

Dynamic Study of Braking Load Distribution on Energy Efficient Cars Based on Road Tests

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Abstract

This study presents the design and evaluation of braking components specifically the steering knuckles, wheel arms, and brake pedal for a prototype-class energy-efficient vehicle. The design objective was to achieve reliable braking while preserving the vehicle's lightweight architecture, so that stopping performance is maintained without penalizing overall efficiency. The workflow comprised determination of braking-force requirements, material selection guided by strength-to-weight considerations, CAD modeling of the components, fabrication, and functional testing on the assembled vehicle. Road trials were conducted at four preset entry speeds of 2.78, 4.17, 5.56, and 6.94 m/s, representing the operating envelope of the prototype. Across these conditions, the system delivered a consistent deceleration of 8.33 m/s². The measured stopping times were 0.35 s, 0.51 s, 0.68 s, and 0.84 s, while the measured stopping distances were 0.79 m, 1.75 m, 3.00 m, and 4.58 m, respectively. These outcomes indicate that the designed components provide stable, predictable braking behavior over the tested speed range and confirm that lightweight construction can be reconciled with effective stopping capability. The results offer a practical reference for component sizing and material selection in energy-efficient vehicle prototypes and form a basis for subsequent optimization of braking response and integration with broader vehicle dynamics studies.

Keywords : braking system, energy-efficient vehicle, steering knuckle, wheel arm, weight optimization

1. INTRODUCTION

At present, the Department of Mechanical Engineering at Politeknik Negeri Bengkalis does not yet possess an energy-efficient vehicle that can serve as a platform for innovation in automotive technology. The existence of such a prototype is highly important, as energy-efficient vehicles play a crucial role in the advancement of environmentally friendly transportation and the improvement of fuel efficiency. In recent years, many universities across Indonesia have actively developed energy-efficient cars to participate in national competitions and to contribute to the global movement toward sustainable technology (Banh, H et al., 2025). The absence of a similar initiative within this campus highlights a gap that, on one hand, presents a challenge in keeping pace with technological progress, but on the other hand, creates an opportunity for the author to propose and realize an innovation that can bring the institution to a more competitive and contributive position in the field of green automotive development.

The rapid depletion of fossil fuel resources, coupled with the ever-increasing demand for energy, has become a pressing global issue that also directly affects Indonesia. This situation compels policymakers, industries, and academic institutions alike to seek effective solutions to mitigate the energy crisis. Among the most promising strategies is the pursuit of research and development projects that emphasize the enhancement of fuel efficiency and the integration of energy-saving technologies into vehicle systems. Within the automotive sector, nearly all major manufacturers and research groups are striving to design products that not only reduce fuel consumption but also maintain safety, performance, and reliability standards, showing how efficiency is no longer an option but a necessity (Ghazali. et al., 2023).

Within this broader context, the braking system of an energy-efficient vehicle holds a particularly critical position, as it is directly tied to safety and performance during operation. Beyond simply stopping the vehicle, the braking system must operate in a way that avoids

unnecessary energy losses, thereby aligning with the overall goal of efficiency (Heyadri et al., 2020). To address this, the present study emphasizes the design of braking components for an energy-efficient prototype vehicle. Key supporting parts such as wheel arms, steering knuckles, brake pedals, and brake brackets are developed to integrate with the vehicle's structural design. The braking mechanism employs standard motorcycle brake calipers, chosen for their availability and compatibility, but with modifications introduced to ensure that the brake pads do not continuously rub against the disc when not in operation (Miri, I. et al., 2020). This adjustment is intended to minimize parasitic energy losses, improving the vehicle's overall efficiency without sacrificing braking strength or safety.

