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DESIGN AND FABRICATION OF BRAKING SYSTEM FOR BATTERY ELECTRIC VEHICLE

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Abstract

This research paper presents the design, fabrication, and testing of a vacuum pump holder and braking circuit for a Battery Electric Vehicle (BEV). The vacuum pump holder was meticulously designed to be lightweight, cost-effective, and durable, utilizing a compact triangular shape. Finite element analysis confirmed the design's robustness, with all stress and displacement values within acceptable limits. The braking circuit assembly and manual bleeding demonstrated excellent performance, validating the design's effectiveness. The study outlines the use of conventional manufacturing processes and material selection, resulting in a cost-efficient fabrication using Al alloy T6 6061. Future work includes exploring advanced manufacturing techniques, integrating smart systems, conducting dynamic testing, and optimizing heat management. The research highlights the successful application of engineering principles and practical techniques, contributing to the BEV's overall reliability and safety. These findings provide a strong foundation for further innovation and improvement of BEV components.

Keywords: BEV, EV, Braking system, Hydraulics

I. INTRODUCTION

The world continues to grapple with the persistent challenge of global warming, compounded by environmental pollution which poses a significant threat to human health. A key contributor to this problem is the exhaust gases emitted by conventional internal combustion engine vehicles. Over the years, the global vehicle count is projected to reach approximately 1.8 billion, and the continuous rise in oil prices underscores the urgency of adopting sustainable and alternative mobility technologies. Plug-in and hybrid vehicles are promising alternatives that hold substantial potential for mitigating these issues. This project focuses on the research and development of a student-designed electric car. Electric vehicles (EVs) are gaining traction worldwide due to their eco-friendly nature and zero emissions. Battery Electric Vehicle (BEV) is an urban concept car that leverages compact geographical area, making it an ideal location for the adoption of electric cars. The continuous escalation of oil prices and the intensifying impact of global warming have necessitated the adoption of alternative mobility technologies. Electric vehicles (EVs) present a compelling alternative to conventional internal combustion engine vehicles [1].

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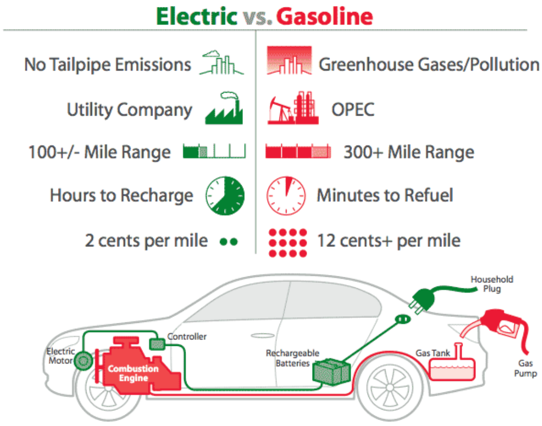

Figure 1: Electric v/s Gasoline [2]

Atmospheric pollution from exhaust gases emitted by internal combustion engines, coupled with the constant rise in oil prices, has paved the way for the adoption of electric cars globally. Electric vehicles offer significant advantages over conventional internal combustion engine vehicles, including lower operating and maintenance costs, as well as higher efficiency as shown in figure 1. Electric cars centralize pollution sources to power stations that generate electricity, whereas conventional cars distribute pollution, making them less efficient. Although the limited range of electric cars has been a discouraging factor, continuous advancements are being made to enhance their range. Numerous automakers, such as Honda, Toyota, Mercedes-Benz, BMW, and Tesla, have already commenced manufacturing electric street and sports cars as shown in figure 2 [3].

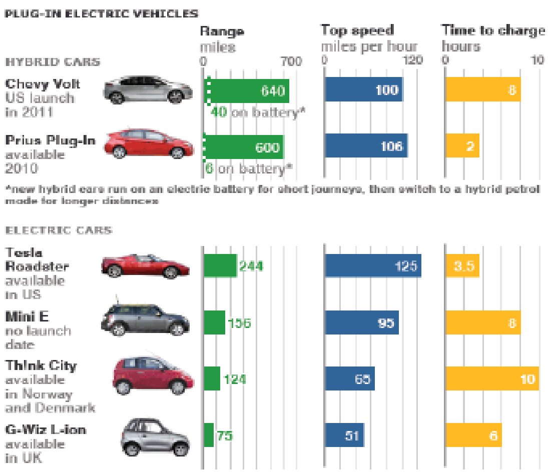

Figure 2: Different plug-in electric cars [3]

An electric car is a vehicle powered by an electric motor, utilizing electrical energy stored in devices such as batteries or capacitors. A plug-in electric car is recharged using an external electricity source. Electric vehicles, including hybrid and plug-in electric cars, are poised to play a crucial role in the future mobility landscape [5]. This project aims to challenge students to design and stimulate their creativity, fostering innovative ideas and solutions to bring first plug-in electric car to life. The concept of the Battery Electric Vehicle (BEV) revolves around generating clean energy from lithium-ion battery packs. The electrical power is directed to the motor through a controller, which in turn drives the rear differential. This paper includes detailed explanations on design, engineering, manufacturing and testing of the braking system for Battery Electric Vehicle.

