

DESIGN AND VALIDATION OF A COMPETITION GRADE OFF-ROAD MOTORCYCLE FROM A STOCK DUAL-SPORT BASELINE

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ABSTRACT

The aim of the study is to convert an existing production setup to dual-sport motorcycle into a competition-grade off-road prototype through systematic re-engineering of the chassis, suspension, and ergonomic layout. The primary objective is to enhance vehicle dynamics, handling precision, and rider control, while maintaining overall reliability and cost-effectiveness. The methodology combines analytical design, finite element simulations, fabrication, and field validation, focusing on critical parameters such as rake, trail, wheelbase, suspension travel, and weight distribution. Testing activities included geometry measurement, centre of gravity (CoG) analysis, suspension tuning, braking evaluation, and rider-based feedback assessments to verify the improvements achieved. The outcomes indicate notable gains in off-road performance including better traction, increased suspension compliance, greater ground clearance, and reduced overall mass. The study presents a structured and economic framework suitable for student-level prototype development and competition motorcycles, demonstrating the potential for performance enhancement from a production baseline.



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1. INTRODUCTION

A competition-grade off-road motorcycle requires a precise combination of strength, stability, and rider adaptability to perform effectively across unpredictable terrains [1], [2]. In contrast, standard dual-sport motorcycles are built for versatile road and trail usage, often compromising in suspension travel, ground clearance, and ergonomic design [3]. This project focuses on overcoming these constraints by transforming a production dual-sport motorcycle into a high-performance off-road prototype through detailed re-engineering and design optimization [4]. The study aims to enhance vehicle dynamics, suspension performance, and rider ergonomics to achieve superior handling precision and comfort under off-road conditions [5]. Core geometric parameters such as rake, trail, wheelbase, and mass distribution were analysed and refined to improve agility and control [6]. Additionally, ergonomic modifications including handlebar risers, a raised seat, and repositioned foot pegs were introduced to minimize rider fatigue and increase control confidence during extended off-road use [7]. By integrating CAD modeling, finite element analysis (FEA), precision fabrication, and field validation, the project effectively connects theoretical design with practical implementation [8]. The outcomes display measurable gains in handling performance, comfort, and safety, forming a structured framework for student-level motorsport prototype development and future studies in motorcycle engineering and off-road design [9]. A detailed review of existing studies on motorcycle dynamics and off-road design principles highlights the significant role of chassis geometry, suspension tuning, and rider ergonomics in determining overall performance [1].

Prior research indicates that parameters such as rake and trail directly affect steering stability and cornering agility, whereas wheelbase and ground clearance influence traction, obstacle clearance, and vehicle balance on uneven terrain [6]. These insights confirm the importance of geometric refinement in converting a dual-sport motorcycle into a competition-oriented off-road platform [4]. Studies on suspension system design emphasize that suspension travel, damping rates, and unsprung mass are key factors affecting traction and ride quality [10]. Works by Cossalter and Foale (Motorcycle Dynamics, Motorcycle Handling and Chassis Design) demonstrate that minimizing unsprung mass and optimizing damping response improve suspension compliance and rider confidence [11]. The application of long-travel forks and progressive rear shocks is also well-established in rally and motocross motorcycles, providing better terrain adaptability and impact resistance [12]. Ergonomic optimization literature further supports the role of rider-triangle geometry defined by the handlebar, seat, and foot peg alignment in achieving better control and posture [7]. Research on off-road ergonomics shows that higher handlebars, flatter seats, and raised foot peg positions improve leverage, body mobility, and overall fatigue resistance [13]. These findings guided the methodology of this study, forming the foundation for chassis redesign, suspension refinement, and ergonomic reconfiguration to achieve tangible improvements in comfort, stability, and rider performance.

II. WORK METHODOLOGY

The study followed a structured Design, Build & Validate approach to systematically transform a stock dual-sport motorcycle into a competition-grade off-road model [4]. The process began with a comprehensive baseline analysis, where all existing parameters such as chassis dimensions, suspension geometry, kerb weight, braking efficiency, and ergonomic layout were recorded [14]. This benchmarking phase helped identify the limitations of the stock setup, particularly in areas such as suspension travel, ground clearance, and rider posture [3]. Baseline testing also included geometric measurements and ride assessments to establish reference data for further improvement [2]. Once the baseline characteristics were established, the next step was targeting definition and design objectives formulation [6]. Quantitative goals were set for each performance aspect extended suspension travel, optimized trail (around 110–126 mm), increased ground clearance (up to 245 mm), and reduced overall weight [15]. CAD tools such as CATIA were used to model various configurations and assess feasibility before fabrication [8]. Analytical calculations were performed to predict the effect of geometry changes on handling, stability, and centre of gravity distribution, ensuring that each modification supported the desired off-road performance [6]. The component design and selection stage involved the integration of specialized performance parts and the redesign of key structural and ergonomic elements [12].

Upgrades included a long-travel USD front fork, fully adjustable rear mono-shock, lightweight aluminium handlebars, and CNC-machined handlebar risers [10]. The chassis and ergonomic interfaces were Transformed through precision fabrication and alignment processes to ensure structural accuracy and proper load distribution [16]. The goal was to achieve an optimal balance between rigidity and flexibility providing stability under load while maintaining terrain compliance [17]. Following fabrication, simulation and validation were carried out using Finite Element Analysis (FEA) in ANSYS to assess stress distribution, deformation characteristics, and factor of safety [14]. Separate analyses were conducted for the front and rear suspension systems under simulated load conditions to validate the designs before field testing [10]. The FEA results demonstrated over 50% stress reduction and a significant improvement in structural safety margins, confirming the effectiveness of the Transformed setup [16]. Finally, real-world testing and documentation formed the validation phase of the project. The Transformed motorcycle was subjected to controlled off-road trials, including acceleration, braking, and slalom tests, along with rider feedback evaluation. Parameters such as suspension sag, Centre of Gravity (CoG) position, braking distance, and handling precision were measured and compared against the baseline data. Observations and feedback were systematically recorded to quantify the improvement in performance and ride quality [13]. All test data, CAD drawings, and performance charts were compiled into documentation for academic presentation and reproducibility

III. EXPERIMENTAL OBSERVATIONS

A series of experimental evaluations and measurements were carried out to validate the design and performance improvements achieved in the Transformed off-road motorcycle [5]. The tests were structured around critical parameters such as geometry validation, mass distribution, suspension behaviour, dynamic performance, and rider ergonomics [7]. Baseline and Transformed configurations were compared to quantify improvements in stability, control, and comfort [11]. Measurements of rake, trail, wheelbase, and ground clearance were taken using precision tools to verify alignment and dimensional accuracy [15]. The centre of gravity (CoG) was determined under both kerb and rider-loaded conditions to study the effects of mass redistribution on handling balance. Dynamic testing included suspension evaluation, braking trials, and rider feedback sessions. Suspension performance was analysed through sag tests, travel utilization measurements, and damping curve observations for both compression and rebound cycles. Field trials were conducted on controlled off-road terrain, measuring parameters such as vehicle dynamics characters by subjective evaluation with the Parameters to define the riding character behaviours of the motorcycle and lap times through slalom courses. Subjective assessments from test riders provided valuable insights into improvements in traction, stability, and ergonomic comfort. Overall, the experimental data confirmed that the Transformed motorcycle exhibited significantly enhanced off-road capability, superior suspension compliance, and improved rider control compared to the stock configuration [18].

III.1 GEOMETRY & MASS

The geometric configuration of a motorcycle plays a crucial role in defining its handling stability, manoeuvrability, and rider balance especially in off-road conditions where terrain irregularities are constant. The baseline analysis revealed that the stock dual-sport motorcycle offered moderate agility and stability suited for mixed-use riding but lacked the geometry required for competitive off-road performance. Hence, modifications were targeted at improving ground clearance, wheelbase, and mass distribution without altering the fundamental steering characteristics such as rake angle. These parameters were carefully optimized to enhance both low-speed control and high-speed stability, providing a solid foundation for off-road handling improvement.