Furthermore, this study concentrates on quantifying the dynamic performance of the braking system by analyzing two essential parameters: braking time and stopping distance. These measurements provide an objective understanding of how effectively the braking system ensures safety during deceleration while also highlighting potential improvements in the design. To complement this, the prototype vehicle's braking arrangement allows independent actuation of the front and rear brakes, as well as simultaneous braking along a single axle. Notably, the front wheels are equipped with a single master cylinder connected to two calipers, ensuring balanced braking distribution. All functions are controlled through a dedicated brake pedal, maintaining a simple yet effective mechanical interface for the driver. By integrating design innovation, theoretical analysis, and experimental validation, the project not only addresses the technical challenges of braking in energy-efficient vehicles but also contributes to the growing body of research aimed at supporting sustainable automotive engineering.

2. REVIEW OF LITERATURE

The braking system in a motorcycle is a crucial component because it is directly related to riding safety. Its function is to slow down or stop the motorcycle by converting the vehicle's kinetic energy (motion) into heat energy (Xu, W et al., 2019). Therefore, the components manufactured for the braking system must be made of materials that not only generate a high level of friction but are also resistant to wear and do not produce excessive heat that could cause the material to melt or deform (Yin, Z. 2023). Such friction-resistant materials are generally composed of a combination of several substances that are processed and bonded together through specific treatments.

Some of these materials include copper, brass, tin, graphite, carbon, Kevlar, resin, fiber, and other additional additives. Several types of braking systems are commonly used, such as single-block brakes, double-block brakes, band brakes, drum brakes, and disc brakes (Lich, T., et al., 2015). In terms of operation, braking systems are generally divided into two categories: mechanical and hydraulic. Among these types, only disc brakes utilize a hydraulic system, while the others operate mechanically. In motor vehicles, the most widely used braking systems are drum brakes and disc brakes (Zhang, J. 2021).

A disc brake consists of a steel disc that is clamped by brake pads on both sides during braking. This type of brake has several advantages, such as ease of control, stable braking performance, and good heat dissipation.



Fig. 1. Disc Brake Construction

A disc brake can be operated mechanically using a steel cable and lever or hydraulically using fluid pressure. In this system, the rotation of the wheel is reduced or stopped by clamping the disc with two brake pads. The disc plate, usually made of stainless steel, rotates together with the wheel (Zhang, X. et al., 2024). When the brake is applied, the disc is pressed by the piston force that works hydraulically. Based on its actuation mechanism, disc brakes are classified into two types: mechanical disc brakes and hydraulic disc brakes, with the hydraulic type being the most commonly used (Xiong, H. 2018).

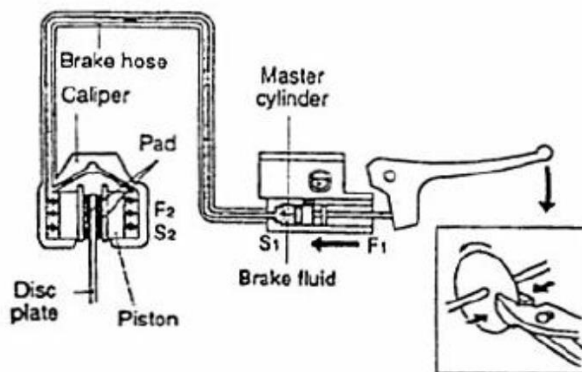


Fig. 2. Disc Brake Working System
(Shigley, J. E. 2015)

In a hydraulic disc brake system, brake fluid is used to transfer the motion from the lever to the brake pads. When the brake lever is pulled, the piston inside the master cylinder is pushed, forcing the brake fluid out of the cylinder. Through the brake hose, this pressure is transmitted by the fluid to push the piston located inside the caliper (Anh, N et al., 2025). As a result, the caliper piston presses the brake pads against the disc, creating the braking action. When the brake lever or pedal is actuated, the master cylinder converts the applied force into hydraulic pressure. The master cylinder consists of a reservoir containing brake fluid and a cylinder where the pressure is generated. The reservoir is usually made of plastic, cast iron, or aluminum alloy and is integrated with the cylinder. A rubber cap is placed at one end of the master cylinder to ensure a proper seal with the cylinder, while another rubber cap at the opposite end prevents fluid leakage.