II. BRAKING SYSTEM OVERVIEW

The braking system is one of the most crucial components of an automobile, essential for ensuring safe and consistent stopping. The braking mechanism functions to decelerate and halt the vehicle within the shortest possible distance by converting the vehicle's kinetic energy into heat energy through friction between moving and stationary parts. Automobiles are equipped with two main braking systems: the service brake system, which is the primary system responsible for stopping the vehicle, and the parking brake system, which serves as a secondary system that typically uses the service brake components to keep the vehicle stationary when parked [13][25]. This study focuses on the primary braking system of Battery Electric Vehicles (BEVs).

Functions of Brakes:

- To decelerate or stop and control the motion of a moving vehicle
- To park the vehicle and keep it stationary in the absence of the driver

Requirements of Automobile Brakes:

- Efficient operation regardless of road condition and quality
- Brake pedal effort must be within the convenient capacity of the driver
- Reliability, unaffected by heat, water, and dust from the surroundings
- Lightweight, easy to maintain and adjust, and long-lasting
- Minimal noise and vibration generation during braking, with a provision for a secondary braking system

Stopping Distance: The minimum distance required to bring a vehicle to a complete stop after the brakes are applied. The stopping distance is influenced by:

- The coefficient of friction between the tire and road surface
- Tire tread design and tire inflation
- The nature of the road surface

This paper details the design and operation of the braking circuit for Battery Electric Vehicle (BEV). It includes an extensive literature review and research on the braking circuits and functioning of a conventional braking circuit. Furthermore, the roles and specifications of each component within the braking system are thoroughly explained.

A. Conventional Braking Circuit

The conventional braking circuit comprises essential components such as a check valve, brake booster, master cylinder, T-splitter, brake callipers, and proportional valve. It consists of two sub-circuits: the hydraulic circuit and the vacuum circuit. The engine intake manifold supplies vacuum to the brake booster, and the vacuum check valve ensures that vacuum does not escape from the circuit when the brakes are not in use or the vehicle is stationary. When the driver applies force to the brake pedal, the pressure difference on either side of the brake booster's diaphragm minimizes the effort required to move the diaphragm. This diaphragm is linked to the piston of the master cylinder, which pressurizes the hydraulic fluid. The fluid transfers motion and amplifies force through the proportional valve, tubing, T-splitter, and brake hose to the brake callipers. This force generates friction between the brake pads and the rotor, slowing or stopping the vehicle by bringing them into contact. When the driver releases the brake pedal, the master cylinder and brake pads retract, as the incompressible brake fluid acts as a linkage mechanism between the brake pedal and pads [18][25].

B. BEV's Braking Circuit

The braking circuit of Battery Electric Vehicle (BEV) includes a vacuum pump, vacuum tank, vacuum switch, check valve, proportional valve, brake booster, master cylinder, T-splitter, battery, and four brake callipers. The braking circuit comprises three sub-circuits: the hydraulic circuit, vacuum circuit, and electrical circuit. The vacuum circuit manages the vacuum in the power brake system. The vacuum pump generates vacuum, which is stored in the vacuum tank and supplied to the brake booster to reduce braking effort. A vacuum switch controls the vacuum pump to maintain the necessary vacuum level. The vacuum check valve prevents vacuum escape when the brakes are not in use or the vehicle is stationary. When the driver applies force to the brake pedal, the pressure difference on either side of the brake booster's diaphragm minimizes the effort required to move the diaphragm. This diaphragm is linked to the master cylinder's piston, which pressurizes the hydraulic fluid, transferring motion and amplifying force through the proportional valve, tubing, T-splitter, and brake hose to the brake callipers. This force generates friction between the brake pads and rotor, decelerating or stopping the vehicle. When the driver releases the brake pedal, the master cylinder and brake pads retract, with the incompressible brake fluid acting as a linkage mechanism. The vacuum pump and switch are powered by the battery [21][25].

Initial drafts of the BEV's braking circuit were created on paper, followed by 2D CAD drawings and a 3D CAD model as shown in figure 3. This process provided a comprehensive overview of the braking system's functionality and assisted in logging component inventories and procuring missing components. The first step involved identifying and obtaining the missing components, considering the requirements and compatibility with the braking system.

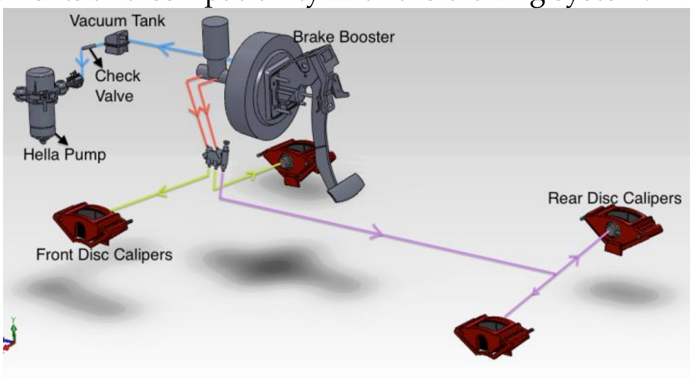

Figure 3: BEV's braking circuit CAD model

C. BEV's Hydraulic Braking System

The hydraulic braking system, which actuates brakes through hydraulic pressure, is a widely used and efficient mechanism in automobiles. The BEV features a hydraulic brake system due to its simplicity, efficiency, reduced wear on brake linings, and uniform braking action across all brakes. The primary braking system in the BEV is operated by a foot pedal that acts on all wheels, each