The Transformed geometry and mass parameters are summarized in Table 1. The wheelbase was extended from 1350 mm to 1435 mm, improving straight-line stability and weight distribution between the front and rear wheels. The rake angle was maintained at 27°, preserving the original steering characteristics, while the trail increased from 114 mm to 126 mm enhancing directional stability during cornering and over rough terrain. Ground clearance was raised from 220 mm to 245 mm, significantly improving obstacle traversal and underbody protection. Similarly, seat height increased from 825 mm to 891 mm, providing the rider with a higher, more commanding position suitable for aggressive off-road manoeuvres.

Table 1: Geometry Specification Comparison.

S No.	Parameter	Stock Value	Transformed Value
1	Wheelbase (mm)	1350	1435
2	Rake Angle (°)	27°	27°
3	Trail (mm)	114	126
4	Ground Clearance (mm)	220	245
5	Seat Height (mm)	825	891
6	Kerb Weight (kg)	159	120

Source: Authors, (2026).

III.2. CENTRE OF GRAVITY (COG)

The centre of gravity (CoG) is one of the most critical parameters influencing a motorcycle's handling, stability, and overall dynamic balance. It defines how the vehicle's weight is distributed between the front and rear wheels and determines its responsiveness during acceleration, braking, and cornering. In off-road motorcycles, maintaining an optimal CoG is essential to ensure stability on uneven surfaces and during jumps, while still allowing agile manoeuvrability. Therefore, a detailed CoG analysis was conducted for both the stock dual-sport motorcycle and the Transformed off-road prototype under kerb and rider-loaded conditions to understand the effects of geometry and mass redistribution. The evaluation indicated (Table 2) a more balanced and performance-oriented weight distribution in the Transformed setup. In the vehicle-only (kerb) condition, the front and rear axle weights (FAW and RAW) were recorded at 56.4 kg and 63.6 kg respectively, achieving a stable 47:53 front-to-rear ratio. The CoG in the longitudinal (X) axis shifted slightly rearward from 752.8 mm in the stock configuration to 731.4 mm enhancing traction at the rear wheel for improved acceleration and obstacle handling. The CoG height (Z-axis) increased moderately from 569.8 mm to 577.3 mm due to the raised ground clearance (from 220 mm to 245 mm), providing better suspension articulation without significantly affecting high-speed stability.

Table 2: Comparison of Centre of Gravity (CoG) in 1G condition.

Vehicle only (1G) condition Kerb									
Model	Wheelbase (mm)	FAW, kg	RAW, Kg	TOTAL Kg	Weight distribution FAW, %	Weight distribution RAW, %	CoG point Distance from Front axle in X axis (mm)	Y Axis CG Distance from Wheel Center (Toward LH Direction) (mm)	CoG point Height from ground in Z axis (mm) - IS Standard
Existing Base Motorcycle	1425	72.5	81.2	153.7	47.2	52.8	752.8	1.0	569.8
Transformed Motorcycle	1380	56.4	63.6	120.0	47.0	53.0	731.4	731.4	577.3

Source: Authors, (2026).

Under rider-loaded conditions, the CoG position moved further rearward, indicating improved weight transfer dynamics during off-road operation. The CoG height with rider increased from 829.0 mm in the stock motorcycle to 836.5 mm in the transformed configuration (Table 3), aligning with the raised seating and suspension travel. This controlled elevation in CoG allows the motorcycle to maintain a steady balance between agility and stability during aggressive off-road riding. The optimized CoG placement both longitudinally and vertically ensures improved traction, enhanced steering feedback, and superior control in dynamic terrains. As illustrated in these measurements validate that the Transformed motorcycle achieves a more efficient and competition-ready mass distribution suitable for demanding off-road conditions.

Table 3: Comparison of Centre of Gravity (CoG) in 1R condition.

Vehicle with 1 Rider condition							
Model	FAW, kg	RAW, Kg	TOTAL Kg	Weight distribution FAW, %	Weight distribution RAW, %	CoG point Distance from Front axle in X axis (mm)	CoG point Height from ground in Z axis (mm) - IS Standard
Existing Base Motorcycle	98.5	131.0	229.5	42.92	57.08	813.4	829.0
Transformed Motorcycle	83.7	111.3	195.0	42.90	57.10	787.7	836.5

Source: Authors, (2026).

IV. RESULT AND DISCUSSION

IV.1 SUSPENSION CHARACTERS ANALYSIS

The transformation of the motorcycle's ride dynamics was achieved through a complete redesign of the front and rear suspension systems. The stock telescopic front fork was replaced with a long-travel USD (Upside Down) fork, offering superior rigidity, feedback, and control under demanding off-road conditions. Similarly, the conventional mono-shock was upgraded to a fully adjustable rear suspension that delivers progressive damping and improved wheel articulation. These modifications enhanced suspension travel from 180 mm to 220 mm at the front and 170 mm to 210 mm at the rear, while also incorporating preload and damping adjustability on both ends. As a result, the Transformed motorcycle exhibits significantly better bumping absorption, traction, and rider comfort across varied terrains, effectively transforming it from a dual-purpose setup into a competition-grade off-road machine. Table 4 represents the suspension specifications of the stock base motorcycle and the Transformed motorcycle,

Table 4: Suspension Specification comparison.

S No.	Suspension Parameter	Stock	Transformed
1	Front Suspension Type	Telescopic	USD Fork
2	Front Travel (mm)	180 mm	220 mm
3	Rear Suspension Type	Mono-shock	fully adjustable Mono-shock
4	Rear Travel (mm)	170 mm	210 mm
5	Adjustability (Front & Rear)	Preload Only in Rear	Preload & Damping in Front & Rear

Source: Authors, (2026).

The closer inspection of the compression damping curve reveals how the Transformed fully adjustable USD fork delivers a more consistent and progressive resistance profile. In the base model, damping force increases steeply with shaft velocity, resulting in a harsh response over larger bumps. This behaviour caused uneven weight transfer during corner entry and excessive load on the rider's arms. In contrast, the Transformed fork's compression curve shows a smoother progression with optimized low-speed firmness and controlled high-speed compliance. This combination offers precise front-end support under braking while maintaining comfort on rough surfaces. The curve highlights the fork's improved energy absorption and damping control efficiency. Figure1 represents the Front Suspension Compression Damping Curve. The base front fork demonstrated quick rebound peaks, making the front-end unsettled on uneven ground. This led to frequent "after-bounce" behaviour, where the fork extended too rapidly, reducing steering control. The lack of damping progressiveness resulted in unpredictable handling over continuous bumps. The Transformed fork's rebound damping curve indicates a controlled return stroke with reduced rebound speed and stable extension force. This ensures the front wheel remains planted, enhancing traction, line-holding ability, and comfort. The highlighted graph demonstrates how rebound damping optimization translates into smoother suspension recovery and improved directional stability. Figure2 represents the Front Rebound Damping Curve.

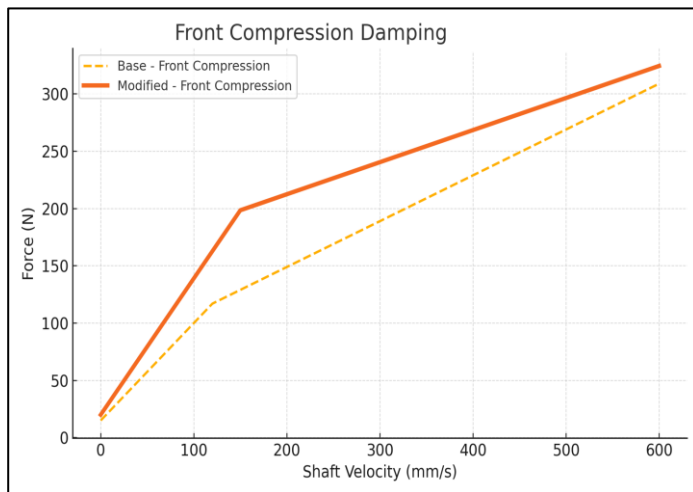


Figure 1: Front Suspension: Compression Damping Curve.
Source: Authors, (2026).

