5.1 Chassis Manufacturing for Tadpole Structured Electric Vehicle

This section delves into the manufacturing process of the chassis for a tadpole-structured electric vehicle, based on the design considerations and optimizations detailed in "Chapter 4". The primary focus is to fabricate a chassis that not only meets the design criteria of weight, strength, and crashworthiness but also aligns with the unique requirements of a tadpole configuration.

5.1.1 Design Considerations

The chosen material for the chassis is AISI 4130 steel, known for its excellent strength-to-weight ratio, fatigue strength, and weldability. The tubing used predominantly has an outer diameter (OD) of 25.4 mm with varying thicknesses from 1 mm to 1.2 mm, supplemented with sheet steel for additional support. This choice ensures a balance between structural integrity and weight efficiency.

5.1.2 Fabrication Techniques

- **Tube Cutting and Bending:** The AISI 4130 steel tubes, selected for their optimal strength and weight characteristics, are cut to specific lengths. Cutting is done with a high-precision laser cutting machine to ensure accuracy and intersection curvature as a crucial factor for the assembly process. The tubes are then shaped using the bending technique whenever required. This process is vital for achieving the necessary chassis geometry while maintaining the material's structural integrity. The bending process is closely monitored to ensure consistency with the design angles and dimensions.
- **Welding and Assembly:** The chassis assembly involves welding the cut and bent tubes. This process employs the TIG welding technique to ensure strong and durable joints. Welding is executed under strict quality control to prevent any defects that might compromise the chassis's strength. Post-welding, the chassis is inspected for alignment. This step is critical to ensure that the chassis conforms to the specified geometrical design. Any misalignments are corrected to ensure that the chassis provides the desired structural integrity and vehicle handling characteristics.

5.1.3 Integration of the Roll Hoop

The chassis incorporates a specially designed roll hoop to enhance safety during rollover scenarios. This feature is particularly important in a tadpole vehicle structure, where the dynamics can differ significantly from traditional vehicles. The roll hoop is integrated into the chassis using bolt connections. This design choice allows for the roll hoop to be removable, facilitating future modifications or replacements as needed. The bolting mechanism is chosen for its strength and ease of assembly and disassembly.

5.1.4 Surface Treatment and Finishing

The chassis undergoes thorough surface cleaning to remove any contaminants, followed by a surface treatment process to enhance paint adhesion and corrosion resistance. A layer of primer is applied, followed by high-quality paint to protect against environmental factors.

5.1.5 Component Integration

Specific mounting points for the suspension, motor, battery pack, and other critical components are marked and prepared on the chassis. The suspension system, steering mechanism, and drivetrain components are assembled and aligned with the chassis.

Fig. 41 : Integrated Chassis

5.2 Rear Swing Arm Manufacturing and Assembly

The rear swing arm plays a critical role in the overall dynamics of a tadpole-structured electric vehicle, as detailed in "Chapter 4". It must be manufactured with precision to ensure proper alignment, strength, and functionality. This section outlines the process of manufacturing and assembly of rear sing arm.

5.2.1 Material Selection

7076 T6 Aluminium alloy selected for its high strength-to-weight ratio, this material is ideal for creating a lightweight yet durable swing arm. The choice of material is crucial for maintaining the balance between performance and efficiency.

5.2.2 Fabrication Techniques

The aluminum alloy is cut and shaped to match the design specifications. Precision-cutting tools are used to ensure accurate dimensions and profiles. The cut materials are machined to create the necessary mounts, pivot points, and attachment areas. This process includes CNC milling, and drilling for such a complex geometry. To enhance corrosion resistance and durability, the swing arm undergoes anodizing and powder coating. This also provides an aesthetic finish to the component.

5.2.3 Integration of Bushings and Bearings

Bushings are inserted at the pivot points to ensure smooth movement and to reduce wear. They are typically made of nylon materials that offer low friction and high durability. Bearings are fitted to the pivot points to handle radial and axial loads. Precision is key in this step to ensure smooth operation and alignment.

5.2.4 Mounting of the Suspension Components

The swingarm is designed with specific attachment points for the suspension components, like the shock absorber. After the suspension components are mounted, an alignment check is performed to ensure that everything is correctly positioned according to the design specifications. The swingarm is mounted to the rear section of the chassis. All bolts and fasteners are tightened to the specified torque settings to ensure secure attachment and to prevent loosening during operation.