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equipped with external contacting or disc brakes. This system utilizes brake fluid to transfer pressure from the foot pedal to the actual braking mechanism. Hydraulic brakes operate based on Pascal's law, which states that "pressure at a point in a fluid is equal in all directions in space." This principle ensures that when pressure is applied to the fluid, it travels equally in all directions, efficiently transferring both motion and force to provide uniform braking action [2].

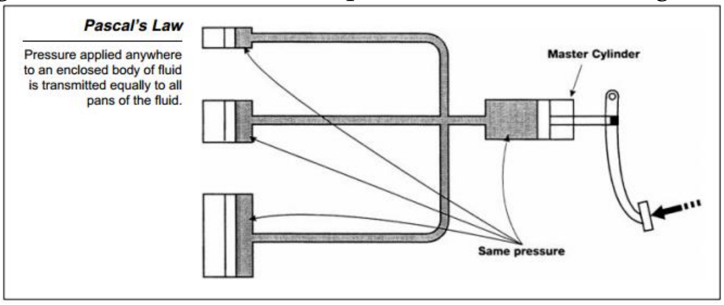

Figure 4: Pascal's law [2]

The components of BEV's Hydraulic Braking System:

1. **Vacuum Brake Booster**: To reduce the pedal force required to brake the car, most vehicles use power brakes. The vacuum brake booster generates high braking force with minimal effort on the brake pedal [2]. It consists of a cylinder with a tight-fitting diaphragm connected to the master cylinder piston. Vacuum is created on one side of the diaphragm and atmospheric pressure on the other side. This pressure difference generates a force on the diaphragm, assisting in pushing the piston into the master cylinder and thereby reducing the braking effort. Typically, the vacuum is supplied from the engine intake manifold in conventional cars. However, in BEVs, a vacuum pump is used to produce the required vacuum for the vacuum booster. In BEVs, the vacuum brake booster is mounted on the firewall, with the master cylinder at the front.

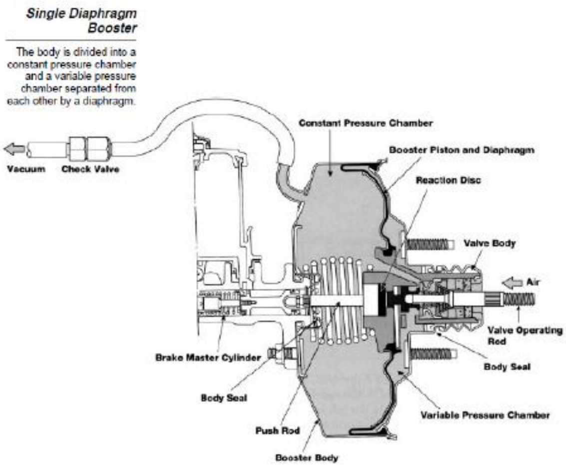

Figure 5: Brake booster [2]

2. **Master Cylinder**: The master cylinder is the core component of the hydraulic braking system. The BEV features a tandem master cylinder, which is considered safer than the conventional master cylinder. In a tandem master cylinder design, if one half of the hydraulic system fails, the remaining half retains enough braking capacity to stop the vehicle. Its primary function is

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to convert the force exerted on the brake pedal into hydraulic pressure to apply the brakes. The master cylinder consists of a brake fluid reservoir, primary and secondary pistons, rubber piston cups, springs, and feed holes. When the driver presses the pedal, it moves a pair of pistons that exert force against the fluid within the master cylinder bore. Given that brake fluid is incompressible, it acts as a linkage between the master cylinder pistons and the brake callipers, effectively transferring the force to the brakes [2][25].

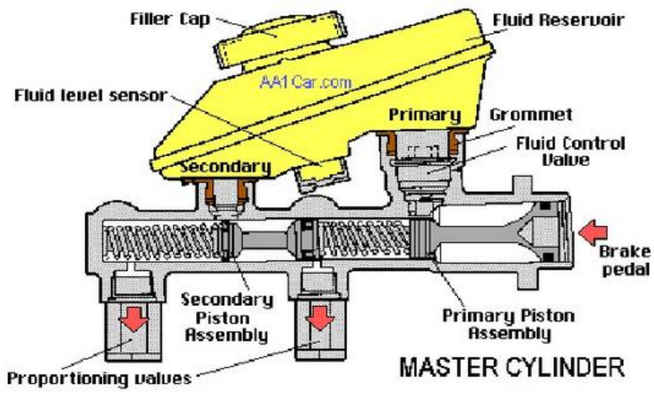

Figure 6: Tandem master cylinder [2]

3. **Disc Brakes:** Disc brakes consist of a rotating disc and two friction pads, which are actuated by the hydraulic braking system. The disc is attached to the rotor hub with the help of bolts, while the caliper is solidly bolted to the steering knuckle. The caliper is cast in one piece and includes a piston and two brake pads. When the brakes are applied, the pistons are hydraulically operated, causing the friction pads to apply equal and opposite forces on both sides of the disc to stop the vehicle [18]. In BEVs, all wheels are equipped with disc brakes.

