# Retrofitting Electric Power Steering to Allow Steer-by-Wire Steering in Electric Buggies

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# Retrofitting Electric Power Steering to Allow Steer-by-Wire Steering in Electric Buggies

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**Abstract:** *This paper explores retrofitting Electric Power Steering (EPS) kits to enable Steer-by-Wire (SbW) steering in electric buggies. EPS systems, which use electric motors to assist steering, offer advantages over hydraulic systems, including improved efficiency and control. SbW technology, which replaces mechanical linkages with electronic controls, provides increased design flexibility and safety features. Retrofitting EPS kits for SbW steering in electric buggies can enhance range efficiency, handling, and integration with advanced driver assistance systems (ADAS). However, challenges include ensuring system reliability, developing robust control algorithms, and addressing safety concerns. Fault-tolerant design strategies and system redundancy are crucial to mitigating risks. This review covers current research and developments in EPS and SbW systems, the feasibility of retrofitting EPS kits for SbW steering, and associated challenges. Continued research is essential to fully realize the potential of SbW technology in electric buggies and other small electric vehicles.*

**Keywords:** Automotive Engineering, Electric Power Steering, Steer-by-Wire, Electric Vehicles

## 1. INTRODUCTION

The transportation industry is undergoing a significant transformation with the advent of electric vehicles (EVs) and advancements in automotive technology. Among these advancements, electric power steering (EPS) systems have emerged as a key innovation, offering improved steering performance, enhanced fuel efficiency, and greater design flexibility compared to traditional hydraulic power steering systems. EPS systems, particularly steer-by-wire (SBW) technology, are gaining traction due to their ability to eliminate mechanical linkages between the steering wheel and the wheels, thereby enabling more precise and customizable control.

This research paper explores the feasibility and process of retrofitting an electric power steering kit to enable steer-by-wire steering in electric buggies. Electric buggies, widely used in various applications ranging from recreational activities to industrial transport, present a unique opportunity to leverage SBW technology for enhanced maneuverability, safety, and user experience. By replacing conventional mechanical steering systems with EPS kits, electric buggies can achieve significant improvements in handling and control, while also opening avenues for integrating advanced driver assistance systems (ADAS) and autonomous driving capabilities.

The primary objective of this study is to design, implement, and evaluate a retrofit EPS kit for electric buggies, transforming them into SBW-enabled vehicles. The paper begins with an overview of the current state of EPS and SBW technologies, highlighting their advantages and potential applications. This is followed by a detailed description of the retrofitting process, including the selection of suitable components.

Through this research, we aim to demonstrate the viability and benefits of SBW technology in electric buggies, providing a foundation for future developments in this field. The insights gained from this study could pave the way for broader adoption of SBW systems in various types of EVs, contributing to the ongoing evolution of the transportation landscape towards more efficient, safer, and smarter vehicles.

## 2. LITERATURE REVIEW

Electric buggies, small electric-powered vehicles used for various purposes, including recreational activities and specialized industrial applications, have seen significant technological advancements in recent years. One such advancement is the transition from traditional hydraulic or mechanical steering systems to electric power steering (EPS) systems. Retrofitting EPS kits to allow steer-by-wire (SBW) steering represents a further evolution, offering numerous advantages such as improved efficiency, enhanced safety, and greater design flexibility. This literature review explores the current state of research and technological developments related to retrofitting EPS kits for SBW steering in electric buggies.

### 2.1 Electric Power Steering (EPS) Systems

EPS systems have gained popularity due to their advantages over traditional hydraulic systems, including lower energy consumption, reduced weight, and improved control. EPS systems utilize an electric motor to assist the driver in steering the vehicle, which is controlled by electronic sensors, specifically torque sensors and steering wheel angle sensors, and an electronic control unit [1].

### 2.2 Steer-by-Wire (SBW) Technology

SBW technology eliminates the mechanical connection between the steering wheel and the steering mechanism, replacing it with electronic controls. This approach offers several advantages, including increased design flexibility, enhanced safety features, and the potential for autonomous driving capabilities.

