bhardwaj, Farhad Danish, Naeem Choudhary and Habib Ur Rehman. The first draft of the manuscript was written by Aditya Bhardwaj and all authors reviewed and commented on previous versions of the manuscript. All authors read and approve the final manuscript.

## REFERENCES

1. AGMA. (2004). Fundamental rating factors and calculation methods for involute spur and helical gear teeth (AGMA 2001-D04). American Gear Manufacturers Association.
2. ASM International. (2018). ASM handbook, volume 1: Properties and selection—Irons, steels, and high-performance alloys. ASM International.
3. ASM International. (2018). ASM handbook, volume 2: Properties and selection—Nonferrous alloys and special-purpose materials. ASM International.
4. BAJA SAE India. (2023). BAJA SAE India rulebook. Society of Automotive Engineers India.
5. Bhandari, V. B. (2010). Design of machine elements (3rd ed.). Tata McGraw-Hill.
6. Briggs & Stratton. (2022). 305 cc engine technical specifications. Briggs & Stratton Corporation.
7. Budynas, R. G. (2013). Advanced strength and applied stress analysis (2nd ed.). McGraw-Hill Education.
8. Budynas, R. G., & Nisbett, J. K. (2015). Shigley's mechanical engineering design (10th ed.). McGraw-Hill Education.
9. Cook, R. D. (2007). Concepts and applications of finite element analysis (4th ed.). John Wiley & Sons.
10. Dudley, D. W. (2012). Handbook of practical gear design. CRC Press.
11. Hamrock, B. J., Schmid, S. R., & Jacobson, B. O. (2004). Fundamentals of machine elements (2nd ed.). McGraw-Hill.
12. Harris, T. A., & Kotzalas, M. N. (2006). Rolling bearing analysis (5th ed.). CRC Press.
13. ISO. (2006). Calculation of load capacity of spur and helical gears (ISO 6336). International Organization for Standardization.
14. Juvinall, R. C., & Marshek, K. M. (2011). Fundamentals of machine component design (5th ed.). John Wiley & Sons.
15. Lalanne, C. (2014). Mechanical vibration and shock analysis. John Wiley & Sons.
16. Litvin, F. L., & Fuentes, A. (2004). Gear geometry and applied theory. Cambridge University Press.
17. Maitra, G. M. (2008). Handbook of gear design (2nd ed.). Tata McGraw-Hill.
18. Niemann, G., Winter, H., & Höhn, B. R. (2019). Machine elements: Design and calculation in mechanical engineering. Springer.
19. Norton, R. L. (2013). Machine design: An integrated approach (5th ed.). Pearson Education.
20. Polaris Industries. (2021). P90 CVT technical specifications and service manual. Polaris Inc.
21. Rao, J. S. (2011). History of rotating machinery dynamics. Springer.
22. Rao, S. S. (2017). The finite element method in engineering (6th ed.). Butterworth-Heinemann.
23. SAE International. (2020). Manual transmission and driveline systems. SAE International.
24. Shigley, J. E., Mischke, C. R., & Budynas, R. G. (2011). Mechanical engineering design (9th ed.). McGraw-Hill.
25. Singh, R. (2016). Applied mechanics and strength of materials. McGraw-Hill Education.
26. Totten, G. E. (2006). Steel heat treatment handbook. CRC Press.
27. Townsend, D. P. (1991). Dudley's gear handbook (2nd ed.). McGraw-Hill.
28. Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. Z. (2013). The finite element method: Its basis and fundamentals (7th ed.). Elsevier.

[25] Totten, G. E. (2006). *Steel heat treatment handbook*. CRC Press.
[26] Townsend, D. P. (1991). *Dudley's gear handbook* (2nd ed.). McGraw-Hill.
[27] Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. Z. (2013). *The finite element method: Its basis and fundamentals* (7th ed.). Elsevier.