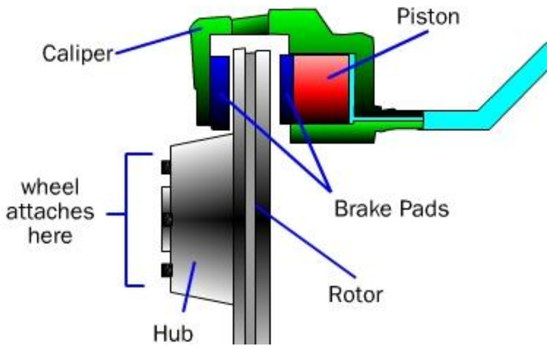

Figure 7: Disc brake [25]

Advantages of Disc Brakes:

- Disc brakes exhibit resistance to wear, as they remain cool even after repeated brake applications.
- Brake pads are easily replaceable and disposable.
- The condition of brake pads can be checked without dismantling the brake system.

4. **Proportional Valve:** The proportional valve is used to adjust the rate of increase in rear brake line pressure relative to the increase in front brake line pressure. During sudden high-pressure

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braking actions, rear wheels may tend to lock before the front wheels, compromising safety and performance. The proportional valve plays a crucial role in preventing this. When the pressure exceeds a certain threshold, known as the split point, greater pressure is applied to the front wheels, while the pressure on the rear wheels remains constant [21]. The BEV is equipped with a single Wildwood manually adjustable proportional valve with two input ports and three output ports. The two input ports supply brake fluid from the master cylinder to the front and rear wheel brakes, respectively. There are two individual output ports for the front wheel brakes and one output port for the rear wheel brakes.

Figure 8: Proportional valve

5. **Vacuum Pump:** The vacuum pump is used to generate vacuum for the vacuum booster. Generally, vacuum pumps are like compressors, with the exception that the outlet is at atmospheric pressure. A vacuum pump converts the input mechanical energy of the rotor into pneumatic energy by removing the air within a closed space [25]. The BEV is equipped with an electric vacuum pump, model UP30, manufactured by Hella.

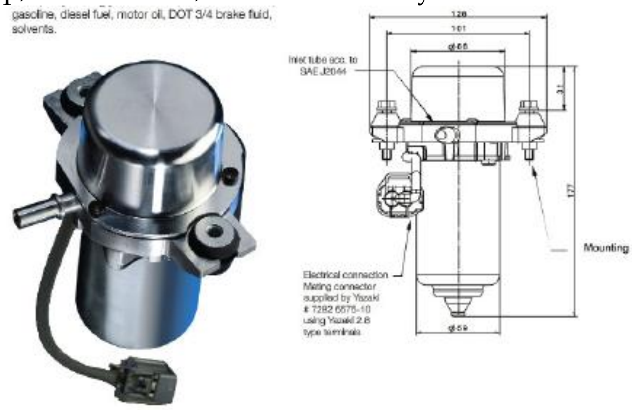

Figure 9: Vacuum pump [26]

6. **Brake Fluid:** Brake fluid is an incompressible fluid which acts as a linkage between master cylinder and brake pads. Brake fluid is precisely distilled so that it can sustain within the environment of high heat, high pressure and moving components. The Society of automobile engineers and department of transportation has established standards for brake fluids. Fluids used in brake applications must satisfy some requirements like it should be viscous, should have a high boiling point and act as a lubricant for moving components. Brake fluid is stored in

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the reservoir and fills the master cylinder bore through vents.

There are two different types of brake fluids that are used in automobile brakes, each of which has its specific attribute and drawbacks.

- Poly-glycol is most commonly used brake fluid in automobiles today & has appearance of amber color. Poly-glycol is highly viscous in nature & a lubricant, which makes it suitable for brake application. One major disadvantage of poly-glycol is that it is hygroscopic in nature, which means it tends to attract water. Water absorption by the brake fluid decreases it boiling point and causes it to evaporate easily. Moisture in the hydraulic circuit would also corrode metal components resulting in leakage.
- Silicon is un-hygroscopic in nature, virtually has no rust and corrosion problems, and has high boiling point and purple in appearance. But silicon has greater affinity towards air, which makes bleeding of hydraulic circuit a complicated task [21][25].

Figure 10: Brake fluid

DOT 4, a poly-glycol based brake fluid, was chosen due to its status as the current mainstream brake fluid. For the BEV, being a passenger car, the hygroscopic nature of the fluid is typically not an issue, as the brakes are generally not subjected to extreme usage. DOT 4 fluid provides an upgrade over DOT 3 fluid by offering a higher boiling point, thus enhancing performance.