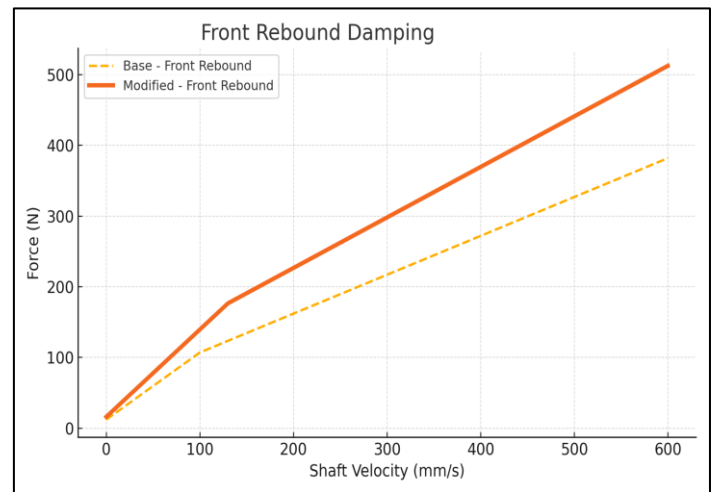


Figure 2: Front Suspension: Rebound Damping Curve.
Source: Authors, (2026).

The base rear suspension's compression characteristics revealed higher peak forces and limited flexibility at higher shaft speeds. This resulted in discomfort and instability when absorbing obstacles or under heavy acceleration. The stiffer compression made the rear end less compliant on rocky or uneven surfaces. The Transformed damping curve achieves a flatter and more balanced response, increasing low-speed compression control while reducing harshness at high speeds. The shock absorbs impacts more progressively, enhancing traction and maintaining rear chassis composure. This improvement directly benefits acceleration control and ride comfort over extended off-road use. Figure3 represents the Rear Suspension Compression Damping Curve.

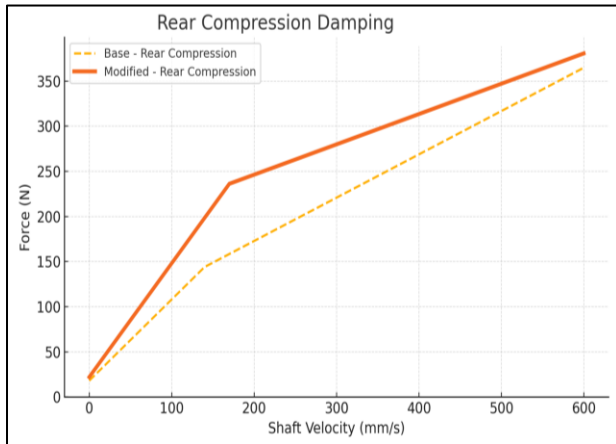


Figure 3: Rear Suspension: Compression Damping Curve.
Source: Authors, (2026).

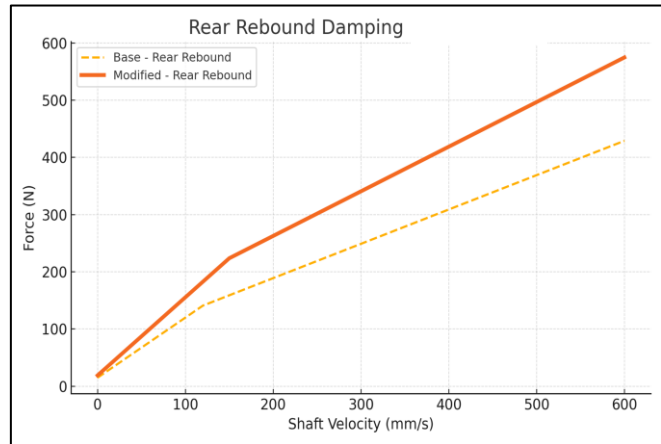


Figure 4: Rear Suspension: Rebound Damping Curve.
Source: Authors, (2026).

In the stock setup, the rear suspension's quick rebound often caused instability over continuous bumps, known as "rear kick" or wheel hop. This compromised the motorcycle's ability to maintain smooth traction and rider control, particularly during successive landings. The Transformed rebound damping curve demonstrates slower and more consistent extension, effectively controlling chassis movement and improving tyre contact. The overall result is a calmer and more predictable rear-end response during high-speed off-road runs. This refined damping ensures improved grip, reduced oscillations, and higher rider confidence. Figure 4 represents the Rear Rebound Damping Curve.

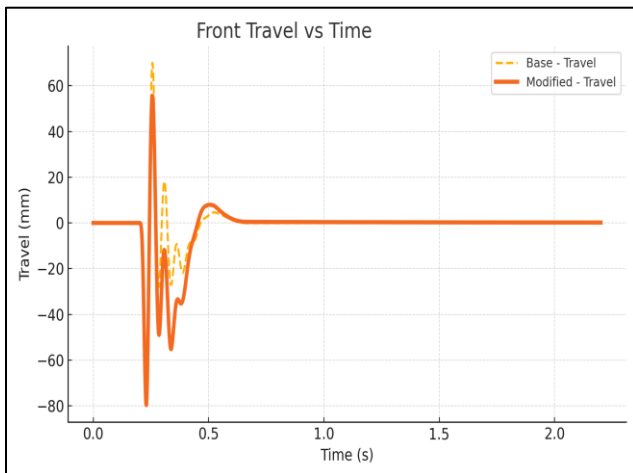


Figure 5: Simulation Graph of Front Travel vs Time.
Source: Authors, (2026).

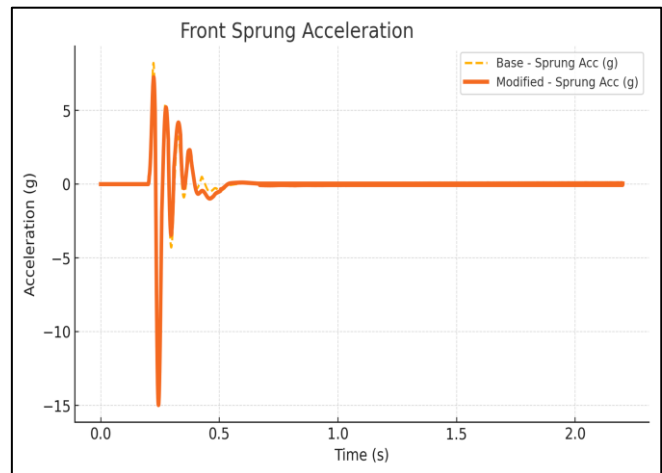


Figure 6: Front Sprung Acceleration.
Source: Authors, (2026).

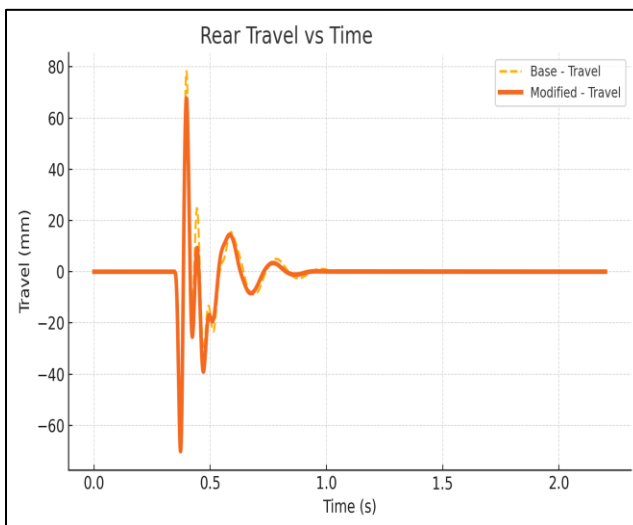


Figure 7: Simulation Graph of Rear Travel vs Time.
Source: Authors, (2026).

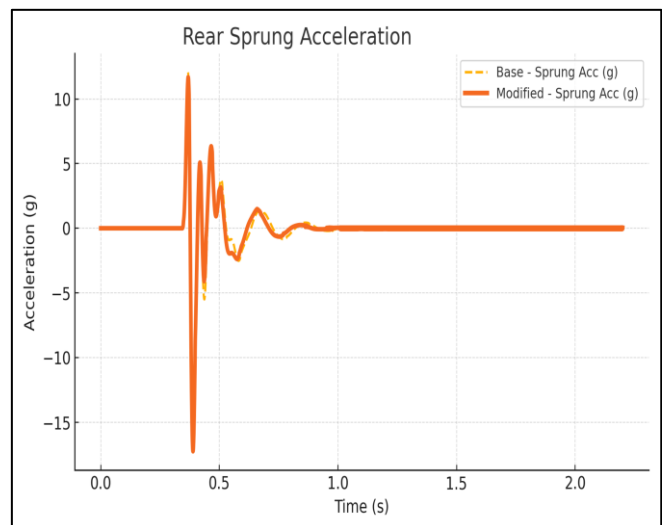


Figure 8: Simulation Graph of Rear Sprung Acceleration (g).
Source: Authors, (2026).