The study by Szumska, E. (2025), entitled “Regenerative Braking Systems in Electric Vehicles: A Comprehensive Review of Design, Control Strategies, and Efficiency Challenges”, aimed to analyze the braking performance of the Asykar Prototype. In this research, the author investigated the causes of braking performance failure in a mechanical braking system, specifically one using a drum brake and steel cable. Mechanical braking systems are generally easier to maintain and repair due to their simple construction. In this system, the pushing motion of the lever is transferred to the brake shoes through the cable; the stronger or longer the lever movement, the greater the force applied by the brake shoes onto

the drum. The results of the study indicated that the main causes of failure were corrosion on the cable, which led to seizing and reduced braking responsiveness, and the decreased elasticity of the steel cable due to excessive braking force, which eventually caused the cable to be unable to withstand the applied load.

The design conducted by Naseri, F (2017), entitled “An Efficient Regenerative Braking System Based on Battery/Supercapacitor for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles With BLDC Motor”, utilized a brake disc with a diameter of 200 mm and a thickness of 2.5 mm, which was able to produce fairly responsive braking performance. However, the stopping distance tended to be longer because the braking was applied gradually rather than fully, as the system required pumping before achieving full braking force. Based on the first test, the brakes were tested at a speed of 20 km/h over a travel distance of 50 meters and managed to stop in 3.05 seconds. In the second test, at a speed of 25 km/h with the same 50-meter travel distance, the vehicle stopped in 3.38 seconds. In the third test, at 30 km/h over 50 meters, the braking time recorded was 3.93 seconds. Finally, in the fourth test at 30 km/h over a longer travel distance of 75 meters, the braking time was 4.04 seconds.

The design carried out by Techalimsakul, P. (2024), entitled “Integrated Vehicle-Following Control for Four-Wheel Independent Drive Based on Regenerative Braking System Control Mechanism for Battery Electric Vehicle Conversion Driven by PMSM 30 kW”, focused on determining the deceleration, stopping distance, and braking time at speeds of 15 m/s, 19 m/s, and 23 m/s. The method used involved collecting experimental test data to obtain stopping distance and braking time values, which were then compared with theoretical calculations. From the results, it was concluded that at the specified speeds of 15 m/s, 19 m/s, and 23 m/s, the deceleration values obtained were 4.2 m/s², 3.9 m/s², and 5 m/s², respectively. The theoretical calculations of braking distance produced values of 2 m, 3.5 m, and 3.6 m with an average of 3 m, while experimental testing gave values of 2 m, 3.4 m, and 3.6 m with an average of 2.8 m. The differences between theoretical and experimental results were 0 m, 0.1 m, and 0 m, respectively. For braking time, theoretical results showed values of 1.0 s, 1.3 s, and 1.1 s with an average of 1.1 s, while experimental testing yielded 1.6 s, 1.4 s, and 1.7 s with an average of 1.56 s. The difference between theoretical and experimental results for braking time was 0.6 s, 0.1 s, and 0.6 s, respectively.

3. METHOD

This study employed an experimental design combined with theoretical analysis to evaluate the braking performance of an energy-efficient prototype vehicle. The research was conducted at the Internal Combustion Engine Workshop of Politeknik Negeri Bengkalis and supported by fabrication activities at Fatih Las Workshop, which provided facilities for the manufacturing and assembly of braking components. The tools used in the fabrication stage included ring and open-end spanners, socket wrenches, pliers, screwdrivers, grinding machines, welding equipment, and a drilling machine. To ensure accurate testing, measurement instruments such as a measuring tape, a digital speedometer, and a stopwatch were employed for recording braking distance, vehicle speed, and braking time. The materials used in constructing the braking system consisted of 3 mm and 5 mm steel plates, ½-inch steel pipes, bolts, M16 fasteners, bearings (type 6001 2RS), and standard motorcycle brake calipers that were modified to suit the prototype configuration.

