Industrial Engineering Journal
ISSN: 0970-2555
Volume : 54, Issue 1, No.1, January : 2025

DEVELOPMENT OF AN ALL-TERRAIN VEHICLE (ATV) USING DMADV METHODOLOGY

Anil Melwyn Rego, Research Scholar,Department of Mechanical Engineering, St. Joseph Engineering College,VTU,Mangalore 575028, India and Department of Mechanical and Automobile Engineering, CHRIST University, Bengaluru, 560074, India. elwyn@gmail.com
Shreeranga Bhat, Department of Mechanical Engineering, St. Joseph Engineering College, Mangalore 575028, India
Gijo E.V, SQC & OR Unit, Indian Statistical Institute, Bangalore, 560059, India

Abstract
This paper presents an extensive research on the development of an All-Terrain Vehicle (ATV) designed to participate in the SAE Baja competition. The research paper used the DMADV methodology of Lean Six Sigma. The research emphasized a structured optimization of important components in the vehicle; this included the roll cage, suspension system, tires, braking system, steering, and transmission, with significant focus on safety, performance, and value. With Pugh's matrix, Pareto analysis, and Quality Function Deployment (QFD) tools, design choice selections were prioritized and optimized in alignment with both the standards of competition and expectations from the customers. AISI 4130 steel was selected for the roll cage because of its higher strength-to-weight ratio, MacPherson strut suspension was used to provide better stability, and vented disc brakes were employed to dissipate heat efficiently. Field testing and simulation studies proved the designs to be efficient in safety, durability, and overall vehicle performance.
Keywords: All-Terrain Vehicle (ATV), DMADV Methodology, Lean Six Sigma, Component Optimization, SAE Baja Competition

1.0 Introduction

The development of the vehicle for special purposes, for instance off-road driving, always challenges the engineers and designers in some unique ways. Notable among these are All-Terrain Vehicles (ATVs) because of their versatile application in navigating rugged terrains from recreational activities to agriculture and industrial operations. The demands for an ATV that is safer, more efficient, and more cost-effective have, over recent years, increasingly brought huge improvements in design and manufacturing methodologies. Lean Six Sigma is widely recognized as a transformation tool in the framework for optimizing processes and innovation that could address such challenges. More precisely, the DMADV methodology has been quite effective in designing innovative products strictly based on rigorous performance standards and customer expectations [1-5].

The DMADV methodology has been successfully applied in various fields for substantial improvements in product and service designs. For instance, Johnson used the DMADV approach to redesign student housing at the University of Miami [6]. The research aimed at improving quality of housing so that the services provided by the university matched the needs of students. Extensive risk analyses and research formed the basis of an innovative design that met hitherto unmet needs. The program improved the satisfaction level of students and increased the number of enrollments. This indicates that DMADV is important for business to align with customer-oriented results.

Similarly, Huang [7] employed DMADV to enhance the production quality of security cameras, specifically addressing inadequate soldering rates. Tools such as Pareto charts and cause-and-effect diagrams were instrumental in identifying the root causes of quality issues. By resolving these problems, the study achieved substantial improvements in product yield and dependability. Huang’s work highlighted the value of systematic problem-solving techniques in manufacturing, showcasing how DMADV can lead to significant advancements in complex industrial settings.

Yet another application was the integration of DFSS principles with Lean tools for designing a hydraulic line test fixture for maritime riser joints by Kibbe [8], where there was an improved test efficiency and cost saving in the oil and gas industry. The study highlighted the need for a structured and methodical approach to product development, especially in complex engineering projects. Through the elimination of waste and process optimization, Kibbe's research was able to establish the potential for tangible payback from Lean Six Sigma methodologies in demanding engineering environments.