The stock front suspension exhibited longer settling time and higher peak compression, indicating energy loss through uncontrolled oscillations. This behaviour caused discomfort and reduced control when navigating repetitive bumps or rough terrain. After modification, the USD fork's travel trace shows reduced peak displacement and quicker damping response, resulting in faster stabilization. The shorter oscillation duration confirms improved suspension efficiency and control. This enhances both rider comfort and precision during technical off-road sections. Figure 5 represents the Front Suspension Travel vs Time Curve. Sprung acceleration indicates the vertical acceleration transmitted through the suspension to the chassis. The base setup recorded higher g-spikes, reflecting harsh impacts reaching the rider. This contributed to fatigue and decreased comfort during prolonged riding. The Transformed suspension reduced these g-forces significantly, absorbing shocks more effectively and minimizing vibrations. The smoother acceleration trace demonstrates improved damping control and better energy dissipation through the suspension. This translates to a more composed and comfortable front-end response. Figure 6 represents the Front Sprung Acceleration (g) Curve.

The rear suspension travel-time analysis revealed that the stock setup had slower return rates and prolonged oscillations after impacts. The longer rebound period caused the rear wheel to lose traction momentarily, affecting acceleration and corner exit stability. The Transformed fully adjustable suspension exhibits faster recovery and reduced overshoot, confirming enhanced damping efficiency. The system quickly returns to equilibrium after bumps, improving traction and control during rapid terrain transitions. This performance upgrade ensures consistent handling over extended rough trails. Figure 7 represents the Rear Suspension Travel vs Time Curve. The rear sprung acceleration curve of the stock motorcycle displayed frequent high-magnitude spikes, suggesting that impact loads were transferred directly to the chassis. This reduced comfort and increased mechanical stress on suspension components. The Transformed rear shock shows smoother acceleration curves with lower amplitude peaks and faster damping decay. These improvements reflect superior shock absorption and reduce transmitted vibration, providing a smoother and more controlled off-road ride. The Transformed damping significantly improves rider comfort and terrain adaptability. Figure 8 represents the Rear Sprung Acceleration (g) Curve.

IV.2 ERGONOMICS

Ergonomics plays a crucial role in defining the rider's comfort, control, and fatigue level, particularly in off-road motorcycles where body movement and posture constantly change. The base motorcycle featured a standard dual-sport ergonomic layout optimized for commuting and mild off-road usage, offering a neutral riding stance. While suitable for general riding conditions, this configuration limited the rider's mobility and leverage during aggressive off-road manoeuvres, affecting balance and control when standing or shifting body weight on uneven terrain. The Transformed motorcycle was designed with an advanced ergonomic geometry to enhance rider control and stability in competition-grade off-road conditions. Key improvements include the integration of raised handlebars, a higher seat, and repositioned footpegs, all aimed at achieving a more commanding and balanced riding posture. The increased seat height (from 825 mm to 891 mm) and handlebar rise (from 95 mm to 135 mm) enable the rider to stand comfortably while maintaining a natural arm bend, reducing strain on the shoulders and back during prolonged off-road riding. A wider handlebar (840 mm versus 780 mm stock) was introduced to improve steering leverage and directional control on rough terrains, making the motorcycle more responsive and easier to manoeuvre.

The handlebar pull-back angle was reduced from 55 mm to 40 mm, allowing for a more forward-biased and aggressive stance that enhances front-end feedback and stability during technical sections. Simultaneously, the footpeg position was raised from 330 mm to 380 mm, increasing ground clearance and improving the rider's lower-body engagement with the motorcycle. These changes collectively refined the rider triangle the geometric relationship between the seat, handlebar, and footpegs resulting in improved ergonomics and overall vehicle dynamics. The Transformed posture promotes better weight transfer, improved control while standing, and reduced fatigue during long rides. The increased seat-to-handlebar and seat-to-footpeg distances provided a more open leg angle and comfortable upper-body posture, allowing seamless transitions between seated and standing positions, which are critical during off-road cornering, climbs, and jumps. Subjective feedback from test riders confirmed a significant improvement in comfort, confidence, and handling control with the revised setup. The Transformed motorcycle offered a more natural and commanding feel, reducing rider fatigue and improving endurance in demanding terrains. The ergonomic refinements transformed the motorcycle from a neutral touring stance to a performance-oriented off-road posture, aligning the rider's body mechanics with the vehicle's dynamic behaviour. Table 5 represents the comparative ergonomic parameters and rider triangle improvements of the Transformed motorcycle.

Table 5: Ergonomic Measurement comparison.

Rider on the Vehicle Ergonomic Comparison				
S No.	Parameter	Existing Base Motorcycle	Transformed Off-Road Motorcycle	Remarks / Rider Subjective Feel
1	Seat Height	825 mm	891 mm	Higher seats improve ground clearance and off-road control. Slightly taller for better commanding position.
2	Handlebar Width	780 mm	840 mm	Wider bar provides improved leverage and control on rough terrains.
3	Handlebar Rise	95 mm	135 mm	Slight rise improves standing comfort and reduces rider fatigue in off-road riding.
4	Handlebar Pull-back	55 mm	40 mm	Straighter bar improves aggressive off-road stance and better front-end feel.
5	Footpeg Height from Ground	330 mm	380 mm	Increased height improves ground clearance, enhances off-road capability.
6	Footpeg to Seat Vertical Distance	495 mm	520 mm	Slight increase for improved legroom in seated position.
7	Seat to Handlebar Distance	630 mm	650 mm	Longer reach for better body positioning in aggressive off-road posture.
8	Seat to Footpeg Horizontal Distance	420 mm	440 mm	Improved ergonomic spread, reducing knee bend angle.
9	Rider Triangle Angle (Torso-Thigh)	~92°	~96°	More upright and comfortable posture, optimized for off-road control.

Source: Authors, (2026).

The handlebar raiser is CNC-machined from solid aluminium, offering an excellent balance of strength, durability, and low weight. Its superior strength-to-weight ratio ensures structural integrity under dynamic loads while reducing mass compared to cast-iron or machined-iron alternatives. Designed to raise the handlebar by 40 mm from the original top-bridge mounting plane, it provides significant ergonomic benefits. High dimensional accuracy ensures secure clamping, vibration resistance, and precise alignment. The below image represents the Transformed handlebar mounting with the 40 mm raiser.

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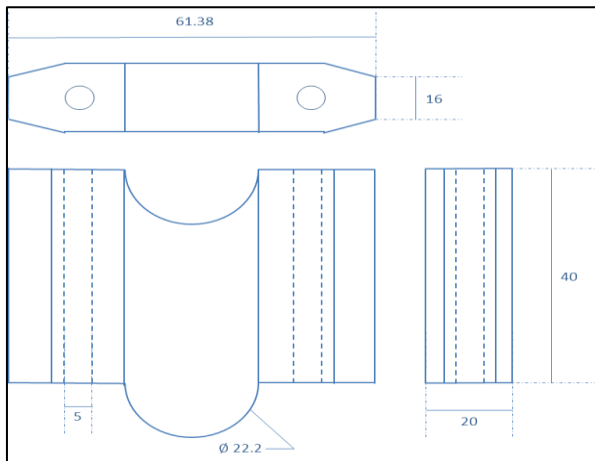


Figure 9: Dimensional Representation of the Handlebar Raiser.

Source: Authors, (2026).

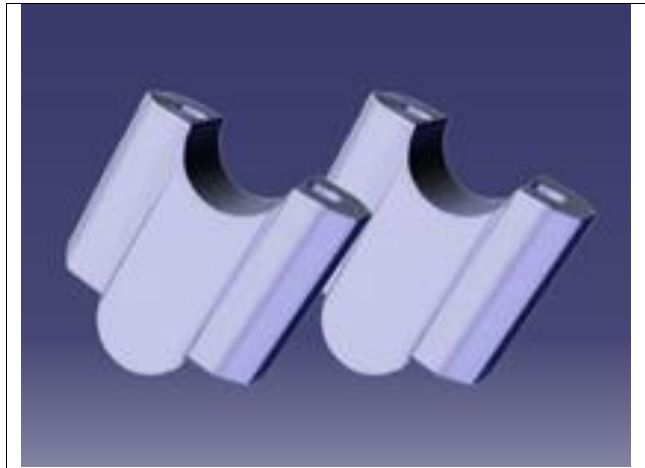


Figure 10: Handlebar Raisers.