An interesting advantage that can be taken into consideration for SBW system is the ratio of steering wheel angle to front wheel angle can be designed without any mechanical constraints as mentioned by Hongyu Zheng et al [2]. Heathershaw devised a steering ratio concept that lowers vehicle understeer while increasing cornering speed [3]. This allows optimal vehicle cornering performance at different speeds thus ensuring better handling of the vehicle. Other than that, Tajima et al. presented the notion of ideal steering ratio, which is derived from a speed-independent vehicle lateral response gain and evaluated its performance using a driving simulator [4]. The ideal steering ratio will ensure yaw rate gain to be at the constant value so that the optimal cornering performance can be achieved without understeering. The ideal steering ratio will then need to be adapted at different speeds by the method of VGRS so that the yaw rate gain can be at constant value at different speeds.

The SBW system represents a steering mechanism without a traditional steering column. It relies on an electrical connection between the steering wheel and the vehicle wheels. By eliminating the direct mechanical linkage between the steering wheel and tires, the system mitigates the direct transmission of most road bumps to the steering wheel, consequently enhancing driver comfort. The SBW system necessitates two distinct control loops: one for managing the steering wheel and another for overseeing the motor drives of the road wheels. The motor drive for the road wheels is responsible for accurately translating the driver's commands to the tires, while the motor drive for the steering wheel aims to provide the driver with a responsive feel of the road surface [5].

The advantages of this system are the reduction of weight and also design flexibility. Nissan has implemented this system in the production of the Q50 and Q60 models [6]. As of 2024, commercial vehicle such as the Tesla Cybertruck is equipped with SBW [7]. Some vehicles also equipped the SBW to allow rear-wheel-steering (RWS) without any mechanical linkages such as the Rolls-Royce Spectre and the Lotus Eletre. [8,9]

The SBW system consists of two primary subsystems known as the Hand-Wheel (HW) and Road-Wheel (RW) modules, illustrated in Figure 1. The primary function of the steering HW module is to receive driver commands and convert the specified angle or torque into an electronic signal using sensors positioned on the steering HW motor shaft. This electronic signal is then transmitted through connecting wires to the RW Electronic Control Unit (ECU) to establish the appropriate command for the vehicle wheels' motor drive. The RW ECU also receives input from speed sensors, accelerometers, angle sensors, and yaw rate sensors to determine the corresponding commands to be relayed to the HW actuator [10], [11], [12].

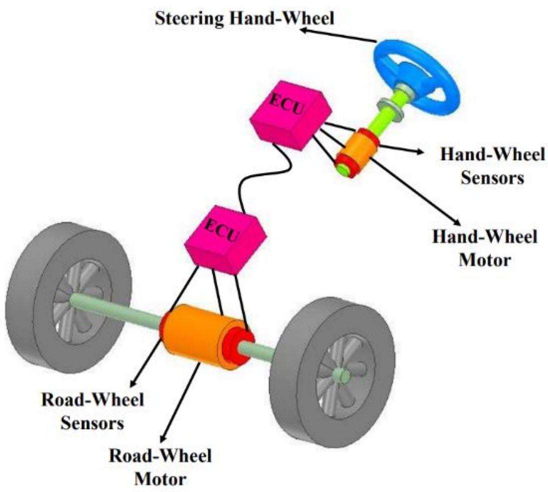


Figure 1: Steer-By-Wire Components Diagram. [13].

Retrofitting EPS kits to allow SBW steering in electric buggies represents a promising advancement in vehicle technology, offering numerous benefits in terms of efficiency, safety, and design flexibility. While significant progress has been made in understanding and developing these systems, challenges related to reliability, safety, and integration with other vehicle systems remain. Continued research and development efforts are essential to fully realize the potential of SBW technology in electric buggies and other vehicle applications.

## 3. METHODOLOGY

### 3.1 Conceptual Design of SBW Retrofit Kit

The conceptual design phase is pivotal in the development of the Steer-by-Wire (SBW) retrofit kit for electric buggies. This phase transforms abstract ideas into tangible plans, visualizing concepts, assessing feasibility, and forming the foundation for detailed design. The process ensures a clear vision, and well-defined parameters guide the subsequent development.