Fig. 42 : Rear Wheel Assembly

5.3 Upright Manufacturing Using CNC Machining

The manufacturing of uprights for a tadpole-structured electric vehicle, as outlined in "Chapter 4", requires precision and accuracy. CNC (Computer Numerical Control) machining is a critical process in this context, offering high precision, repeatability, and efficiency. This section describes the manufacturing process of the uprights using CNC machining techniques.

5.3.1 Material Selection

Typically, materials like Al 6061 T6 grade aluminum are used for uprights due to their high tensile strength and lightweight properties. This material is particularly suited for CNC machining.

5.3.2 CNC Machining Process

The CAD model is translated into a CNC program using CAM (Computer-Aided Manufacturing) software. This program directs the CNC machine on how to move, cut, and shape the material. The CNC machine performs various operations such as drilling, milling, and tapping to create the complex geometries of the upright. This includes the creation of bearing housings, brake caliper mounts, and attachment points for suspension components.

5.3.3 Surface Treatment and Finishing

After machining, the uprights may undergo surface finishing processes like sandblasting or polishing to improve their appearance and surface quality. To enhance corrosion resistance and durability, the uprights are coated with protective materials.

5.3.4 Integration and Assembly

The uprights are integrated with other suspension components like wheel hubs, bearings, and suspension arms, and steering rods.

5.4 Integration of Vehicle Components: Suspension, Steering, Motor, Battery, and Electrical Connections

The integration of various components like the suspension, steering, motor, battery, and electrical connections is a critical phase in the assembly of a tadpole-structured electric vehicle, as outlined in "Chapter 4". This process involves careful coordination and precision to ensure optimal vehicle performance, safety, and reliability.

5.4.1 Mounting of Suspension Components

- **Front Suspension - Double Wishbone Setup:** The double wishbone suspension, known for its superior handling and control, is installed at the front. Each component, including the upper and lower arms, springs, and shock absorbers, is carefully positioned and secured to the chassis. Precision is key in aligning the wishbones to maintain the correct geometry, which is essential for effective shock absorption and maintaining tire contact with the road. The shock absorbers and springs are mounted within the wishbone structure. This setup is critical for absorbing impacts and providing a smooth ride.
- **Rear Suspension - Swing Arm Assembly:** The rear swing arm, pivotal for the vehicle's stability and handling, is mounted to the rear of the chassis. This component acts as the main linkage between the chassis and the rear wheel. The rear shock absorber is attached to the swing arm. The positioning and securing of the shock absorber are crucial for effective damping and response to road irregularities.

In both the front and rear suspension setups, every bolt and fastener is tightened to specified torque settings. This precision ensures the suspension system remains intact and functions correctly under various driving conditions.

5.4.2 Steering System Assembly

The assembly of the steering system is a critical component in the construction of a tadpole-structured electric vehicle, ensuring precise maneuverability and handling. This section outlines the integration process of the steering mechanism, focusing on the steering rack and pinion, linkages and tie rods, and wheel alignment.

Steering Mechanism Integration

- **Steering Rack and Pinion:** The steering rack is mounted onto the vehicle's chassis. This mounting must be robust and secure to withstand the forces exerted during steering. The pinion, which is attached to the steering column, is carefully aligned and connected to the steering rack. Precise alignment is crucial to ensure that the steering input from the driver is accurately transmitted to the steering mechanism. Once the rack and pinion are connected, the assembly is checked for smooth operation. Any resistance or irregularity in movement necessitates an adjustment to ensure steering response.
- **Linkage and Tie Rods:** Steering linkages are installed to connect the steering rack to the tie rods. This setup converts the linear motion of the rack into the angular motion required to turn the wheels. The tie rods are attached to the ends of the steering rack. These rods are critical for transmitting the steering forces to the wheels. The tie rods are adjusted to achieve the correct toe settings, which are essential for optimal tire wear and vehicle handling.
- **Wheel Alignment:** Proper wheel alignment is conducted to ensure the vehicle’s wheels are set to the angles specified in the design. This includes camber, caster, and toe adjustments. Correct wheel alignment is essential for predictable vehicle handling and stability. It also ensures even tire wear and optimal driving performance.