The prototype vehicle employed in this study was designed according to the standards of the energy-efficient car competition (KMHE). It is a lightweight, single-passenger vehicle constructed with a tubular steel frame and compact dimensions to minimize weight and aerodynamic drag. The main technical details, including dimensions, weight, braking configuration, and power system, are summarized in Table 3.1.

Table 1. Vehicle Specifications

Dimensions (m)	Value
Wheelbase (L)	0.83 m
Width (l)	0.50 m
Height (t)	0.75 m
Length (p)	2.70 m
Distance from front axle to driver	0.70 m
Driver height from axle (Hp)	0.40 m
Vehicle Weight (kg)	Value
Front weight (Mf)	33.6 kg
Rear weight (Mr)	33.4 kg
Total weight	67 kg
Driver weight	50 kg
Total vehicle + driver weight	117 kg
Vehicle frontal area	0.35 m ²
Component Weight (kg)	Value
Steering knuckle	1.0 kg
Wheel connecting rod	1.0 kg
Accelerator and brake pedal connecting rod	1.0 kg
Accelerator and brake pedals	0.3 kg

The research procedure began with problem identification and a literature review, particularly referencing previous studies and the official guidelines of the Kontes Mobil Hemat Energi (KMHE). The braking components including wheel arms, steering knuckle, brake pedal, and brackets were then designed using SolidWorks CAD software to ensure integration with the prototype vehicle. Once the design was finalized, fabrication and assembly were carried out using the prepared tools and materials. The assembled braking system was subsequently tested under controlled conditions on asphalt roads. Braking trials were performed at speeds of 10, 15, 20, and 25 km/h, with each test repeated three times to obtain reliable averages of braking time and stopping distance.

The data obtained from the experimental tests were compared with theoretical predictions based on Newton's second law, braking force distribution equations, aerodynamic drag, rolling resistance, and center of gravity analysis. Through this comparison, the study aimed to highlight the differences between theoretical expectations and actual performance, providing a comprehensive understanding of the dynamic braking force distribution in the energy-efficient prototype vehicle.

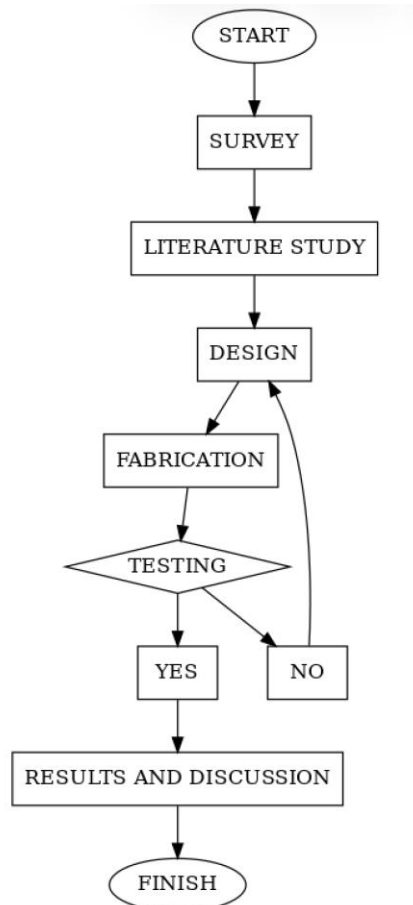


Fig. 3. Flowchart system

The research procedure began with a literature study followed by the collection of vehicle specification data. Afterward, the total mass of the vehicle was measured as the basis for further calculations. The next step was to determine the vehicle's center of gravity, both without the driver and with the driver, to understand the effect of load distribution. The theoretical calculation stage involved determining the braking force required when braking on flat roads and on slopes with an 11.3° gradient at vehicle speeds of 10, 15, 20, and 25 km/h. Subsequently, the theoretical stopping distance and braking time were calculated for the same speed variations. These results were then compared with experimental data obtained through direct braking tests conducted under identical speed conditions. The comparison focused on analyzing differences between theoretical predictions and actual performance, particularly in terms of braking time and stopping distance. The evaluation continued until the error margin between theoretical and experimental results was less than 10%. If the error exceeded this threshold, the testing and calculation stages were repeated. Once the error was within the acceptable range, the process proceeded to the stage of results and conclusions, marking the completion of the study.