The initial step involves thoroughly studying the native steering system of the electric buggy. Understanding the working principles and constraints of the original system is crucial to making informed modifications. The native steering system is disassembled from the electric buggy (Figure 2) and compared side by side with the proposed Electric Power Steering (EPS) system. This comparison is essential to identify differences and potential integration challenges.

Figure 2: The 8-seater electric buggy utilized in this research.

The proposed EPS system, sourced from a Perodua Axia, includes the EPS motor and the universal joint. Figure 3 illustrates the native steering system alongside the proposed EPS system. Measurements are taken from both assemblies and the available space on the electric buggy to ensure compatibility. This data informs the development of a comprehensive Product Design Specification (PDS), as shown in Table 1, outlining the retrofit kit's function, performance, size, weight, shape, cost, environmental conditions, serviceability, and materials.

Figure 3: The native steering system put side by side with the proposed EPS system.

Table 1

| Product Design Specification of SBW With VGRS | |
|---|---|
| Function | Allows the control of the steering system via Steer-by-Wire with redundant controls if the system malfunctions. |
| Performance | Strength: Able to withstand the equivalent maximum stress with minimum deformation when manoeuvring the steering wheel. |
| Size | Volume: Length, 730 mm x Height, 200 mm x Width, 250 mm<br>Weight: Below 20 kg.<br>Thickness: 3 mm mild steel plate for bracketry.<br>Shape: Geometry near identical to the native steering system. |
| Cost | Raw material cost: RM1200 which includes the cost for the EPS, mild steel, paint and accessories needed to complete the retrofit kit. |
| Environment | Presence of moisture<br>Low-medium heat sources<br>Exposure to dirt and dust |
| Serviceability | Modularity: Every part of the retrofit kit can be disassembled, assembled and also replaced, thus allowing maintenance. |
| Materials | Mild Steel<br>Acrylonitrile Styrene Acrylate (ASA) |

Prior to the conceptual design process, constraints are established to minimize design flaws. These constraints include:

- A balanced center of gravity to accommodate the cantilever design of the long steering shaft.
- Bearing blocks to support the long steering shaft and ensure concentric turning.
- Utilization of the original mounting points to minimize chassis modifications.
- A modular design to facilitate maintenance of the SBW retrofit kit.

The resultant conceptual design is depicted in Figures 4 and 5, showing the SBW retrofit kit from various angles. Key elements of the design include:

- Positioning the EPS near the mounting point of the retrofit kit to reduce the moment at the steering wheel.
- Making the steering wheel detachable from the EPS shaft via a boss kit to simulate the SBW system.
- Ensuring the retrofit kit is modular, allowing disassembly or part replacement as needed.
- Equipping the SBW retrofit system with an encoder to measure the rotation of the steering wheel angle accurately.

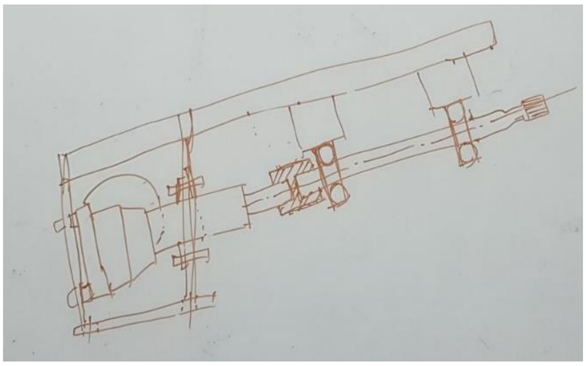

Figure 4: The conceptual design of the SBW from side view.