Hassan [9] used the DMADV methodology to design a portable water filtering machine. The requirements were mainly customer needs, as well as the sustainability objectives. Quality Function Deployment, morphological charts, and SolidWorks modeling techniques have been used in order to design a product which can meet the specifications of clients while minimizing environmental impact. The study proved the efficacy of DMADV in fostering creativity and attaining design superiority, particularly in relation to sustainable water filtration systems. It underscored the need of aligning product development processes with ecological and consumer requirements. Furthermore, Attia [10] used DMADV to improve the efficiency of hydraulic/pneumatic screen printing apparatus. The research identified substantial design deficiencies in the current framework and proposed an infallible remedy for these problems. The study enhanced product quality and assured operational dependability by minimizing waste and streamlining manufacturing procedures. Attia's research is significant for elucidating the actual use of DMADV in intricate production settings to address formidable technical challenges.

Collectively, these studies have shown that the DMADV methodology can be used in a versatile and effective manner to bring innovation into the process and deliver excellent products in almost all industries. From housing solutions to manufacturing systems or sustainable product development, DMADV gives a structured framework, focusing on the customer, reducing waste, and helping organizations reach their goals. This systematic approach allows the identification of major problems in the design phase to ensure optimal outcomes in quality and performance.

The novelty of the work is based on the fact that this project applied the Define, Measure, Analyze, Design, and Verify (DMADV) methodology of Lean Six Sigma for the systematic development of an All-Terrain Vehicle (ATV) and it's a first-time approach within the framework of SAE Baja competitions. This research is distinct from typical design techniques since it straightens client needs with the technical factors directly through tools like Pugh's matrix, Pareto analysis, and Quality Function Deployment. This method is based on a real-world constraint and in line with industrial standards for balancing performance, safety, and cost-effectiveness. It is distinctive in its comprehensive strategy for enhancing essential vehicle components—roll cage, suspension, tires, braking system, steering, and transmission—through a data-driven technique. The study illustrates the effective use of multidisciplinary cooperation and sophisticated engineering techniques to ensure that academic research aligns with industrial norms, therefore establishing a robust foundation for future engineering endeavors.

This study is of a multidisciplinary character since its objective is to establish a development process for an All-Terrain Vehicle (ATV) that is comprehensive and well-structured. The primary objective here is to integrate the objectives of the client into the design process in such a way that the finished product satisfies the expectations of the users with regard to its usefulness, ergonomics, and safety. This approach, being consumer-oriented, is enhanced further by strengthening critical parts such as performance and life span of such parts. Some of these critical parts are roll cage suspension system, tires, brakes, steering, and gear box. These decisions for designs are prioritized using techniques such as Pugh's matrix and Quality Function Deployment. The vehicle must also be able to maintain some degree of competitiveness while remaining within the economic reachability of competing in the SAE Baja competition. This is another condition that must be met. Finding a balance between the aspects of cost and performance is another necessity.

An important aspect of the designing approach includes material selection and testing which revolves around the selection of compatible materials and systems, following strict observation of the standards for SAE, but maximizing durability, toughness, and weight efficiency with regard to the design under test. That indicates such a study also has very specific aims within the context of interdisciplinary co-operation, innovation, as well as the adoption of industry relevant practices in an academic framework. The research leverages state-of-the-art simulation software and analytical techniques in making totally comprehensive validations of design decisions according to stringent performance and safety requirements. The study is aimed at producing a framework that can become a repeatable model for other academic and professional teams working on challenging engineering projects. The study meets all these objectives by linking research in academia with industrial methods while setting a new benchmark for the systematic development of ATVs and similar technical issues.

2.0 Methodology

The DMADV methodology guided the development of the ATV, which is a structured approach within the Lean Six Sigma framework that ensures both the optimization of design and functionality. The methodology stands for Define, Measure, Analyze, Design, and Verify, referring to the five critical phases of the project implemented systematically. This technique was sufficiently complete to guarantee that the design process was efficient and aligned with safety, performance, and cost-effectiveness. The process started with the definition phase, during which the project's overarching goals are explicitly articulated. The major objective was to create an ATV that would excel in safety, performance, and cost-effectiveness to withstand harsh situations. A state gate diagram was developed during this stage to visualize the workflow process of the project and understand the key milestones. Customer requirements were also gathered via questionnaires and interviews for the direct insight into expectations and priorities of the users. All these requirements were the basis for designing the product, ensuring that at the end of the process, the delivered product would meet both the functional needs and customer satisfaction.