7. **Rubber hose:** Flexible rubber hoses for brake caliper connections are essential due to the pivoting nature of the front wheels while steering and the independent deflection of each wheel in an independent suspension system. Each wheel is served by its individual hose. Rubber hoses are also used to make connections between the vacuum pump and tank, brake booster, and vacuum switch. These hoses are typically made of rayon, which is rubber reinforced with woven fabric, and the size of the hoses is determined by their internal diameter. The primary function of the fabric is to restrict the expansion of the hose under pressure [25]. The inner layer of the rubber comes into contact with the brake fluid, while two layers of fabric are sandwiched between three layers of rubber, providing protection to the fabric layers. The outermost rubber layer of the hose is susceptible to degradation due to UV light and moisture. Rubber hoses for brake caliper connections were included as components when the brake calipers were procured. A rubber hose with a 9.5 mm internal diameter was selected for vacuum circuit connections.

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Figure 11: Brake hose

8. **Brake Lines (Tubing):** Brake lines, also known as tubing, are routed to the brake calipers along the chassis, suspension, and axles. They are typically made of double-walled steel or copper and coated with a material to prevent corrosion. Their sizes are classified by the outer diameter. When the brake pedal is applied, it moves fluid from the master cylinder to the brake calipers, causing them to clamp down on the brake rotors to slow the vehicle. The fluid is carried through the brake lines, making them a critical component of the braking system. Various types of connectors, such as male-female connectors and a female T-splitter, are used to join the tubing to different brake components. Metal clips with rubber insulation hold the tubing tightly in place to prevent slacking and vibration. Copper brake lines with an outer diameter of 5 mm were used for testing the braking circuit. Although these copper brake lines do not have sufficient burst strength and durability for long-term use, they are relatively inexpensive and suitable for testing purposes.

Figure 12: Brake lines.

9. **Vacuum tank:** Modern car models are equipped with a separate vacuum tank or reservoir to ensure consistent braking effort. The vacuum tank supplies vacuum to the brake booster, reducing the effort required for braking. The vacuum tank has a vacuum capacity of 30 in. Hg.

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Figure 13: Vacuum tank

10. **Vacuum Switch:** The vacuum switch functions as a relay, controlling the vacuum pump to switch on and off within a specified pressure range [18]. The BEV utilizes an electro-mechanical vacuum switch with an adjustable pressure range that converts a vacuum signal into an electrical signal. When the vacuum level falls below 18 in. Hg, the vacuum switch activates the vacuum pump to generate the necessary vacuum, as 18 in. Hg is the minimum vacuum level required for proper functioning of power brakes. Voit's vacuum switch was selected due to its wide adjustable range of 13 to 29 in. Hg, various wiring options (normally open or closed configuration), and its compact, reliable, and cost-effective design.

Figure 14: Vacuum switch

11. **Check Valve:** The check valve is designed to maintain residual vacuum in the brake system when the brakes are not in use while driving. This one-way valve prevents the vacuum from escaping the vacuum tank and, consequently, the brake booster. When the vacuum pump is off, the check valve moves against its seat to prevent air from entering the vacuum tank and, ultimately, the brake booster. The check valve is a critical component of the braking system. In the BEV's circuit, the check valve is an integral part of the vacuum tank.

12. **Flared Fittings & Connections:** Flare fittings are used to connect the ends of brake lines to other brake components, such as proportional valves or brake calipers. Flares are utilized for high-pressure applications, such as brakes. There are two main types of flares used in automobiles: the SAE type 45° double flare and the ISO flare, also known as the bubble flare.

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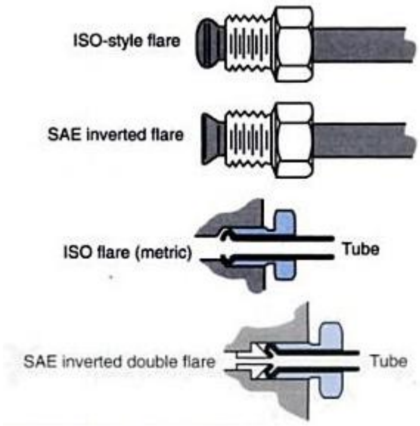

Figure 15: Flare fitting [13]

The selection of the type of flare and flare fittings was guided by the proportional valve, which already came with specific male and female fittings. The size and angle of the male fittings of the proportional valve were determined to be M10 x 1 mm with a 45° angle, while the female fitting had a 42° angle. According to SAE standards, a 45° flare was recommended for an interference fit to achieve positive sealing. Consequently, 45° inverted flare fittings were procured for the rest of the brake line connections, along with a T-splitter with the same fitting specification. Brake lines always have double flare fittings because single flared lines tend to split at the seam [13].

III. DESIGN AND FABRICATION

The design and fabrication process of the vacuum pump holder involved several key steps and considerations. The primary aim was to create a holder that supports the vacuum pump's weight and maintains it in an upright position for proper operation. The following design criteria were taken into account:

- Lightweight
- Cost-effective and easy to manufacture
- Compact and durable

The steps in designing the vacuum pump holder were as follows:

1. The dimensions of the vacuum pump, such as hole diameter, center-to-center distance of the holes, length, and maximum radius (breadth), were measured. The position of the inlet and outlet of the vacuum pump was also considered to ensure that the holder design did not block them.