4. RESULT & DISCUSSION

Braking in a vehicle does not only occur on flat and level roads, but also on road segments that have slopes, whether uphill or downhill. When a vehicle travels on an inclined surface, the braking process becomes more complex because it must counteract not only the vehicle's inertia but also the additional component of gravitational force acting along the slope. On a downhill slope, this gravitational component increases the braking demand, requiring greater braking force to bring the vehicle to a stop. Conversely, when traveling uphill, the gravitational force works against the direction of motion, partially assisting the braking action and reducing the required braking force.

To analyze this phenomenon, the braking system is examined using a free body diagram of forces acting on the inclined plane. This diagram illustrates the relationship between the vehicle's weight, the normal force, the component of gravitational force parallel to the slope, the frictional force, and the braking force itself. By breaking down these forces, it is possible to calculate the total braking force required under various slope conditions. This approach allows for a more accurate evaluation of the braking performance of the vehicle in real operating conditions, ensuring that the system can maintain both safety and efficiency across different terrains.

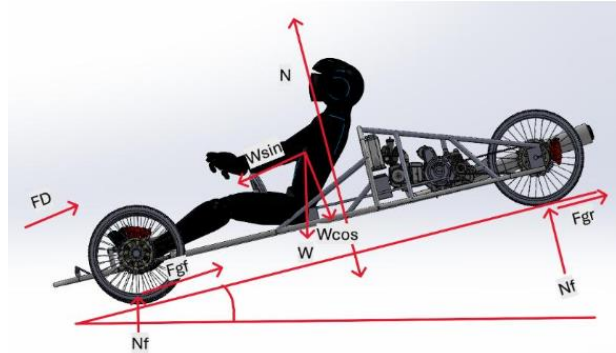


Fig. 4. Free Body Diagram of a Vehicle on an Inclined Plane

To determine the magnitude of the braking force (F_b) required to resist the movement of the vehicle, the calculation can be carried out by applying the equilibrium of forces on an inclined plane using magnitude of the deceleration is influenced by the condition of the road surface, which is commonly expressed as the coefficient of friction (μ). In this design, a value of $\mu = 0.85$ was used, corresponding to the actual road conditions during testing.

$$\begin{aligned} a &= \mu \cdot g \\ a &= 0.85 \times 9.8 \text{ m/s}^2 \\ a &= 8.33 \text{ m/s}^2 \end{aligned}$$

Thus, the braking deceleration value is 8.33 m/s^2 .