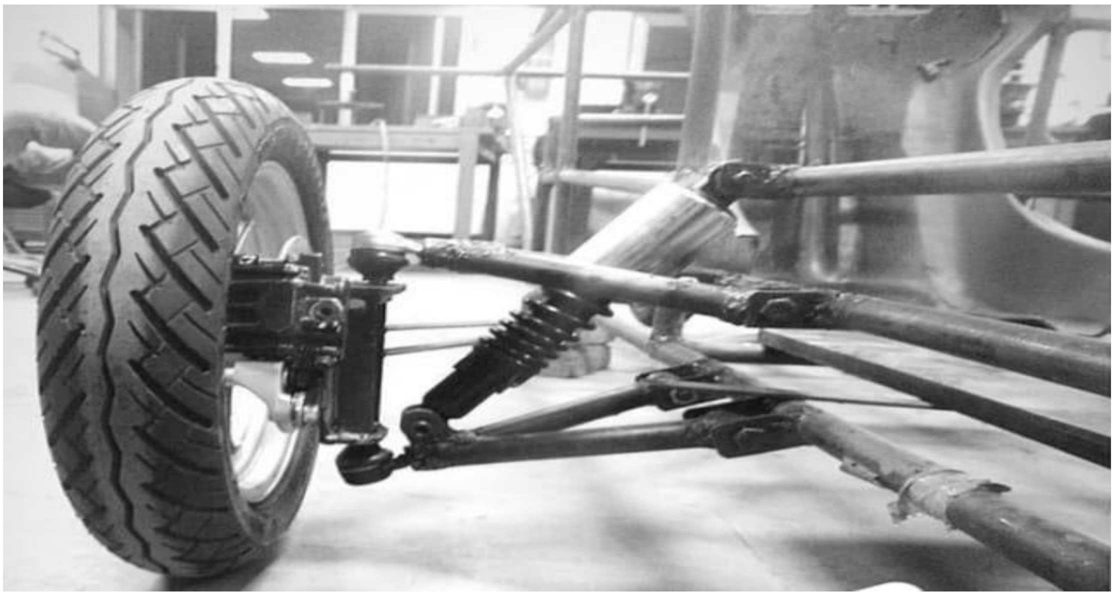

Figure 43 : Front Wheel Assembly

5.4.3 Motor and Drive Train Installation

The installation of the motor and drive train is a pivotal aspect of assembling a tadpole-structured electric vehicle, playing a crucial role in the vehicle's power delivery and overall performance. This process demands meticulous attention to detail in both the positioning and alignment of the motor and its integration with the drive train.

The electric motor is strategically positioned within the chassis. This location is carefully chosen to maintain the vehicle's center of gravity and to ensure optimal weight distribution, which is essential for the vehicle's handling and stability. The motor is securely mounted onto the chassis using robust mounting brackets and fasteners. These mounts are designed to handle the torque produced by the motor and to minimize vibrations. Precise alignment of the motor is critical. Misalignment can lead to inefficient power transmission and increased wear on the drive train components. The alignment is checked and adjusted to ensure that the motor shaft is parallel and co-axial with the drive train components.

5.4.4 Battery System Integration

The battery pack is installed in a position that maintains the vehicle's center of gravity and does not interfere with handling. This often involves a secure, vibration-resistant mounting system. Electrical Connections: The battery is connected to the electric motor and the vehicle's electrical system. This includes high-voltage connections and the integration of the Battery Management System (BMS).[91]

The battery pack is positioned to maintain the vehicle's center of gravity. Its location is strategically chosen to ensure it does not adversely affect the vehicle's handling and stability. This is particularly important in a tadpole configuration where weight distribution can significantly influence driving dynamics. The battery pack is secured using a mounting system designed to withstand vibrations and shocks that are typical in vehicle operation. This system often includes reinforced brackets and vibration-resistant materials to ensure the battery remains stable in various driving conditions. The mounting design also considers ease of access for maintenance, ensuring that the battery pack can be easily inspected, serviced, or replaced as needed.

5.4.5 Electrical Connections

The battery pack is connected to the electric motor through high-voltage cabling. This connection must be robust and well-insulated to handle the high power levels safely. The battery also powers the vehicle's electrical system, including lighting, instrumentation, and control units. These connections are carefully routed and secured to prevent any electrical interference or hazards.

The Battery Management System is a crucial component that monitors and manages the battery's health, state of charge, and temperature. Integrating the BMS involves connecting it to the battery cells and calibrating it to ensure it accurately assesses and reports the battery's status. Post-integration, comprehensive safety checks are performed. These include testing for short circuits, and insulation resistance, and ensuring all electrical connections are secure and properly insulated.