2. The center-to-center hole distance and maximum radius of the pump were used to determine the position of the mounting points. A clearance value of 6 mm from the firewall was set to ensure that the outlet of the pump was not blocked. A 3D solid CAD model was sketched after deciding the dimensions of the holder. The holder design was inspired by the geometry of the isosceles triangle, which has two sides of equal length and the same angle. Two individual isosceles triangle-shaped holders were used to support one vacuum pump. Each vacuum holder had three through holes of equal diameters, corresponding to the diameter of the

mounting hole on the vacuum pump. Two holes were for bolts used to mount the holder on the firewall, and one was for the mounting bolt of the vacuum pump. The inner and outer sharp edges of both vacuum holders were rounded off for safety and to reduce stress concentration.

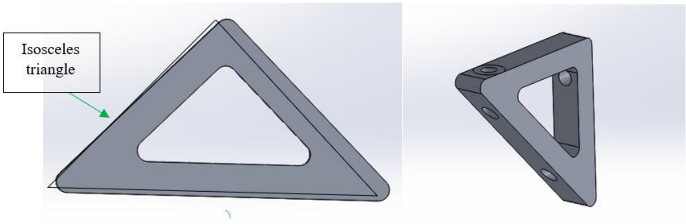

Figure 16: 3D CAD Model Design

This geometry and shape were chosen because they met all the design criteria for the vacuum pump holder. The triangular shape as shown in figure 16 provided symmetry and compactness, simplifying the manufacturing process. A significant amount of material was removed from the center to create a hollow isosceles triangle, which contributed to the lightweight nature of the holder. Furthermore, the holder was fabricated using scrap pieces of Al alloy T6 6061 available in the laboratory, resulting in negligible cost.

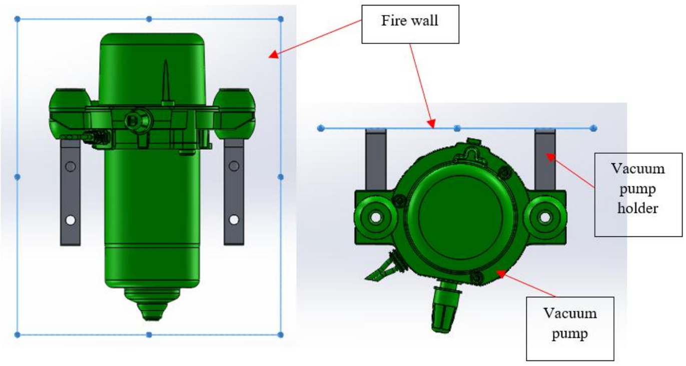

Figure 17: Vacuum pump assembly

3. The final step involved performing a finite element analysis (FEA) on one vacuum pump holder to ensure that the design could support the weight of the vacuum pump. Static analysis was conducted, as the holders were only required to support the weight of the vacuum pump. Pre-defined steps for FEA were followed.

The material used for the vacuum pump holder was Al alloy T6 6061, selected due to nominal material requirements. The holder was designed to support the vacuum pump's weight, necessitating a material with nominal strength, minimum weight, and minimum cost. A fixed geometry fixture was applied at the two through holes used to mount each holder onto the firewall. The external load acting on each holder was half the weight of the pump at the mounting holes. In the figure 18, pink arrows represent the external load, and orange arrows represent the fixed geometry.

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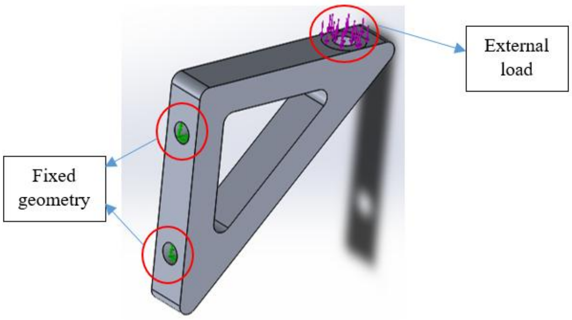

Figure 18: FEA setup of vacuum pump holder

4. After meshing and running the simulation, the results were analyzed using stress, strain, displacement, and factor of safety plots. As shown in the factor of safety plot in figure 19, no areas with a factor of safety below 3 were indicated. This confirmed that the design met the desired specifications.