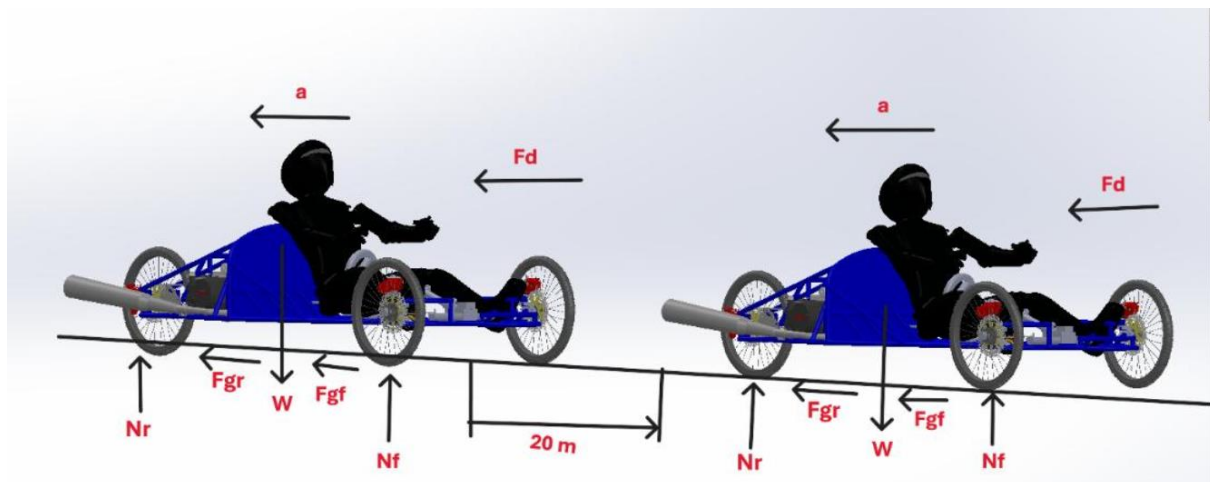


Fig.5. Free Body Diagram of Vehicle Deceleration

After determining the dynamic load acting during braking, the required braking force to counter this load can be calculated. Based on the analysis, the braking force on each wheel was obtained by multiplying the dynamic load with the road friction coefficient of 0.85. For the front wheel, the calculation resulted in a braking force of 679 N, while for the rear wheel the braking force was 677 N. These values indicate that the braking force on the front and rear wheels is nearly balanced, ensuring stability during the deceleration process. The total braking force required to stop the vehicle was therefore the sum of both values, amounting to 1,356 N.

This result provides an important basis for evaluating the performance of the braking system, as it reflects the capacity of the braking components to withstand the forces generated during actual operating conditions.

After conducting the test, the test results were obtained, as seen in the table below:

Table 2. Field testing results

Speed (km/h)	Test Platform (m)	Specific Braking Values							
		Downtime(s)				Stopping Distance (m)			
		1	2	3	Average	1	2	3	Average
10	20	0.40	0.30	0.35	0.35	0.67	0.90	0.80	0.79
15	20	0.50	0.53	0.51	0.51	1.75	1.85	1.70	1.75
20	20	0.69	0.65	0.70	0.68	3.0	3.02	3.05	3
25	20	0.85	0.81	0.87	0.84	4.58	4.57	4.60	4.58

The results exhibit a clear monotonic trend: as initial speed increases from 10 to 25 km/h, the average stopping time rises from 0.35 s to 0.84 s and the average stopping distance increases from 0.79 m to 4.58 m. This agrees with basic kinematics, where stopping distance grows faster than time because it scales roughly with the square of speed under near-constant deceleration.

Using the averaged time values, the effective deceleration estimated by $a \approx v/t$ (with speed in m/s) remains tightly clustered around $\sim 8.1\text{--}8.3\text{ m/s}^2$ for all speeds. This consistency indicates that the braking system delivers a similar braking effort across the tested range and that road–tire conditions were comparatively uniform during the trials.

The repeatability across the three repetitions is good, especially at higher speeds: the spread among 1-3 is small for both time and distance at 20–25 km/h, while the 10 km/h case shows slightly larger scatter reasonable given the very short times and distances involved. Overall, the table portrays a braking system that behaves consistently with theory: higher entry speeds yield longer times and markedly longer distances, while the underlying deceleration remains essentially constant across tests.