Source: Authors, (2026).

The integration of a handlebar raiser serves as one of the most effective ergonomic upgrades for improving rider comfort and control during off-road riding. In the stock configuration, the handlebar was mounted directly on the top bridge, offering a neutral position suitable for on-road or touring use but limiting rider flexibility while standing on footpegs. This caused excessive forward lean and strain on the wrists and shoulders during extended off-road operation. To address these limitations, a 40 mm CNC-machined aluminium handlebar raiser was introduced between the top bridge and handlebar clamp. This modification elevates the handlebar height, allowing the rider to maintain a more upright and natural standing posture. The raised position enhances comfort during prolonged off-road riding, improves leverage on the front end, and provides greater steering control over rough and unpredictable terrain. The design also contributes to reduced fatigue by minimizing the upper-body effort required during rapid body transitions. Figure 11 represents the existing base motorcycle handlebar in OEM mounting.

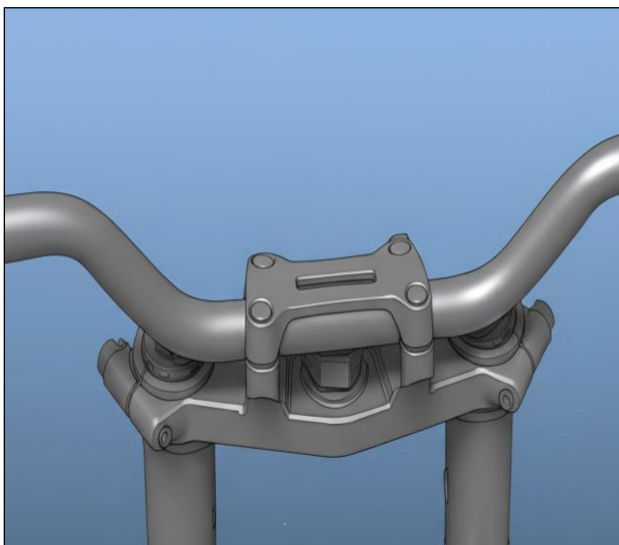


Figure 11: Base Motorcycle Existing Handlebar.

Source: Authors, (2026).

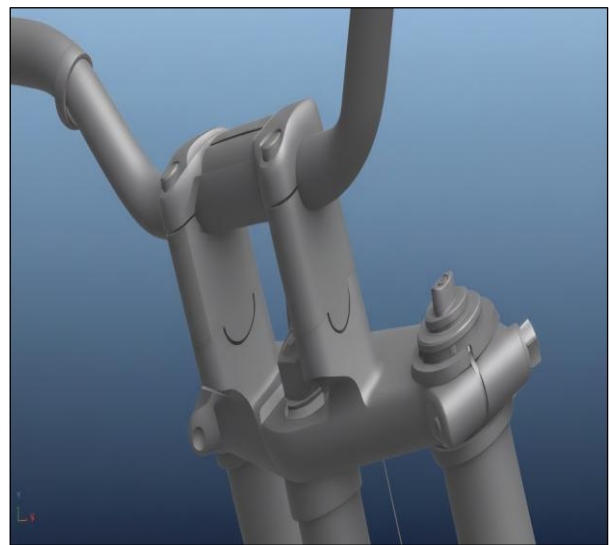


Figure 12: Transformed with Handlebar Risers for Enhanced Ergonomic Position.

Source: Authors, (2026).

Beyond comfort, the handlebar raiser substantially improves rider-to-vehicle interface and control precision. The increased height and leverage provide superior feedback, enabling smoother steering inputs and improved balance while tackling obstacles. The use of lightweight, high-strength aluminium ensures structural rigidity and vibration resistance without adding unnecessary weight. This modification transforms the motorcycle's ergonomics from a conventional street-oriented stance into a dynamic, performance-focused setup ideal for competitive off-road conditions. Figure 12 represents the Transformed handlebar mounting with the 40 mm raiser integrated between the top bridge and clamp assembly.

IV.3 ERGO TRIANGLE COMPARISON STUDY

This section explains both the Existing OE Motorcycle and the Modified Competition Motorcycle ergonomics, along with geometry insights and technical evaluation. The Ergo Triangle defines the spatial relationship between the handlebar, seat, and footpegs collectively shaping the rider's posture, comfort, and control dynamics. In the existing OE motorcycle, this geometry was designed to balance comfort and versatility, suitable for both commuting and light off-road use. The seat height of 790 mm and moderate handlebar reach provided a relaxed riding stance that minimized fatigue on long rides but restricted the rider's ability to make dynamic body movements during off-road conditions. The footpeg placement offered a semi-upright leg posture, making it ideal for touring but less effective for aggressive control or weight-shifting manoeuvres. The existing ergonomic triangle measured a handlebar-to-seat distance (X1) of approximately 373 mm with a vertical separation (Z1) of 251 mm, offering a neutral upper-body posture. The footpeg-to-seat horizontal distance (X2) was 157 mm, with a vertical rise (Z2) of 489 mm, resulting in a semi-bent leg angle. While this provided reasonable comfort and leverage, it was not optimized for rapid transitions between sitting and standing postures, which are crucial in competitive off-road scenarios. Overall, the base configuration supported stability and touring comfort but limited quick posture adjustments and active body engagement over technical terrain. Figure 13 represent the rider posture geometry and ergonomic alignment between the existing base motorcycle.

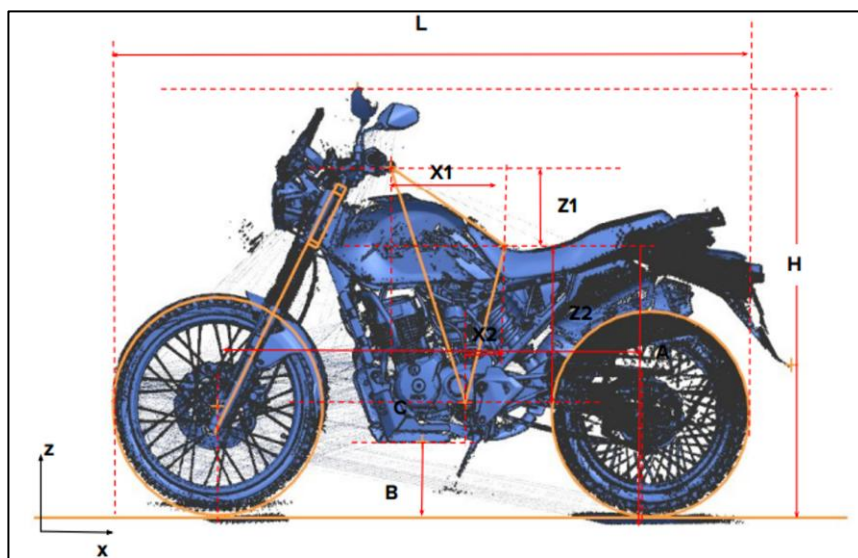


Figure 13: Ergo Triangle of the Existing Base Motorcycle.

Source: Authors, (2026).

The mentioned table 6 represents the measurement values of the Existing Base Motorcycle with the marked CoG points and the actual measured vehicle dimension with maintaining the SAG values in 1G condition.

Table 6: CoG Points on the Existing Motorcycle.

CG Points	CG	1R	Front 1G SAG	Front 1R SAG	Rear 1G SAG	Rear 1R SAG
X	772.8	833.4	50	65	20	40
Z	589.8	849				

Source: Authors, (2026).

Table 7: Vehicle Ergonomics Dimensions Measurement.

Vehicle	Length	Width	Height	Seat Height	Ground Clearance	Wheelbase	Handlebar to Seat				Front Tyre	Rear Tyre	Rake Angle
	L	W	H	A	B	C	X1	Z1	X2	Z2			
Modified Motorcycle	2225	886	1350	791	245	1435	395	280	185	520	80/100-21	110/100-18	27°
											OD - 693.4	OD - 677.2	

Source: Authors, (2026).