Data collection and analysis for measuring the importance of customer requirements in the Measure phase. Pareto analysis and Quality Function Deployment (QFD) tools were used in this phase to systematize prioritization. A matrix of relative importance was constructed for all design elements so that the design elements of greatest criticality were accentuated. Resources were allocated towards areas of most significant improvement, based on both performance and user satisfaction. The whole process guaranteed data-driven decision-making to ensure the critical customer needs are not ignored. In the Analyze phase, there established strong relationships between customer requirements and technical parameters. With the use of the "what/how" matrix, the team worked out how specific technical features can serve to address the prioritized customer needs. Moreover, Pugh's matrix was applied in determining the best design solutions among other alternatives for key components like the roll cage and suspension system. A number of options were then examined against defined criteria by evaluating the performance, safety, and cost of these proposed solutions. This extremely analytical approach made all the design decisions justifiable and compatible with the aims of the project. The team of experts utilized sophisticated engineering tools and simulations in meticulously implementing the required design features during the design phase. Some of the key determinants of this stage involved material selection based on statutory needs, customer requirements, and performance demands. The choices of materials like AISI 4130 steel would be made on the premise of higher strength-to-weight ratio and adherence to safe standards. Computational simulations were crucial for validating the viability of these ideas prior to the construction of a physical prototype, therefore conserving time and money while ensuring design accuracy. Finally came the Verification phase, intended to check the designs made by means of thorough examination with simulations. The prototypes came for elaborate evaluations, ensuring that products came against competition and customer expectations; also undertaken within tests on static and dynamic load, thermal and stress tests, as well as simulation of actual competition conditions via field trials. This means that there was confidence gained into whether the product would perform on the market or not when given the full application. The DMADV methodology was integrated into the development of the ATV, and thus, its development was structured and systematic to address complex design challenges. This guaranteed the fulfillment of all functional and performance specifications while considering customer happiness, cost-effectiveness, and regulatory compliance. The method was iterative, facilitating ongoing improvement, so establishing a resilient foundation for technical innovation.

3.0 Results and Discussion

3.1 DMADV

The KPIs align competition goals with DMADV initiatives, focusing on optimized design, technical requirements, project timeline, and customer requirements. To design and manufacture ATV, the first task involved selecting DMADV, a six-sigma selection tool, which can be used to design processes or products with positive outcomes. The work involved five stages: define, measure, analyze, design, and verify. The application of the DMADV methodology resulted in several key outcomes that significantly improved the ATV's design and performance. The emphasis given to safety, durability, and performance helped create a vehicle meeting stringent competition criteria. Below are the Key findings.

3.1.1 Roll Cage Design

The roll cage serves as the main safety structure for a Baja vehicle during rollovers or collision events. The authors chose AISI 4130 steel, a low alloy steel containing chromium and molybdenum, for this specific Baja vehicle because of its exceptional mechanical qualities and suitability for racing applications. AISI 4130 steel is acknowledged for its excellent strength-to-weight ratio, outstanding toughness, and favorable weldability, rendering it a preferred choice in high-performance engineering fields. This material comes with an approximate tensile strength of about 560 MPa and a yield strength of 460 MPa, so it can withstand considerable impact forces. In addition, its density comes at 7.85 g/cm^3, light enough that it is to be of great importance when enhancing handling and acceleration power in vehicles. A lighter roll cage reduces overall mass, which improves maneuverability and fuel efficiency while maintaining the structural robustness required for safety. The selection procedure for AISI 4130 steel included a stringent methodology using Pugh's Matrix Analysis. This facilitated the assessment of several materials, including mild steel, aluminum alloys, and composite materials, according to criteria such as cost, manufacturability, weight, and adherence to SAE Baja specifications. The AISI 4130 came out as the best choice because it excelled more than all alternatives in its performances. Exceptional strength with ease of production and competitive pricing made this critical safety element an ideal option. Dynamic and static finite element analyses were also undertaken to test the actual case of the material under use and design of roll cages. Static load testing simulated rollover and frontal collision conditions, where the roll cage was shown to remain intact under such extreme forces without a single failure. Dynamic impact tests assess the roll cage's energy absorption behavior for high-speed impacts as compared to other vehicles on similar roads and under natural road conditions. The analytical model showed that AISI 4130 steel represents superior safety and structural characteristics over vehicle dynamics. Characterized by the material of which it is made up of, a systematic procedure followed in selecting the material, followed by thorough validation, forms a basis of a secure vehicle called Baja. [11].