5.4.6 Electrical System and Wiring

The installation of the electrical system and wiring is a fundamental aspect of assembling a tadpole-structured electric vehicle. It involves the meticulous installation of the wiring harness and the connection of various electrical components. This process is crucial for the reliable operation of the vehicle's electrical and electronic systems.

- **Wiring Harness Installation:** The wiring harness, comprising a network of wires and connectors, is carefully laid out and routed throughout the vehicle.

The routing is planned to avoid areas of high heat, moving parts, and sharp edges that could damage the wiring. The harness is securely fastened using clips and ties to prevent it from moving or chafing, which could lead to electrical shorts or disconnections. Special attention is given to ensure that the wiring does not interfere with the vehicle's mechanical components. The harness is protected against environmental factors such as moisture and dust. This is often achieved using conduit or protective sleeving, especially in areas exposed to the external environment.

- **Connection to Electrical Components:** The wiring harness is connected to the vehicle's lighting system, including headlights, taillights, turn signals, and brake lights. These connections are crucial for safety and legal compliance. Various sensors and control units are connected to the harness. These include the vehicle speed sensor, battery management system, motor controller, and any other sensors required for the vehicle's operation. The dashboard and instrumentation, which provide the driver with vital information such as speed, battery charge level, and warning indicators, are connected to the harness. This ensures the driver has access to accurate and up-to-date vehicle information. Additional electrical components such as the audio system, air conditioning controls, and interior lighting are also connected to the wiring harness. These connections are made to ensure functionality and user comfort.

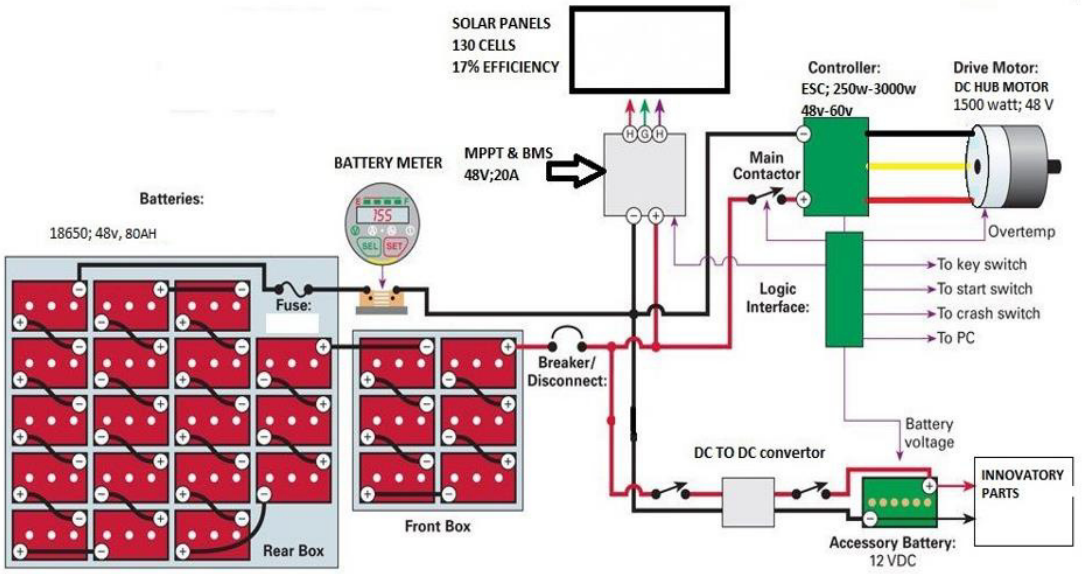

Fig. 44 : Wire Diagram of Tadpole Structured EV

5.4.7 Braking System Integration

The manufacturing process of the braking system components for a tadpole electric vehicle involves meticulous design and fabrication techniques, especially considering the unique demands of electric vehicles. Let's delve into the details of the manufacturing processes for the calipers, discs, brake pads, and hydraulic lines:

- **Calipers and Discs:** Calipers often made from high-strength materials like aluminum alloys, which offer a good balance between strength, weight, and heat dissipation. Discs are typically constructed from cast iron or reinforced carbon-carbon composites, especially for high-performance vehicles, due to their excellent heat dissipation properties.
- **Machining Process**: Precision machining is employed to ensure the calipers and discs meet exact dimensions and tolerances. This includes CNC (Computer Numerical Control) machining for accurate and consistent results. Surface treatments or coatings might be applied to the discs for added durability and performance under high-temperature conditions.
- **Brake Pads:** Made from a composite of materials including metals, ceramics, and organic fibers. The exact composition is tailored to provide the desired balance of friction, wear resistance, and heat dissipation. The materials are mixed, pressed into the shape of the brake pad, and then heat-cured in an oven to create a dense, durable material. Surface treatments or coatings can be added to optimize performance and reduce noise and dust.
- **Hydraulic Lines:** Hydraulic lines are made from materials like reinforced rubber or stainless steel. The choice depends on factors like flexibility, strength, and resistance to high-pressure conditions. For rubber lines, the rubber is extruded into the desired shape and then reinforced with materials like Kevlar or steel wire for added strength. Metal lines are typically bent and shaped using precision tools to fit the specific layout of the vehicle's braking system.
- **Installation of the Braking System:** The installation of the braking system in a tadpole electric vehicle is a critical process that involves several key steps to ensure the system's effectiveness and safety. Calipers are attached to the wheel hubs using bolts. The mounting must be secure and precise to ensure proper

alignment with the brake discs. In tadpole vehicles, front wheel assemblies usually bear more braking force, so the front calipers and discs are particularly robust. Brake discs are mounted onto the wheel assembly. Precision is crucial to ensure that the discs are perfectly aligned to avoid wobbling or uneven wear.

- **Brake Pads and Fluid:** Brake pads are inserted into the calipers. It's essential that they are correctly positioned for effective braking and to prevent noise or premature wear. The hydraulic system is filled with brake fluid. This process must be performed carefully to avoid air entrapment in the system, as air bubbles can significantly reduce braking efficiency. The system is then 'bled' to remove any trapped air. This is done by forcing brake fluid through the system until only fluid, with no air bubbles, emerges from the bleed valves. Hydraulic lines are routed from the master cylinder to each of the brake calipers. The routing must ensure there are no kinks or sharp bends that could impede fluid flow. The lines are securely connected to the master cylinder, which actuates the brakes when the brake pedal is pressed.

Fig. 45 : Braking System Master Cylinder

- **Adjustment and Balancing:** The braking force is adjusted to ensure a proper balance between the front and rear brakes. This balance is crucial, especially in a tadpole configuration, to prevent instability or uneven braking during operation. Modern electric vehicles often include electronic systems for enhanced braking functions, such as regenerative braking. These systems require the integration of ECUs and sensors with the mechanical braking system.

The system is calibrated to ensure that the electronic and mechanical components work seamlessly together. This includes adjusting sensor readings and actuator responses. Proper installation is crucial for the safety, efficiency, and longevity of the braking system in a tadpole electric vehicle.

5.5 Bill of Material and Cost Sheet

Table 5.1: Bill of Material and Cost

Sr. NO.	Component	Description	Quantity	Total Cost (Rs.)
1	Chassis Pipes	AISI 4130 (1mm Thickness)	110 ft	14,200
2	MPPT	Brand UNGE	1	8,913
3	Motor (Hub)	1.5 kW	1	16,000
4	Motor Controller	1.5 KW	1	4,000
6	Battery	Li-FePo4	1	1,10,000
7	Miscallaneous (Electronics)			20,000
8	Rack and Pinion Set	6:1 Steering Ratio	1	4,000
9	Steering Wheel	10 inch	1	1,000
10	Body Material	Acrylic	1	4,000
		Aluminium	1	2,000
11	Suspension Struts		3	2,000
12	Upright	Custom Made	2	6,000
13	Brake Assembly		3	7,000
14	Swing Arm		1	2,000
15	Miscallaneous (Mechanical)			7,000
			Total	**2,08,113**

5.6 Prototype Testing

5.6.1 Brake Test

A. Stopping Distance Test: The Stopping Distance Test is a fundamental part of vehicle brake testing, providing essential data on the effectiveness and safety of the braking system. This test is critical for evaluating how quickly a vehicle can come to a complete stop under various conditions. Here's an in-depth look at how the Stopping Distance Test is conducted. [92] The primary goal of the Stopping Distance Test is to measure the distance a vehicle travels from the time the brakes are applied until it comes to a complete stop. This data is crucial for assessing the effectiveness of the braking system and ensuring it meets safety standards.