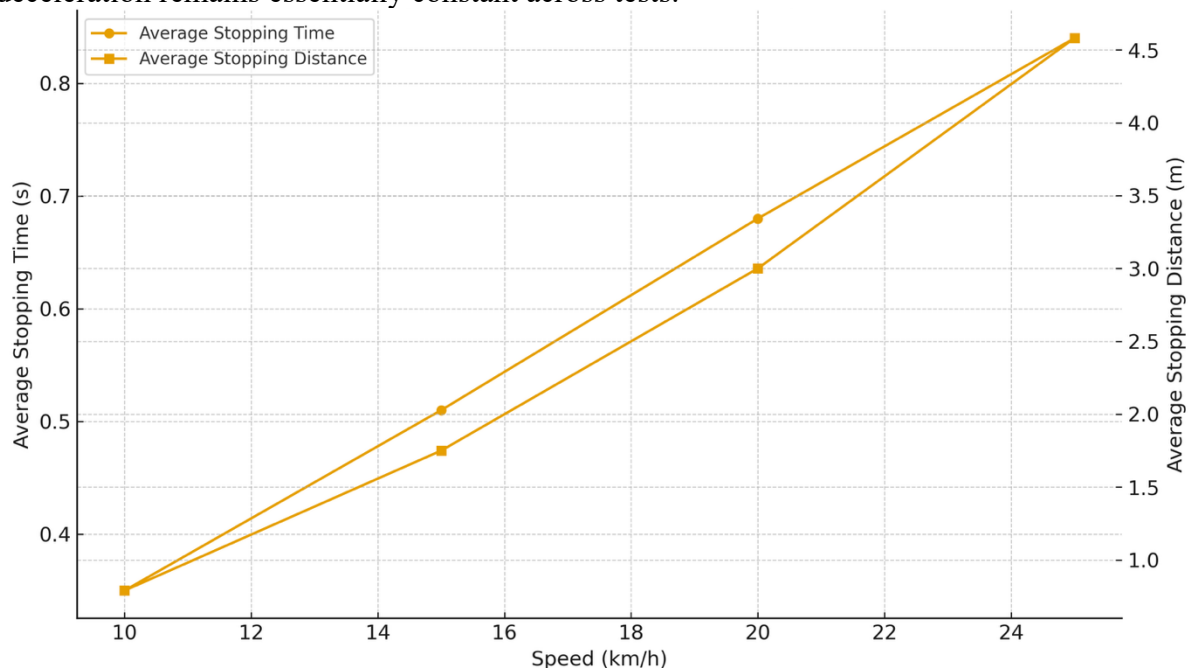


Fig. 6. Stopping Time and Distance vs Speed

Figure 6 condenses the braking behavior into a single view with dual y-axes. Both curves rise with speed, but they do so at different sensitivities. The stopping time grows almost linearly, with a nearly constant increment of $\sim 0.16\text{--}0.17\text{ s}$ for each 5 km/h step, which is characteristic of braking under an approximately constant deceleration. By contrast, the

stopping distance shows a progressively steeper slope: the increase per 5 km/h is about 0.96 m (10→15), 1.25 m (15→20), and 1.58 m (20→25). This acceleration of the distance curve with speed is consistent with kinematic expectations that stopping distance rises approximately with v^2 when deceleration is roughly constant. The parallel rise of both curves without outliers suggests uniform tire road conditions and stable brake actuation across tests. Practically, the plot indicates that modest increases in entry speed have limited impact on time to stop but a disproportionately larger effect on the distance required, underscoring the importance of speed control for low-energy vehicles operating in confined spaces.

5. CONCLUSION

To synthesize the findings from the design, fabrication, and testing stages of the Prototype class Energy Efficient Vehicle's braking system, we evaluated performance at four entry speeds (2.78, 4.17, 5.56, and 6.94 m/s) and compared experimental outcomes with kinematic predictions. Across all trials, the system delivered a near-constant deceleration of 8.33 m/s². The measured stopping times 0.35, 0.51, 0.68, 0.84 s closely aligned with the theoretical values 0.33, 0.50, 0.66, 0.83 s. Similarly, the measured stopping distances 0.79, 1.75, 3.00, 4.58 m were in near agreement with the predicted distances 0.77, 1.73, 3.00, 4.57 m. These small deviations fall within practical expectations for real-world braking, indicating stable system behavior and a representative road tire friction condition during testing.

Taken together, the evidence supports the adequacy of the current brake sizing and actuation for low to moderate speeds typical of energy efficient prototypes. The strong correspondence between theory and experiment validates the analytical model used for design decisions and provides a reliable baseline for future refinement. Subsequent work can focus on minor reductions in measurement scatter and on marginal optimization of system compliance and response, but the present configuration already achieves performance that is consistent, predictable, and well supported by first-principles analysis.

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