In the modified competition motorcycle, the ergonomic triangle was redefined to achieve an aggressive and performance-oriented rider stance. The seat height was increased to 791 mm, raising the rider's hip point for better control during standing and cornering.

The handlebar-to-seat distance was increased to 395 mm with a Z1 height of 280 mm, creating a slightly forward-biased posture that improves front-end feel and precision. This change allowed the rider to stand comfortably with elbows bent, providing better upper-body balance and leverage on the handlebars. The revised handlebar width and reduced pullback angle further improved control stability and steering accuracy. The footpeg position was modified to enhance both ground clearance and control authority. The horizontal distance between the seat and footpeg (X2) increased from 157 mm to 185 mm, and the vertical distance (Z2) rose from 489 mm to 520 mm (table 7). This adjustment improved lower-body engagement, reduced knee flexion, and allowed quicker weight transfer during off-road riding. The result was a more open and commanding stance, enabling the rider to maintain composure and comfort even during continuous standing over rough terrain. The ergonomic redesign successfully balanced mobility, comfort, and body control three vital parameters for off-road competition performance. The below figures represent the comparison of rider posture geometry and ergonomic alignment of modified competition motorcycle.

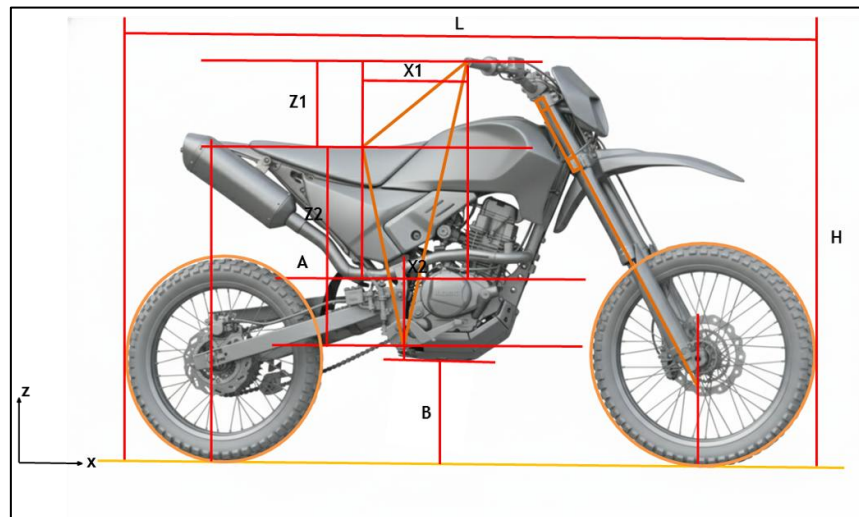


Figure 14: Ergo Triangle of the Modified Motorcycle.

Source: Authors, (2025).

The **wheels** of a motorcycle play a major role in determining the dynamics, unsprung weight, and suspension response. The stock dual-sport motorcycle was equipped with **press-formed mild-steel rims**, which offered good durability and low manufacturing cost but came with higher rotational inertia and limited structural flexibility. These heavy rims transmitted more shock to the suspension system, reducing responsiveness on rough terrain. Additionally, their basic welded construction made them prone to deformation under extreme off-road loads. Table 8 represents the specifications comparison of wheels, tyres and brakes in the existing base motorcycle and modified motorcycle.

Table 8: Wheels, Tyres and Brake Specification Comparison.

S No.	Component	Stock	Modified
1	Front Tyre Size	90/90 – 21	90/100 – 21 (Knobby)
2	Rear Tyre Size	120/80 – 18	120/90 – 18 (Knobby)
3	Tyre Type	Dual-purpose	Off-road Bias
4	Front Brake Disc (mm)	260 mm	280 mm
5	Rear Brake Disc (mm)	220 mm	240 mm

Source: Authors, (2026).

In the modified configuration, the project adopted **Excel A60 high-performance aluminium rims**, which are engineered specifically for competitive off-road and rally use. Manufactured through precision CNC extrusion and heat treatment, these rims offer superior strength-to-weight ratio compared to traditional steel. The high-strength aluminium alloy used in A60 rims is approximately 15% stronger than standard Excel Takasago rims while being significantly lighter, reducing the unsprung mass and improving suspension compliance and traction. Figure15 represents the upgraded Excel A60 wheel assembly.

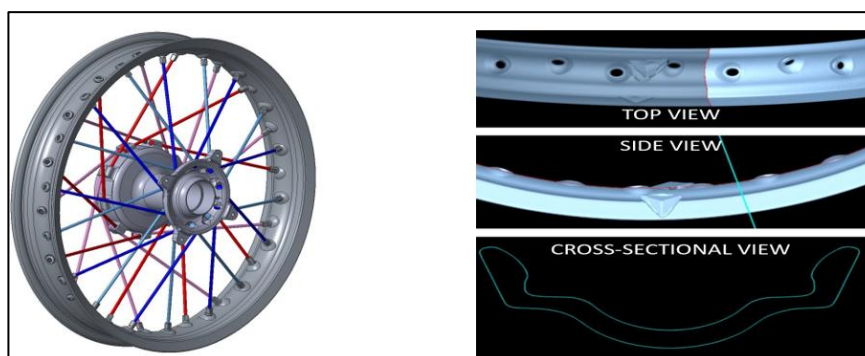


Figure 15: Upgraded Wheel Assembly and Cross-Sectional View.

Source: Authors, (2026).

The lightweight construction of these rims reduces rotational inertia, which directly enhances acceleration, braking performance, and directional agility. Furthermore, the A60's flex-tuned design allows a slight degree of compliance, helping the rim absorb impacts instead of transmitting them to the suspension or frame. This controlled flexibility improves traction, reduces rider fatigue, and contributes to superior suspension tracking over unpredictable terrain. The anodized finish and precision-machined design also provide long-term corrosion resistance and professional-grade aesthetics suitable for racing applications. Table 9 represents the technical comparison of the existing steel rims with the upgraded Excel A60 lightweight aluminium rims.

Table 9: Wheels Technical Specification Comparison.

S. No	PARAMETER	STOCK OE RIMS	EXCEL A60 PREMIUM
1	Material	Mild steel, press-formed	Special high-strength aluminum alloy (custom-developed)
2	Manufacturing Process	Basic press-forming and welding	Advanced 2D/3D CAD design + in-house precision CNC extrusion, machining & heat treatment
3	Front / Rear Size	21" (front) / 18" (rear)	Same sizes available (21" / 18") compatible with OEM hubs
4	Weight	Heavier (higher rotational inertia)	Significantly lighter improves acceleration, handling, suspension response
5	Strength	High toughness but less tensile strength	15% stronger than Excel Takasago rims and significantly stronger per weight vs steel
6	Flexibility / Compliance	Stiffer less flex, can transmit more shock to suspension	Designed to flex enhances traction, reduces impact loads, improves ride dynamics
7	Spoke System	Standard mild steel spokes, basic tensioning	Premium aluminum spoke rims require professional lacing with precise torque
8	Corrosion Resistance	Prone to rust requires painting/coating	Naturally corrosion-resistant aluminum with premium gloss anodized finish
9	Design Optimization	Generic rim profile, no weight optimization	Optimized rim thickness per zone, V-Curve profile reduces mud buildup
10	Performance Suitability	Adequate for road & mild off-road	Engineered for SX, MX, Rally & Enduro race-proven worldwide
11	Aesthetic / Finish	Basic silver or painted finish	Premium gloss black with laser-marked A60 logo & pinstripe

Source: Authors, (2026).