- **Test Setup:**

1. **Test Track Selection**: A flat, straight, and level track is chosen to ensure consistent and accurate results. The surface condition (dry, wet, gravel, etc.) is noted as it significantly impacts stopping distances.

Fig. 46 : Track Selected for Braking & Acceleration Test

2. **Vehicle Preparation**: The vehicle is inspected to ensure it's in a standard driving condition with no modifications that could affect braking performance. Tires are checked for proper inflation and tread condition. The brake system is inspected for proper functionality.
3. **Instrumentation**: The vehicle is equipped with sensors to accurately measure speed and stopping distance. A high-speed camera may be used for additional data collection and analysis.

- **Test Procedure:**

1. **Speed Variations**: The vehicle is accelerated to various predetermined speeds (e.g., 30, 50, 60 Kmph). Different speeds are tested to assess braking performance under various driving conditions.
2. **Brake Application**: At each test speed, the brakes are applied firmly and consistently to simulate an emergency stop. The force applied to the brake pedal should be the same for each test to ensure consistency.
3. **Measurement**: The distance from the point where the brakes are applied to where the vehicle comes to a complete stop is recorded. The test is repeated multiple times at each speed to ensure reliability and accuracy of the data.

- **Data Analysis:** The data collected is analyzed to determine the average stopping distance at each speed. The results are compared to standard safety benchmarks and regulations.

B. High-Speed Braking Test: Tests the stability and control of the vehicle when brakes are applied at high speeds. Essential for assessing the risk of skidding or loss of control. The High-Speed Braking Test is a crucial part of vehicle safety assessments, particularly aimed at evaluating the stability and control of a vehicle under high-speed braking conditions. This test is vital for determining how effectively a vehicle can maintain control and prevent skidding when the brakes are applied at high speeds. The primary aim is to assess a vehicle's braking performance, stability, and control at high speeds. This test helps identify any potential risks of skidding or losing control during sudden or emergency braking scenarios.[93]

- **Test Procedure:**

The vehicle is accelerated to a high speed, typically above highway cruising speeds, to simulate emergency braking situations on fast roads or highways. At the predetermined speed, brakes are applied firmly to simulate a sudden stop. The force and method of brake application are kept consistent in each test iteration for reliable results. The vehicle's response, including any tendency to skid or lose control, is closely monitored. The stopping distance and time are recorded, along with any deviation from a straight-line stop. The test is repeated several times to account for variability and to ensure data reliability. Data on stopping distance, vehicle stability, and any control loss incidents are analyzed. The vehicle’s behavior under braking is evaluated, with particular attention to any skidding, fishtailing, or loss of directional control.

Table 5.2 : Brake Test Performance of Vehicle

Test Run No.	Initial Speed (kmph)	Stopping Distance (m)	Time to Stop (seconds)	Skid Marks (yes/no)	Vehicle Control (Stable/Unstable)	Brake System Response	Additional Notes
1	30	1.5	3.2	No	Stable	Good	-
2	30	1.3	3.4	No	Stable	Good	-
3	50	4.0	4.8	No	Stable	Good	-
4	50	3.5	4.6	Yes	Stable	Good	-
5	60	4.5	6.1	Yes	Unstable	Poor	Skidding occurred
6	60	4.7	6.0	No	Unstable	Average	Slight vibration in the pedal

5.6.2 Aerodynamic Drag Test

Performing an aerodynamic drag test on a vehicle is crucial for assessing its efficiency and performance, especially at higher speeds where drag significantly impacts fuel economy and acceleration. Here's a detailed overview of how to conduct an aerodynamic drag test. [94]

- **Preparation and Setup:** Ensure the vehicle is in standard driving condition. All tires should be properly inflated, and the vehicle's surface should be clean and free from any modifications that could affect aerodynamics.
- **Open Road Testing (Coastdown Testing):** Open Road Testing, also known as Coastdown Testing, is a practical method to evaluate a vehicle's aerodynamic drag and overall resistance. [95]
- **Test Procedure:** The vehicle is accelerated to a specific speed, which is usually representative of common driving conditions (e.g., highway speeds). Ensure that the vehicle reaches and maintains this speed steadily before beginning the coastdown phase. Once the predetermined speed is reached, the motor power is disengaged, and the vehicle is allowed to coast down naturally.

The transition from powered to coasting should be smooth to avoid influencing the test results. During the coastdown, record the time taken for the vehicle to slow down to a lower specified speed. Use precise instruments (like GPS speedometers) to record speed over time accurately. Conduct the test several times under similar conditions to ensure data reliability. Variations in wind, road grade, and other environmental factors can affect the results, so multiple runs help average out these variables.