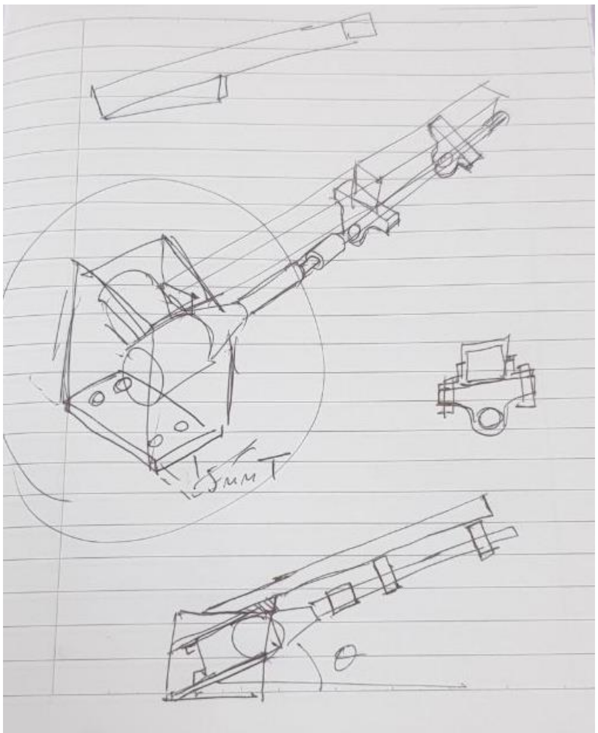

Figure 5: The conceptual design of the SBW from multiple angles.

The conceptual design phase culminates in a well-defined plan for the SBW retrofit kit, laying the groundwork for detailed design, implementation, and testing. This approach ensures the retrofit kit meets the desired specifications, performs reliably, and integrates seamlessly with the existing electric buggy architecture.

### 3.2 Detailed Design of SBW Retrofit Kit

The detailed design phase is a critical step in the development of the Steer-by-Wire (SBW) retrofit kit for electric buggies, refining conceptual ideas into precise and actionable plans. This phase ensures technical accuracy, comprehensive documentation, and consideration of manufacturability and regulatory compliance, ultimately serving as a blueprint for the construction or production of the retrofit kit.

Building on the conceptual design, the detailed design process involves refining all design concepts to align with their respective dimensions, including the material thickness and the angle of the steering shaft. This precision ensures that every component fits perfectly within the existing structure of the electric buggy and meets the required performance standards.

Using Catia V5R21, a robust computer-aided design (CAD) software, the detailed design of the SBW retrofit kit is developed (Figure 9). This software allows for meticulous modeling of each component, ensuring that all dimensions and specifications are accurately represented. The detailed design includes:

- Exact dimensions of all components, ensuring compatibility and ease of integration with the existing buggy structure.
- Specification of material thickness, particularly the 3 mm mild steel plate used for bracketry, to ensure structural integrity and durability.
- Precise angles and alignment of the steering shaft to ensure optimal steering performance and reliability.
- Detailed geometry that closely matches the native steering system to minimize the need for extensive modifications.

Before finalizing the detailed design, each component undergoes rigorous structural analysis to verify its strength and durability under various operational conditions. This analysis ensures that the retrofit kit can withstand the maximum stresses encountered during steering maneuvers with minimal deformation. Adjustments are made based on the results of the structural analysis to enhance the design's robustness and reliability. This iterative process ensures that the final detailed design meets all performance and safety standards.

The result of the detailed design phase is a comprehensive set of documents, including detailed drawings, material specifications, and assembly instructions. These documents provide all the necessary information for the fabrication process, ensuring that the EPS retrofit kit is manufactured accurately and efficiently.

The detailed design also considers manufacturability and regulatory compliance. By refining cost estimates and ensuring that all components and processes adhere to relevant standards and regulations, the detailed design phase lays the groundwork for successful production and deployment of the SBW retrofit kit.

The detailed design of the SBW retrofit kit is a precise and thorough blueprint that guides the fabrication process. It ensures that the retrofit kit is manufactured to exact specifications, performs reliably, and integrates seamlessly with the electric buggy. This phase marks the transition from design to production, ensuring that the envisioned improvements in steering performance and user experience are realized in the final product.