3.1.2. Suspension System

The suspension system is an essential part that keeps the tires in contact with the road, guaranteeing stability, handling, and ride comfort in all conditions. The MacPherson strut system was chosen for this Baja vehicle due to its light weight, cost-effectiveness, and outstanding shock absorption capabilities, which are vital for the demanding terrains encountered in Baja competitions. This technology comes with a number of benefits that make it highly applicable to the needs of off-road racing. First, the compact design allows smooth assimilation into the vehicle structure and optimizes space use. Such features are more important in vehicles where space and weight are very important.

The MacPherson strut system is economical as it features a straightforward design and possesses fewer components. The straightforward design not only lowers production expenses but also diminishes maintenance needs, making it a practical option for competitive situations. The system is proficient in shock absorption as well, a characteristic that greatly improves the vehicle's capacity to navigate rough and uneven landscapes. This capability guarantees that the tires maintain consistent contact with the road, thereby enhancing traction, stability, and overall control. For validating the performance of the MacPherson strut system, finite element analysis (FEA) has been conducted on suspension components under dynamic loading conditions. To test vertical loading, which impacts the obstacles such as rocks and ditches, are prevalent in an off-road setting. Besides that, the durability analysis determined the life cycles in which those same components endure repeated loading; that is why this suspension system is so reliable and has a long lifespan. The results of these simulations showed that the MacPherson strut system offers an optimal balance between strength and flexibility, allowing consistent operation on different surfaces. Dynamic field tests were carried out on actual prototypes of the suspension system to improve the theoretical investigation. The test results justified the concept, proving that the technology was indeed capable of reducing shock inputs and providing a smooth ride to ensure improved driver comfort and handling. The combination of good design principles, sophisticated simulations, and actual test proves the efficiency of the MacPherson strut system in high-performance Baja vehicles [12-13].

3.1.3 Tire Selection

Tires are essential for any vehicle, greatly impacting its traction, handling, and overall performance, especially in challenging conditions like those encountered in Baja races. For this vehicle, Kenda Bearclaw tires were chosen because of their robust construction, excellent traction capabilities, and distinctive self-cleaning tread design. They are designed to tackle the diverse and tough landscapes that Baja vehicles encounter, such as loose sand, muddy trails, and rocky paths.

Kenda Bearclaw tires have a durable design that includes enhanced sidewall support. This feature suggests that the tires offer greater resistance to punctures and abrasion. This extends their life for a long time off the roads where sharp rocks and uneven terrain are common. Aggressive tread patterns of the tires help to improve grip, which is very essential to retain control on uneven or slippery grounds. In all difficult situations, this tread design ensures that tires provide enough grip that increases vehicle stability and control.

A key advantage of Kenda Bearclaw tires is their self-cleaning capability. This guarantees reduced buildup of mud and other debris in the tread for steady performance. Such characteristics are highly crucial in competitions, especially Baja, which involve shifting from one surface to another. A clean tread means the tires can endure the grip without slippage, hence increasing speed and handling. Tires were rigorously tested for their appropriateness for Baja terrains under both simulated and actual situations. Traction tests are performed on various surfaces to get ideal grip and braking performance on sand, mud, and gravel. These tests confirm that the tires provided dependable traction for traversing rough terrains. Additionally, durability testing assessed the tire's wear rate and puncture resistance under harsh circumstances. The test findings indicated that Kenda Bearclaw tires excel in durability and dependability, giving them an optimal selection for competitive usage. Their innovative design and strong build, with proven performance, make them a key part of a high-performance Baja vehicle [14-15].