- **Data Analysis for Drag Coefficient:** The primary goal is to calculate the vehicle's drag coefficient (Cd), a measure of its aerodynamic efficiency. Use the formula Drag force (D) can be derived from the deceleration rates observed during the coastdown.

$$C_d = \frac{2D}{\rho v^2 A}$$

Where,

D - Drag force

ρ - Air density

v – Velocity

A - Frontal area of the vehicle

Table 5.3 : Results of Aerodynamic Drag Coefficient

Test Run No.	Initial Speed (kmph)	Final Speed (kmph)	Coasting Time (seconds)	Calculated Drag Coefficient (Cd)	Observations
1	40	20	12.5	0.32	Stable descent, no turbulence noticed
2	45	25	13.0	0.33	Minor turbulence at rear end
3	50	30	11.8	0.31	Smooth coastdown, consistent with previous run
4	55	35	12.1	0.32	Slight vibration observed in chassis
5	60	40	10.5	0.30	Very stable, efficient airflow

5.6.3 Yaw Rate Testing

To measure the vehicle's response to steering inputs, particularly its ability to rotate around its vertical axis (yaw).[48], [96]

- **Test Setup:** A flat, dry surface is ideal, often marked with cones to define a test path. Equipped with sensors to measure yaw rate, steering angle, and lateral acceleration. Experienced drivers are required to maintain consistency in maneuver execution.
- **Test Procedure:** The Slalom Test involves driving through a series of cones placed in a straight line at regular intervals, requiring quick left and right steering inputs. Sudden Lane Change Test simulates an emergency lane change maneuver at various speeds. Yaw rate sensors measure the rate of turn, and data is analyzed to assess the vehicle's stability and response time.

Table 5.4 : Yaw Rate for Different Test Types

Test Run No.	Manoeuvre Type	Initial Speed (Kmph)	Max Yaw Rate (degrees/sec)	Time to Steady Yaw (sec)	Observations
1	Slalom	20	15.2	2.8	Stable, responsive handling
2	Slalom	30	18.5	3.1	Minor understeer noticed
3	Sudden Lane Change	40	25.3	1.9	Oversteer at high speed
4	Sudden Lane Change	50	28.7	2.2	Brief loss of control
5	Fishhook	25	20.1	2.6	Stable with good recovery
6	Fishhook	30	23.6	2.9	Controlled oversteer

5.6.4 Pitch Testing

To evaluate the vehicle's response to acceleration and braking, causing its front or rear to rise or dip (pitch). A straight track section where the vehicle can accelerate and brake safely. Sensors to measure pitch angle, acceleration, and deceleration forces.[97]

- **Test Procedure:**

1. Acceleration Test: From a standstill, the vehicle is accelerated rapidly to a specific speed.
2. Braking Test: At a constant high speed, brakes are applied firmly to bring the vehicle to a stop.
3. Data Analysis: Observing the pitch angle during these maneuvers helps understand weight distribution and suspension effectiveness.

Table 5.5 : Pitch Angles for Different Speed

Test Run No.	Test Type	Initial Speed (kmph)	Max Pitch Angle (degrees)	Time to Level Out (sec)	Observations
1	Acceleration	0	4.5	1.8	Smooth acceleration
2	Acceleration	0	4.7	2.0	Slight delay in leveling out
3	Braking	20	-5.2	2.3	Stable deceleration
4	Braking	20	-5.5	2.5	Noticeable front dip
5	Braking	40	-6.8	2.8	Pronounced nose dive
6	Braking	40	-7.0	3.0	Minor skidding observed

5.6.5 Rollover Testing

To assess the vehicle's susceptibility to rollover under various driving conditions.

- **Test Setup:** A closed track with a designated area to perform maneuvers. Rollover tests pose higher risks, requiring comprehensive safety measures.
- **Test Procedure:**

1. Fishhook Maneuver: A rapid steering input to induce potential rollover conditions.
2. J-Turn Test: A high-speed turn followed by sudden deceleration.
3. Tilt Table Test: For non-dynamic testing, a tilt table tilts the vehicle to determine the rollover threshold angle.

- **Data Analysis and Safety:** In-depth analysis of the collected data to assess the vehicle's dynamic behavior. Ensuring the vehicle meets regulatory standards and safety requirements.