Figure 6 illustrates the comprehensive detailed design, showcasing the meticulous attention to detail that defines this phase of the methodology. The completed detailed design is now ready for fabrication, leading to the next stages of testing and implementation.

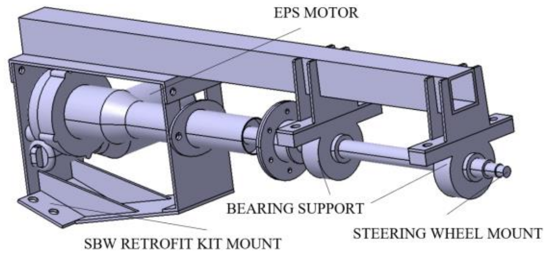


Figure 6: The detailed design of the SBW retrofit kit.

### 3.3 Structural Analysis of SBW Design

The structural analysis phase is essential to ensure that the Steer-by-Wire (SBW) retrofit kit can withstand the loads and deformations induced by steering maneuvers and the torque from the Electric Power Steering (EPS) system. This analysis leverages the capabilities of ANSYS 2023 to validate the robustness and reliability of the detailed design developed in the previous phase.

The detailed design created in Catia V5R21 is exported in .stp format and imported into ANSYS 2023. This allows for an accurate representation of the geometry and dimensions of the SBW retrofit kit. The chosen material for this analysis is structural steel, which is commonly used in fabrication due to its strength and durability.

To prepare for the structural analysis, the geometry is meshed with a resolution number of 5. This resolution is selected to balance the total number of elements within the allowable limit of the ANSYS student version while maximizing the mesh's detail and quality. The mesh model is depicted in Figure 7, with quality metrics shown in Table 2 and statistics in Table 3. The skewness average of 0.48377 indicates a very good quality mesh according to ANSYS recommendations (Figure 8). The mesh consists of 54,063 nodes and 21,855 elements, ensuring a detailed and accurate analysis.

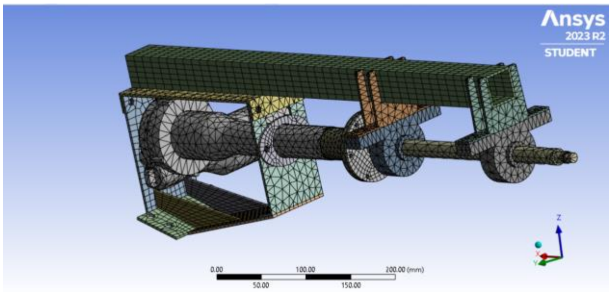


Figure 7: The SBW retrofit kit mesh model.

Table 2: The mesh model quality of the SBW retrofit kit design.

| Quality | |
|---|---|
| Check Mesh Quality | Yes, Errors |
| Error Limits | Aggressive Mechanical |
| Target Element Quality | Default (5.e-002) |
| Smoothing | Medium |
| Mesh Metric | Skewness |
| Min | 1.3073e-010 |
| Max | 0.99998 |
| Average | 0.48377 |
| Standard Deviation | 0.23774 |


Figure 8: The skewness mesh metrics spectrum as recommended by ANSYS. (Courtesy of ANSYS)

Table 3: The statistics of the mesh model.

| Statistics | |
|---|---|
| Nodes | 54063 |
| Elements | 21855 |
| Show Detailed Statistics | Yes |
| Corner Nodes | 11208 |
| Mid Nodes | 42855 |
| Solid Elements | 21855 |
| Tet10 | 19606 |
| Hex20 | 2241 |
| Wedge15 | 8 |

The force required to turn the steering wheel is measured at 15 N at a diameter of 350 mm, resulting in a moment of 2625 N.mm in the counterclockwise direction at the steering shaft. This moment, along with the fixed support at the base of the SBW retrofit kit, is established in ANSYS as shown in Figure 9. The analysis is repeated for the clockwise direction to account for the bi-directional nature of steering.