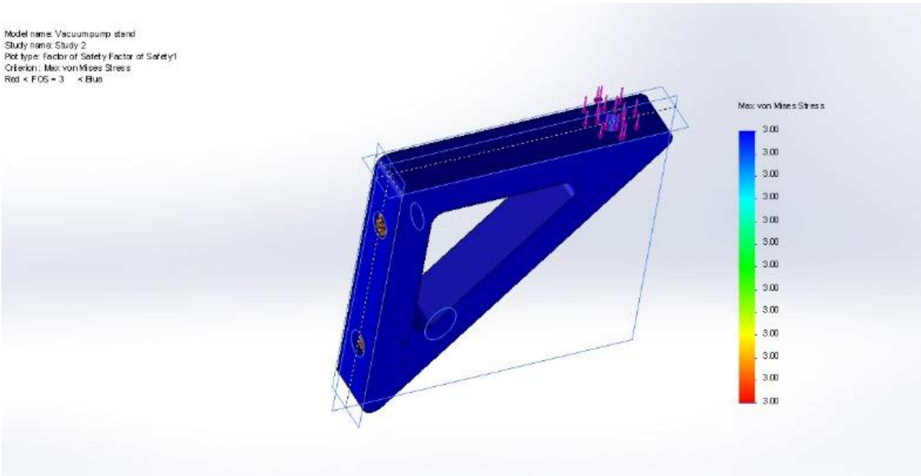

Figure 19: Factor of safety plot

Figure 20 displays the displacement plot of the holder. As expected, the maximum displacement occurs at the mount point of the vacuum pump, with a maximum displacement value of 0.45 µm, which is considered negligible.

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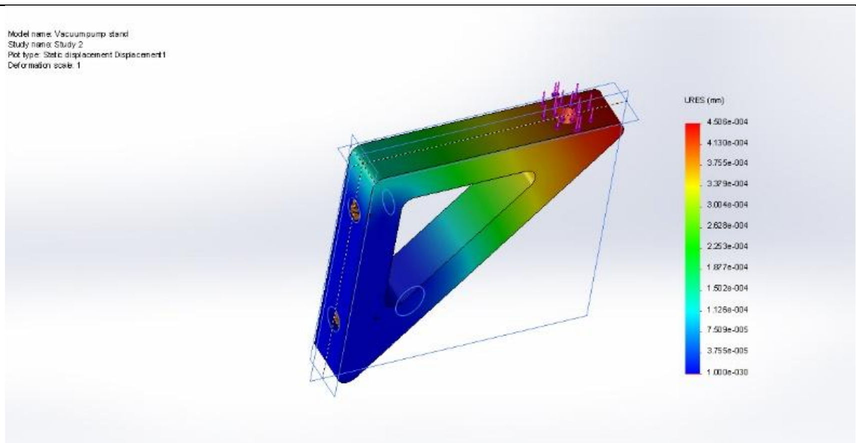

Figure 20: Displacement plot

Figure 21 shows that no area exceeds the maximum allowable stress or yield stress of the T6 6061. The maximum indicated stress is approximately 22 MPa. After analyzing the results, it was confirmed that the design met the specified criteria.

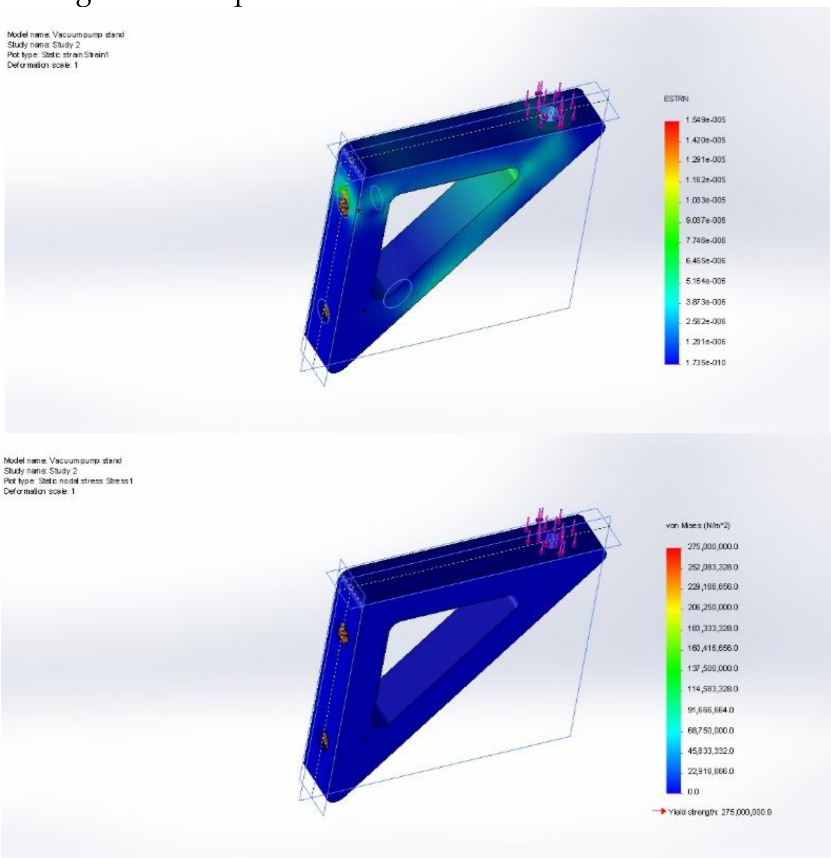

Figure 21: Strain plot (top) & stress plot (bottom)

5. Additionally, a 2D CAD of the vacuum pump holder was created to facilitate the fabrication process.

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Figure 22: Fabricated vacuum pump holders

The vacuum pump holders in figure 22 were fabricated using conventional manufacturing processes, including milling, drilling, and band-sawing.