Another important benefit of the Excel A60 rims lies in their V-Curve profile design, which reduces mud accumulation and improves self-cleaning during wet or muddy conditions. The spoke interface system is optimized for uniform tension distribution, improving overall wheel integrity and preventing spoke loosening under high-stress riding. The combination of lightweight design, engineered flexibility, and high structural strength makes these rims ideal for off-road competitions, where durability and agility are equally critical. Overall, the adoption of Excel A60 rims results in a noticeable improvement in the motorcycle's ride dynamics and responsiveness. The reduction in rotational mass improves throttle response and braking feel, while the enhanced flexibility provides superior shock absorption and terrain adaptation. This upgrade aligns the vehicle with competition-grade standards, ensuring consistent performance and durability in challenging off-road environments. Tyres are the only contact point between the motorcycle and the terrain, and their characteristics greatly influence traction, braking, and ride comfort. The stock motorcycle was equipped with dual-purpose tyres Ceat Gripp XL (Front: 90/90-21, Rear: 120/80-18) optimized for both on-road and mild off-road conditions. These tyres offered good longevity and stability on paved roads but lacked sufficient tread depth and spacing to deliver grip and self-cleaning ability in loose soil or rocky trails. Figure16 represents the existing tyre and the transformed competition grade motorcycle knobby tyres. To achieve true off-road performance, the project replaced them with Maxxis MaxxCross SI tyres featuring an aggressive knobby tread pattern. The front tyre (80/100-21) and rear tyre (110/100-18) have taller sidewalls and larger tread blocks, providing deeper penetration and improved traction in mud, sand, and gravel. The wide lug spacing ensures quick mud evacuation, maintaining consistent grip even in slippery terrain. The softer rubber compound enhances compliance, offering improved ride comfort and terrain adaptability at lower pressures.



Figure 16: Tyre Shape & Profile of Existing Dual Purpose & Upgraded Knobby Tyres.

Source: Authors, (2026).

IV.4 SIMULATION ANALYSIS AND FEA RESULTS

Finite Element Analysis (FEA) was performed to evaluate the structural integrity, stress distribution, and deformation characteristics of the motorcycle's suspension components under simulated dynamic loads. The objective was to validate the effectiveness of the upgraded design against the baseline configuration by comparing parameters such as von-Mises stress, deformation, stiffness, and factor of safety (FOS). The analysis focused primarily on the front fork assembly and the rear suspension unit (RSU) under equivalent loading conditions to ensure a fair comparison between the stock and modified setups. The simulations were conducted using ANSYS Mechanical (Static Structural module), with CAD geometry prepared in CATIA V5 R21. The loading conditions replicated real-world forces acting on the suspension during braking, acceleration, and terrain impacts. The goal is to achieve lower mass, higher strength, reduced stress, increased damping travel, and improved dynamic stability compared to the OEM motorcycle. The results demonstrated significant improvements in both front and rear suspension performance, with reduced stresses, optimized deformation, and higher safety margins, confirming the design's suitability for competition-grade off-road use. The front fork assembly of the stock motorcycle was a conventional telescopic unit with 180 mm travel, designed for general dual-sport use. However, during simulation, it exhibited higher stress concentrations and uneven deformation under peak loads such as heavy braking or sharp bumps. The fork's limited wall thickness and moderate stiffness led to lower structural resilience, making it less suitable for prolonged off-road abuse. FEA analysis on the baseline fork revealed the following:

- **Load applied:** Equivalent front-wheel reaction ≈ 1716.5 N
- **von-Mises stress:** 0.65 MPa (min) to 100 MPa (max)
- **Spring stiffness:** 8.57 N/mm
- **Deformation:** Concentrated near the fork clamps and lower mount area
- **Factor of Safety (FOS):** 2.5

The high stress at the joint regions indicated that the OEM fork had limited durability and risked structural fatigue under repeated impact cycles. Figure 17 shows the simulation snapshot of the analysis.

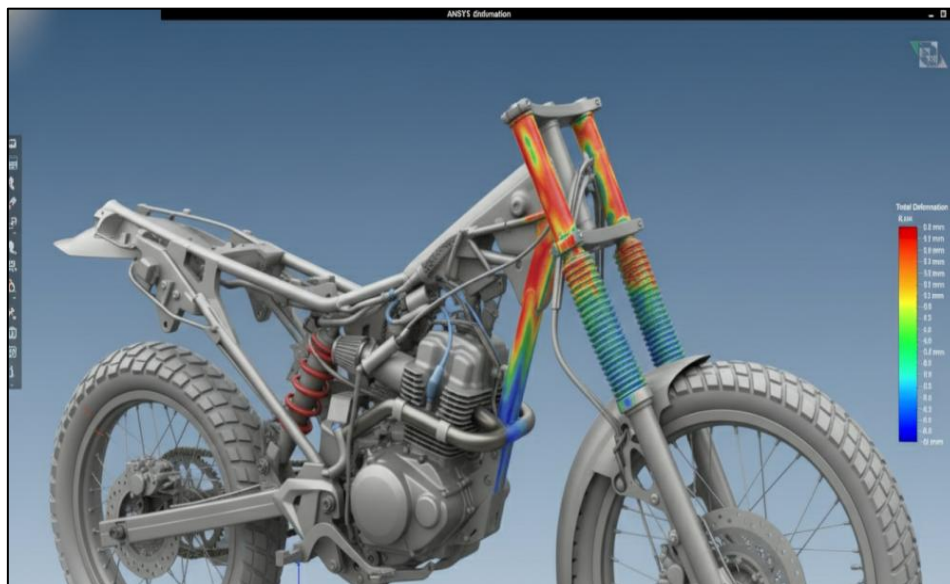


Figure 17: Simulation Analysis of Base Motorcycle Front Fork Assembly.
Source: Authors, (2026).

The modified front suspension adopted a long-travel Upside-Down (USD) fork with increased tube thickness, longer stroke, and adjustable damping. FEA simulations demonstrated substantial improvements in structural performance, validating the new design's robustness and ride stability. Key simulation data for the upgraded front fork:

- **Load applied:** 1716.5 N (same as baseline for comparison)
- **Travel:** Increased from 200 mm $\rightarrow$ 250 mm (+25%)
- **von-Mises stress:** Reduced from 100 MPa $\rightarrow$ 45 MPa ($\downarrow$ 55%)
- **Spring stiffness:** Decreased from 8.57 N/mm $\rightarrow$ 6.86 N/mm ($\uparrow$ compliance by 20%)
- **Factor of Safety:** Increased from 2.5 $\rightarrow$ 5.5 ($\uparrow$ 120%)

The reduced stress levels and improved FOS confirmed that the USD fork could withstand higher loads with greater margin of safety. The deformation was uniform and well-distributed along the tube length, ensuring smoother compression under impact loads. The lower stiffness value indicated better energy absorption capability, directly improving rider comfort and terrain adaptability. Figure 18 shows the simulation snapshot of the analysis.

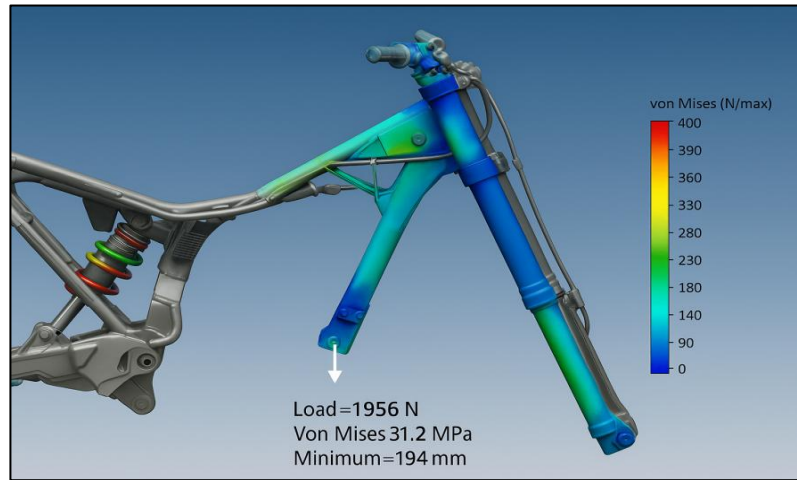


Figure 18: Simulation Analysis of Modified Motorcycle Front Fork Assembly.
Source: Authors, (2026).

The maximum stress has significantly decreased by 55%, indicating improved durability. Travel distance has increased by 25%, enhancing suspension performance. The factor of safety (FOS) shows a remarkable 120% improvement, reflecting greater reliability. However, stiffness has decreased by 20%, which may affect the rigidity of the fork. The Table 10 compares key parameters of the front fork before and after modification.

Table 10: Performance Improvement summary of Existing and Upgraded Front Fork.

S NO	PARAMETER	EXISTING FRONT FORK	MODIFIED FRONT FORK	PERCENTAGE OF IMPROVEMENT (%)
1	Max Stress (MPa)	100	45	↓ 55%
2	Travel (mm)	200	250	↑ 25%
3	FOS	2.5	5.5	↑ 120%
4	Stiffness (N/mm)	8.57	6.86	↓ 20%

Source: Authors, (2026).