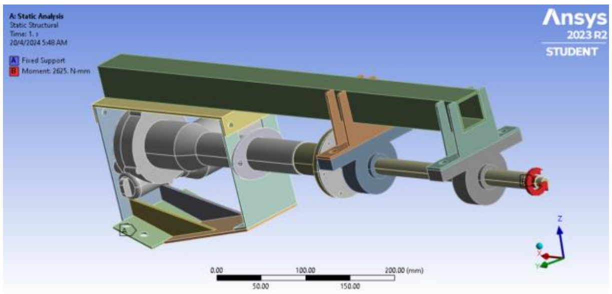


Figure 9: The SBW retrofit kit design in ANSYS with the fixed support and moment in counterclockwise direction established.

Additional analyses are conducted for different loading scenarios, including side-to-side, up, down, and in & out loads, to ensure the design's robustness under various conditions. These loads are applied at the end of the shaft, as illustrated in Figure 10.

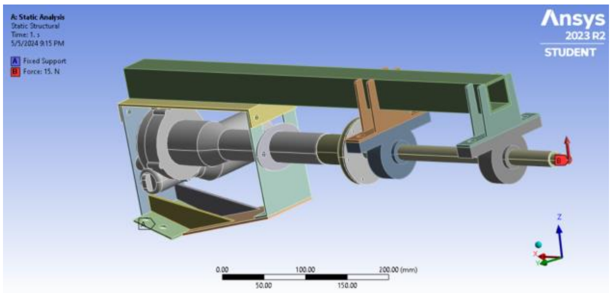


Figure 10: The SBW retrofit kit design in ANSYS with the fixed support and force in upwards direction established.

The structural analysis in ANSYS involves evaluating the stress distribution, deformation, and overall structural integrity of the SBW retrofit kit under the applied loads. This step is crucial for identifying potential weaknesses or areas of excessive stress that may require design modifications.

By thoroughly analyzing these aspects, it can be confirmed that the SBW retrofit kit design can withstand the operational loads without compromising safety or performance. The results from ANSYS provide valuable insights into the strength and durability of the design, ensuring that it meets the required standards for real-world application.

The structural analysis phase validates the detailed design of the SBW retrofit kit, confirming its capability to endure the mechanical loads encountered during steering. This analysis ensures that the design is robust, reliable, and ready for the fabrication process. The insights gained from this phase guide any necessary adjustments to optimize the design further, ensuring a successful implementation of the SBW retrofit kit in electric buggies.

### 3.4 Fabrication of SBW Prototype

The prototype fabrication phase is a pivotal stage in product development, where detailed design plans are transformed into physical models. This phase involves the precise manufacturing and assembly of components to create a working prototype of the Steer-by-Wire (SBW) retrofit kit, following the specifications outlined in the detailed design.

The fabrication process begins with the preparation of raw materials. The primary material used is mild steel with a thickness of 3 mm, chosen for its strength and ease of fabrication. The raw materials are cut into specific sizes according to the dimensions provided in the detailed design.

The top beam is cut to size using a grinder, ensuring precise measurements. The remaining brackетry components are cut using a waterjet cutting machine (Figure 11). This process involves converting the detailed design file into .dxf format, which is compatible with the cutting machine. The design file is then transferred to the machine, which cuts the components with high precision.

Figure 11: The bracketry of the SBW retrofit kit after being committed to a waterjet cutting machine.

Once the components are cut to size, they are assembled using both welding and fasteners, depending on the requirement for permanent or temporary joints:

- Welding Process: Components that require permanent joints are assembled using welding (Figure 12). This ensures a strong and durable connection between the parts.
- Fasteners: Bolts and nuts are used where disassembly might be necessary in the future (Figure 13). All fasteners are secured with thread lock to prevent loosening due to vibrations during operation.