3.1.4. Braking System

An important component of vehicle design is safety, and this is where braking comes in as an element that ensures control and reliable stopping ability under varying conditions of driving. In the Baja vehicle used, vented disc brakes have been utilized to improve dissipation of heat and better braking performance. The benefits of vented disc systems over solid disc systems, especially in high-performance conditions where dependable braking performance is highly required, are considerable. These discs are designed to increase the rate of heat dissipation while braking, which in turn lowers the probability of brake fade that may be presented with long or extreme usage. This is very important for Baja racing, as most vehicles have to withstand severe conditions like steep downhill drops and sharp, forceful braking maneuvers. High-grade cast iron was used to make the vented disc brakes, a material known for high thermal stability and resistance to wear. The repeated thermal cycling does

not impair structural integrity or performance so that these brakes become a system that can keep on working consistently under intensive conditions of thermal stress and guarantees safety for the driver with vehicle reliability.
Thermal simulations were done for evaluating the performance and reliability of braking system by generating heat due to braking events. Those studies have shown that vented discs ensure perfect functionality even in the severest of conditions; thereby high-demand applications, like emergencies and long downhill stops are perfectly suitable for vented discs. The simulations thus brought out the benefits of a vented design for heat management and dissipation. The thermal behavior of the system was thus clearly understood. Field testing, which simulated the Baja competition by testing the endurance of the braking system, validated the findings from the thermal analysis. Braking performance, stopping range, and longevity of the system during extended use were assessed. The braking ability was outstanding for its stopping distance and it had the reliability that followed after several usage. Coupled with innovative design and robust material selection, coupled together with thorough validation, underscores a reason for vented disc brakes in the assurance of competitive performance and safety for this Baja vehicle [16-17].

3.1.5. Steering and Transmission

Steering and drive systems are key components of any Baja car since they make it easier to handle and also make the vehicle stronger. As such, this vehicle was provided with a rack and pinion steering system and a 4-wheel drive engine in order to enhance precision, traction, and stability in various terrain conditions. The rack and pinion turning system was chosen because it is simple, reliable, and easy to use. This makes it a great choice for the rough conditions of Baja events. This technology has a lot of useful benefits, such as exact turning response, which is important for off-road racing where there are sharp bends, quick turns, and obstacles. The small size and light weight of the system make it easier to move around and save energy. The steering system works with the 4-wheel drive transmission technology to improve control and grip on a range of surfaces. This setup of the gearbox sends power to all four wheels, which makes grip much better and sliding much less likely, especially on rough or slippery surfaces. The 4-wheel drive system is also constructed with a lot of strength to be able to handle high power needs and intense conditions created while racing in Baja. These features ensure that the vehicle remains safe and under the driver's control in case of things going wrong.
The steering and engine systems were proven to work through a series of models and field tests. For direction analysis, dynamic models were used to test efficiency in a range of terrain conditions. The results showed that the system was accurate and quick to respond when navigating, which meant that it would be easy to handle during competitions. The method for delivering power was tested under heavy loads to see how well it worked and how long it would last. Through tests, it was shown that the device could reliably send power to each wheel and keep working well for long periods of time. The results of all of these tests show that combining the rack and pinion steering system with the 4-wheel drive engine gives you a complete way to control and distribute power, which gives you a big edge in Baja races. Table 1 shows the different kinds of driving methods and the numbers that go with them.

Table 1 Different types of steering system and their respective ratios

3*Sl. No.	3*Steering mechanism	Steering System				Steering Ratio	
		2*Manual	Power steering			2*Constant	2*Variable
			Hydraulic	Electro-hydraulic	Electric		
1.	Worm and Roller	1	1	0	0	1	1
2.	Recirculating Ball screw and Nut	1	1	0	0	1	0
3.	Rack and Pinion	1	1	1	1	1	1
4.	Geroter	1	1	1	0	1	0

The optimal drivetrain for an ATV will be determined by evaluating the results of Pugh's matrix, which can be found in Table.2. The Pugh table assigns weight ratings ranging from 1 to 1.6 to customer requirements, followed by a ranking system for each drivetrain ranging from 0 to 2.