IV. TESTING

Testing and bleeding the braking circuit of the BEV was necessary to ensure proper functioning before installation. The following steps were taken to test out the braking system:

1. The first step involved cutting the tubing or brake lines to the required length and ensuring a square end. To achieve a high-quality cut that required no post-finishing, a tube cutter was used. The tube cutter was tightened against the tubing and then rolled around it. With each rotation, the handle was tightened to advance the cutter radially as the tubing was cut. Burrs typically appeared on either end of the tubing after cutting.

2. The second step was dressing off the ends of the cut tubing using a filer and chamfering the ends. An appropriate file size was selected, and after securing the workpiece with clamps, the filing operation was carried out. The flaring tool, which always consists of a reamer blade, was used to open up and slightly chamfer the ends of the tubing. An air pressure gun was used to remove metallic chips and debris from the tubing, as this could affect the braking system's performance.

Figure 23: Filling & chamfering brake lines

3. The next step involved flaring the ends of the tubing using a flaring tool with an SAE double flare. This two-step process is described and shown in figure 24 below:

- The flaring was first slipped onto the tubing. The correct size hole in the flaring tool bar was selected, and the tubing was clamped into the flaring bar tool, ensuring it extended out by the width of the flaring tool adapter. The flaring tool and a threaded flaring cone were then used to form the end of the tubing.
- The adapter was inserted into the end of the tubing and tightened down with the flaring tool until it reached the bottom. After removing the adapter, a 45-degree flaring cone and flaring

tool were used to complete the flare.

Figure 24: Flaring process

4. The initial step involved assembling the four brake calipers, master cylinder, proportional valve, and brake booster, and connecting them with the previously fabricated flared brake lines. The manual bleeding procedure followed these steps:

- The bleed screw was loosened by one turn, and the brake pedal was slowly pushed to the floor.
- After closing the bleed screw, the brake pedal was released.
- This process was repeated until the fluid coming out of the bleed screw was free of air.
- Precautions were taken to ensure that the master cylinder fluid level was refilled before it dropped too low, preventing air from entering the system.

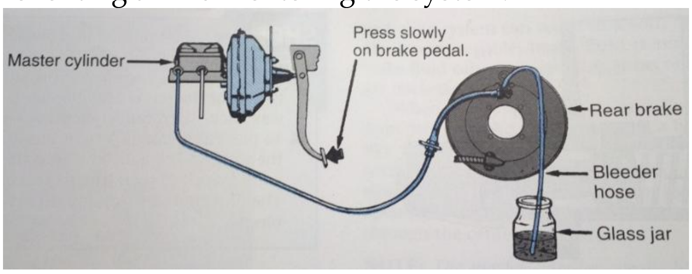

Figure 25: Manual brake bleeding [13]

After bleeding the brakes, the electrical and vacuum sub-circuits of the brake circuit were connected, and the complete brake circuit was assembled for testing. The tests were conducted 4-5 times, and the results were positive, confirming that all four brake calipers were in excellent working condition. This test validated that the BEV's brake circuit design was perfect and ready for installation on the BEV.

Figure 26: Brake circuit test rig

V. FUTURE WORK

Building upon the successful design, fabrication, and testing of the vacuum pump holder and

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braking circuit for the BEV, several avenues for future research and development can be explored.

1. **Material Optimization:** Investigate alternative lightweight and cost-effective materials that could further enhance the performance and durability of the vacuum pump holder and braking circuit components.
2. **Advanced Manufacturing Techniques:** Explore the application of advanced manufacturing techniques, such as additive manufacturing, to optimize the design and reduce material waste.
3. **Integration with Smart Systems**: Develop and integrate smart sensor systems for real-time monitoring of the vacuum pump holder and braking circuit performance, enabling predictive maintenance and enhancing safety.
4. **Dynamic Testing**: Conduct dynamic testing of the braking circuit under various operating conditions to assess its performance and reliability in real-world scenarios.
5. **Heat Management**: Evaluate the thermal performance of the vacuum pump holder and braking circuit components to ensure their reliability under different environmental conditions.
6. **Design Iteration and Improvement**: Continuously iterate and improve the design based on feedback from testing and real-world applications to achieve optimal performance and reliability.

These future research directions will contribute to the continuous improvement and innovation of the BEV's vacuum pump holder and braking circuit, ensuring the vehicle's overall efficiency, safety, and reliability.

VI. CONCLUSIONS

The design, fabrication, and testing of the vacuum pump holder and braking circuit for the BEV involved a series of meticulous steps and considerations to ensure optimal functionality and safety. The vacuum pump holder was designed with criteria such as lightweight, cost-effectiveness, and durability, employing a symmetrical and compact triangular shape that simplified manufacturing. Finite element analysis confirmed the design's robustness, with all stress and displacement values within acceptable limits.

The braking circuit, after assembly and manual bleeding, demonstrated excellent performance in multiple tests, validating the design's effectiveness. By integrating the electrical and vacuum sub-circuits, the complete brake circuit was tested and confirmed to be in perfect working condition.

These outcomes validate the design decisions made throughout the project, showcasing the successful application of engineering principles and practical manufacturing techniques. The methodologies and results provide a strong foundation for the implementation of these components in the BEV, contributing to the vehicle's overall reliability and safety.

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