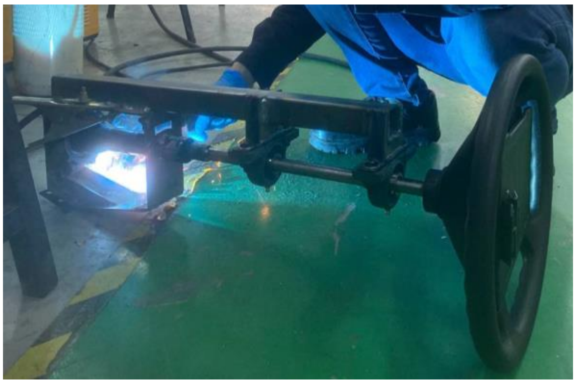

Figure 12: The SBW retrofit kit during welding process.

Figure 13: The SBW retrofit kit being assembled with thread lock to ensure they sustain any vibrations.

After assembly, the fabricated design undergoes a cleaning process to remove any debris, oil, or residues from the fabrication process. The cleaned prototype is then painted to prevent rust and corrosion, ensuring the longevity of the SBW retrofit kit.

The final step in the fabrication process is the installation of the SBW retrofit kit onto the electric buggy. This step involves:

- Carefully mounting the retrofit kit onto the buggy, ensuring all components are securely fastened.
- Verifying the alignment and fit of the retrofit kit with the existing structure of the buggy.
- Conducting initial tests to check the functionality of the SBW system, ensuring that the steering operates smoothly and responds accurately to inputs.

The prototype fabrication phase concludes with a fully assembled and functional SBW retrofit kit, ready for further testing and validation. This prototype serves as a tangible model that can be evaluated for performance, reliability, and potential improvements. The successful completion of this phase is crucial for advancing to the testing and refinement stages of product development.

## 4. STRUCTURAL ANALYSIS RESULTS

Preliminary structural analysis of the SBW retrofit kit yielded promising results, confirming the design's safety and robustness for real-world application. The analysis focused on assessing the deformation, stress, and strain experienced by the retrofit kit under various loading conditions induced by the steering maneuvers and torque from the EPS motor.

### 4.1 Deformation Analysis

The maximum total deformation of the SBW retrofit kit was found to be 0.011698 mm, as illustrated in Figure 14. This minimal deformation indicates that the structure maintains its integrity and does not experience significant distortion under operational loads. The low deformation value ensures that the steering system remains precise and responsive, crucial for effective vehicle control.

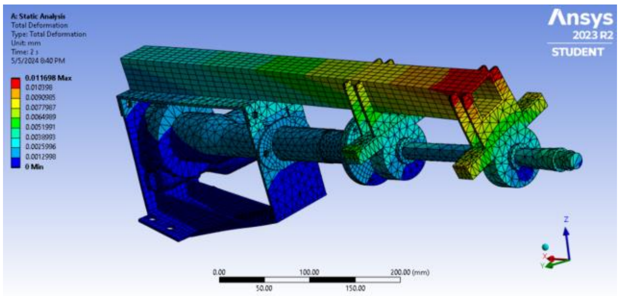


Figure 14: Maximum total deformation of the SBW retrofit kit.

### 4.2 Stress Analysis

The equivalent stress analysis revealed a maximum stress value of 8.3154 MPa, shown in Figure 15. This value is significantly below the tensile yield stress of the structural steel used, which is 250 MPa. The resulting safety factor of 30.065, calculated by dividing the material's yield stress by the maximum induced stress, demonstrates a substantial margin of safety. This high safety factor confirms that the retrofit kit can comfortably withstand the operational stresses without risk of failure.

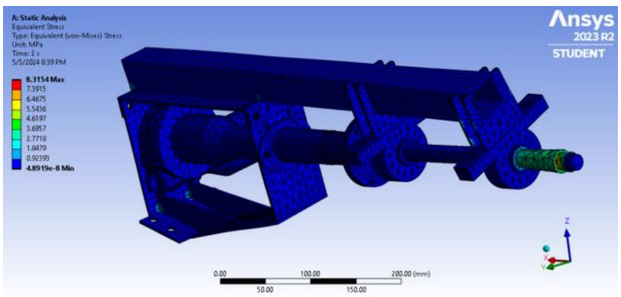


Figure 15: The equivalent stress of the SBW retrofit kit.