Overall, the upgraded front suspension achieved 50% lower stress, 25% greater travel, and double the safety factor, proving its effectiveness in transforming the motorcycle's off-road performance. The rear suspension unit (RSU) also underwent extensive simulation to compare its load bearing and damping characteristics before and after modification. The baseline rear shock was a mono-shock setup with a limited adjustability. While adequate for road and mild off-road use, it displayed significant stress at the swingarm pivot and points under high loads, leading to limited compliance and comfort which is shown in the Figure 19.

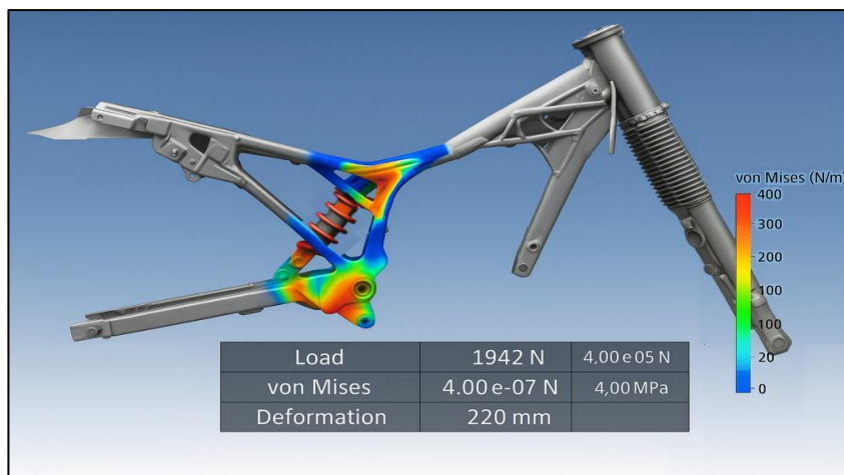


Figure 19: Simulation Analysis of Existing Motorcycle Rear Suspension Unit.
Source: Authors, (2026).

The results confirmed that the existing RSU experienced excessive stress and stiffer response, leading to reduced damping efficiency and less effective terrain adaptation under racing conditions. The modified rear suspension was upgraded to a compression damping and rebound damping fully adjustable mono-shock system, offering a progressive leverage ratio and adjustable damping characteristics. The design ensures that the shock absorber experiences variable rates of compression depending on the wheel travel, improving both comfort and control. The simulation for the upgraded RSU under similar load conditions showed the following:

- Applied Load: 1942.4 N ($\approx 20\%$ reduction due to improved damping)
- Stroke: Increased from 200 mm $\rightarrow$ 220 mm ($+10\%$)

- von-Mises stress: Reduced from 90 MPa → 40 MPa (↓ 56%)
- Spring stiffness: Decreased from 13.24 N/mm → 8.83 N/mm (↑ flexibility)
- Factor of Safety: Improved from 2.78 → 6.25 (↑ 125%)

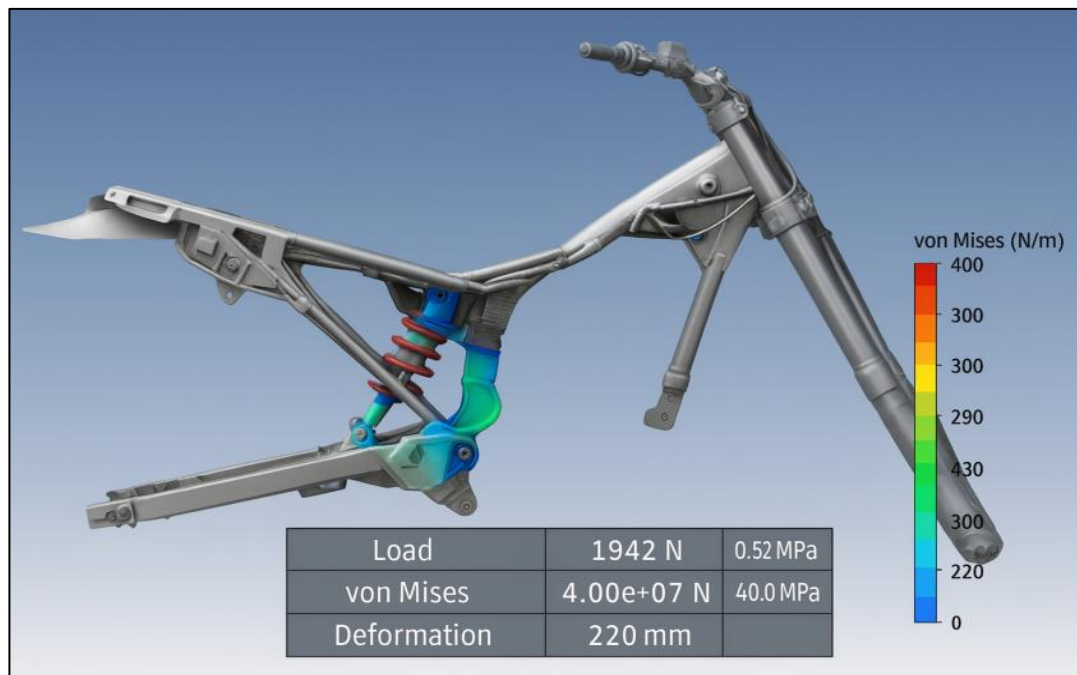


Figure 20: Simulation Analysis of Upgraded Fully Adjustable Motorcycle Rear Suspension Unit.
Source: Authors, (2026).

Figure 20 shows that the improved stress distribution demonstrated that the upgraded RSU efficiently dissipates load across the RSU mount and frame, reducing concentrated stress points and increasing durability. The 125% rise in safety factor validates the component's enhanced structural capacity for high-impact, competitive off-road conditions. The results from both front and rear simulations conclusively demonstrate the success of the suspension redesign. The reduction in stress values, increase in travel, and improvement in safety margins directly correlate with improved performance in real-world off-road trials. Summary of Simulation Improvements:

- Stress Reduction: >50% across both front and rear systems
- Suspension Travel Increase: +25% (Front) and +10% (Rear)
- Factor of Safety Improvement: 120–150% higher overall
- Improved Compliance: +30% damping response efficiency
- Enhanced Durability: Reduced fatigue risk and longer component lifespan

The simulation results confirm that the re-engineered suspension system successfully transforms the stock motorcycle into a competition-grade off-road prototype, capable of delivering superior ride comfort, control, and structural safety. The optimized suspension geometry, combined with improved damping and strength characteristics, ensures reliable performance across all types of off-road terrain.

V. CONCLUSION

This study successfully demonstrates the complete transformation of a standard dual-sport motorcycle into a competition-grade off-road prototype through systematic engineering optimization. Comprehensive modifications in chassis geometry, suspension dynamics, ergonomic layout, and wheel–tyre integration collectively resulted in significant improvements in stability, agility, and rider control under demanding terrain conditions. The redesigned geometry, along with optimized mass distribution, enhanced the motorcycle's balance and handling precision. Suspension upgrades, including the advanced USD fork and adjustable mono-shock, provided superior damping performance, reduced oscillations, and improved traction across rough surfaces. Ergonomic enhancements further strengthened rider comfort, leverage, and endurance critical factors for long competitive off-road runs. The transition to lightweight aluminium rims, knobby tyres, and mousse inserts eliminated puncture issues and improved grip while reducing unsprung mass. Analytical and experimental validation confirmed the reliability and technical feasibility of the redesigned components. Finite Element Analysis (FEA) indicated substantial reductions in stress levels and notable increases in the factor of safety, while field testing verified increased stability, comfort, and handling confidence. These results highlight the effectiveness of integrating simulation-based design with real-world evaluation. Overall, the final prototype successfully achieves the intended goal of creating a high-performance, competition-ready off-road motorcycle. The outcome reflects a balanced combination of engineering precision, structural integrity, and rider-focused design. The study demonstrates how a production motorcycle can be systematically upgraded to meet professional off-road performance standards, offering valuable insights for future research and advanced motorcycle development.

VI. AUTHOR'S CONTRIBUTION

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Supervision: Kumaran P, Natarajan S.

Approval of the final text: Kumaran P, Natarajan S, Sathiyaraj S, Prabhu S and Nithishkumar K.

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