Table.2 Pugh's matrix for Transmission design selection

2*Selection criterion	2*Weightage(W)	2WD		4WD		AWD	
		Value (V)	WxV	Value (V)	WxV	Value (V)	WxV
Customer Perspective (Weight age values given on the basis of 'Importance Matrix')							
Safety	1.6	0	0	2	3.2	1	1.6
Ergonomics	1.5	-	-	-	-	-	-
Durability	1.35	0	0	2	2.7	2	2.7
Performance	1.35	-1	-1.35	2	2.7	1	1.35
Mileage	1.2	2	2.4	0	0	0	0
Cost	1.1	0	0	-1	-1.1	-1	-1.1
Aesthetics	1.0	0	0	-1	-1	-1	-1
Total	-		1.05		6.5		3.55

4.0 Conclusions

[1]. The DMADV technique provided an organized and data-driven approach to ATV development, ensuring compliance with safety, performance, and cost restrictions while adhering to competitive standards.

[2]. AISI 4130 steel was determined to be appropriate for roll cage construction in racing applications, as shown by the superior safety and structural integrity demonstrated by finite element analysis (FEA) and dynamic testing.

[3]. The adoption of MacPherson strut suspension, Kenda Bearclaw tires, vented disc brakes, and a rack-and-pinion steering system with 4-wheel drive transmission improved handling, stability, and durability over varied terrains of the ATV.

[4]. Extensive field testing and simulations confirmed all the vehicle components' performance and reliability, thus ensuring compliance with the standards of SAE Baja competition and improving competitiveness.

[5]. A study sets up a replicable framework for academic and professional teams where Lean Six Sigma principles combine with advanced engineering tools, leading to optimized product development while keeping pace with industry standards.

References

[1]. George, M. L., Rowlands, D., Price, M., & Maxey, J. (2005). *The Lean Six Sigma Pocket Toolbook*. McGraw-Hill.

[2]. Pande, P. S., Neuman, R. P., & Cavanagh, R. R. (2000). *The Six Sigma Way: How GE, Motorola, and Other Top Companies Are Honing Their Performance*. McGraw-Hill.

[3]. Stamatis, D. H. (2004). *Six Sigma Fundamentals: A Complete Guide to the System, Methods, and Tools*. Productivity Press.

[4]. Montgomery, D. C. (2019). *Design and Analysis of Experiments* (10th ed.). Wiley.

[5]. ASQ. (2023). *Lean Six Sigma and DMADV Methodologies: Applications in Engineering*. Retrieved from https://asq.org.

[6]. Huang, C.-T. (2013). Quality improvement in surveillance camera production using DMADV. Journal of Manufacturing Processes, 15(2), 139-149.

[7]. Kibbe, C. G. (2010). Designing a marine riser joint hydraulic line test fixture using DFSS and lean tools. Journal of Engineering Design, 21(3), 287-299.

[8]. Hassan, M. F. (2013). Potable water filtration unit design using DMADV. Journal of Environmental Engineering, 139(7), 934-944.

[9]. Attia, E.-A. (2016). Process improvement in hydraulic/pneumatic screen printing machines using DMADV. Journal of Manufacturing Engineering, 33(6), 511-523.
[10]. Johnson, J. A. (2010). Using DMADV to redesign student housing at the University of Miami. Journal of Business Research, 63(5), 510-518.
[11]. Budynas, R. G., & Nisbett, J. K. (2020). *Shigley's Mechanical Engineering Design* (11th ed.). McGraw-Hill Education.
[12]. Dixon, J. C. (2009). *Suspension Geometry and Computation*. Wiley.
[13]. Milliken, W. F., & Milliken, D. L. (1995). *Race Car Vehicle Dynamics*. SAE International.
[14]. Kenda Tires. (2022). *Bearclaw Tire Specifications and Performance Guide*. Retrieved from https://www.kendatire.com.
[15]. SAE International. (2022). *SAE Baja Competition Guidelines and Tire Recommendations*. Retrieved from https://www.sae.org.
[16]. Smith, C. (2004). *Engineer to Win*. Motorbooks International.
[17]. Dixon, J. C. (2009). *Suspension, Steering, and Handling*. SAE International.