### 4.3 Strain Analysis

The analysis of the equivalent total strain showed a maximum value of 4.3425e-5 mm/mm, as depicted in Figure 16. This very low strain value suggests that the material experiences minimal elongation under load, further corroborating the design's ability to maintain structural integrity and resist deformation.

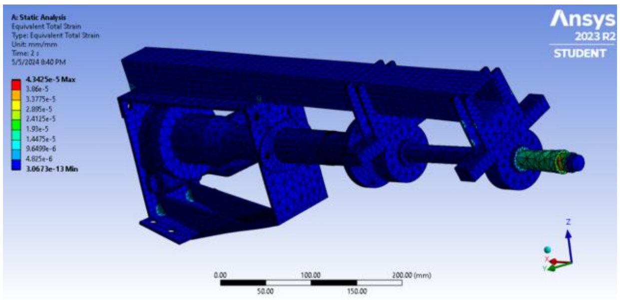


Figure 16: The maximum value of equivalent total strain of the SBW retrofit kit.

### 4.4 Fabrication and Installation

Following the positive outcomes of the structural analysis, the fabrication of the SBW retrofit kit was initiated. The components were accurately cut using a combination of grinding and waterjet cutting machines and assembled using welding and fasteners. The use of thread lock on all bolts and nuts ensured stability and resistance to vibrations during operation.

The fabricated SBW retrofit kit was then installed on an electric buggy (Figure 17). The installation process involved securely mounting the kit onto the buggy and verifying alignment and fit. Initial functional tests were conducted by temporarily applying voltage to the EPS motor, resulting in successful operation of the steering shaft in both clockwise and counterclockwise directions.

Figure 17: The SBW retrofit kit installed on the buggy.

The SBW retrofit kit is successfully fabricated and installed on the electric buggy as shown in Figure 24. It is then tested by temporarily applying voltage to EPS motor to turn the steering shaft clockwise and counterclockwise directions.

The results from the structural analysis and the subsequent fabrication and installation processes demonstrate the viability of retrofitting electric buggies with an EPS kit to enable SBW steering. The high safety factor indicates a robust design capable of handling the mechanical loads associated with steering operations. The minimal deformation and strain values suggest that the retrofit kit will perform reliably under typical usage conditions.

The successful fabrication and installation of the SBW retrofit kit highlights the effectiveness of the detailed design and structural analysis phases in guiding the development process. The use of precise cutting techniques and careful assembly ensured that the prototype met the design specifications and performed as expected during initial tests.

## 5. CONCLUSION

The transition to electric power steering (EPS) systems and the subsequent retrofitting to enable steer-by-wire (SBW) steering in electric buggies signifies a significant technological leap forward. This evolution promises to enhance vehicle efficiency, safety, and design flexibility, crucial for the diverse applications of electric buggies. The literature reveals substantial progress in understanding the technical underpinnings and benefits of EPS and SBW systems, including improved fuel efficiency, better handling, and potential integration with advanced driver assistance systems (ADAS).

Preliminary results from the structural analysis of the SBW retrofit kit indicate that the design is robust and capable of withstanding the anticipated loads and deformations, thus validating the feasibility of the proposed approach. The SBW retrofit kit is also successfully fabricated and installed on the electric buggy.

Despite the promising advantages, several challenges remain, particularly regarding system reliability, robust control algorithm development, and addressing safety concerns. Fault-tolerant design strategies and system redundancy are essential to mitigate the risks associated with electronic failures and loss of steering control. Furthermore, integrating SBW systems with other vehicle technologies, such as ADAS and autonomous driving features, adds complexity but also unlocks new functionalities like automated parking and lane-keeping assistance.

Continued research and development efforts are vital to overcoming these challenges. Focusing on enhancing system reliability, ensuring fail-safe operations, and standardizing communication protocols for integration will be key to fully realizing the potential of SBW technology in electric buggies. As the automotive industry progresses toward more advanced and automated vehicles, the successful implementation of retrofitted EPS kits for SBW steering will play a pivotal role in shaping the future of electric buggies and other small electric vehicles.

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