Table 5.6 : Rollover Threshold Degrees at Different Speed and Test Type

Test Run No.	Test Type	Speed (kmph)	Manoeuvre	Rollover Threshold (degrees)	Observations
1	Fishhook	30	Left	28	Stable, no rollover
2	Fishhook	30	Right	27	Minor tire lift
3	J-Turn	40	Left	32	Approaching rollover threshold
4	J-Turn	40	Right	31	Controlled, no rollover
5	Slalom	35	Mixed	29	Stable through manoeuvre
6	Slalom	45	Mixed	35	Noticeable tilt, risky

5.6.6 Testing the Center of Gravity (CG)

Testing the Center of Gravity (CG) of a vehicle is crucial for understanding its stability and handling characteristics. The CG is the point where the vehicle's mass is considered to be concentrated, and its position significantly influences how the vehicle behaves, especially in terms of rollover risk, cornering, and braking. Here's an overview of how CG testing is typically conducted:

- **Preparation and Setup:** Ensure the vehicle is in a standard condition, with all fluids at normal levels and no additional load. Tires should be properly inflated and in good condition. A flat, level surface is essential for accurate CG testing. An indoor facility is often preferred to eliminate wind or other environmental factors. Scales or load cells are used to measure the weight distribution of the vehicle. Additional equipment may include height gauges and plumb lines for precise measurements.[98]

- **Testing Procedure:** Place scales under each wheel of the vehicle to measure individual wheel loads. The total weight of the vehicle is recorded. To determine the height of the CG Tilt Table Method is used. The vehicle is tilted until it tips over. The angle of tilt at the moment of tipping, combined with vehicle dimensions, is used to calculate the height of the CG. The longitudinal CG location can be determined by measuring front and rear axle weights. The lateral CG location is found by tilting the vehicle sideways or using calculations based on vehicle dynamics in cornering.
- **Data Analysis:** Use collected data and vehicle dimensions to calculate the CG location in three dimensions (X, Y, Z axes). Software tools and mathematical formulas are often employed for precise calculations.

Table 5.7 : CG Position Results by Using Tilt Table Method

Test Run No.	Method Used	CG Height (mm)	Longitudinal CG Location (% from front)	Lateral CG Location (% from left)	Observations
1	Tilt Table	508	55	50	CG centered, stable
4	Tilt Table	559	57	49	Higher CG, more rearward

5.6.7 Lateral Force Testing

Lateral force testing is a crucial aspect of evaluating a vehicle's handling characteristics, particularly its response to side forces during maneuvers like cornering or when subjected to side winds. This test is essential for assessing vehicle stability, tire performance, and the effectiveness of suspension systems under lateral load conditions. Here’s an overview of how lateral force testing is typically conducted. [99]

- **Preparation and Setup:** Ensure the vehicle is in standard driving condition, with appropriate tire pressure and alignment. Check that all systems, especially the suspension and steering, are functioning correctly. Equip the vehicle with sensors to measure lateral forces, tire slip angles, and vehicle dynamics (such as yaw rate and lateral acceleration). Data logging equipment is necessary to record the test results accurately.

- **Slalom Test Procedure**: A series of cones is set up in a straight line for the vehicle to weave through, applying lateral forces as it changes direction. The spacing of the cones and the speed of the vehicle can be varied to alter the test's intensity.
- **Data Analysis:** Analyze the lateral forces experienced by the vehicle and its stability in responding to these forces. Assess how the tires, suspension, and overall vehicle design cope with lateral loads. Evaluate the grip, slip angle, and response of tires under lateral forces. Determine the tire's contribution to overall vehicle stability and handling.

Table 5.8 : Lateral Force Observed and Vehicle Stability

Test Run No.	Test Type	Speed (kmph)	Max Lateral Force (N)	Lateral Grip Level	Vehicle Stability	Observations
3	Slalom	45	1700	High	Stable	Responsive steering
4	Slalom	55	2200	Medium	Unstable	Oversteer at higher speeds

5.6.8 Acceleration and Speed Test

To measure the vehicle's acceleration capability from a standstill to a specific speed (commonly 0 to 60 Kmph) and determine its top speed capabilities. This test provides insights into the vehicle's powertrain efficiency, motor performance, and overall dynamics.

- **Procedure:** Use a straight, flat, and well-maintained track, free of obstacles and traffic, to ensure safety and consistency in testing. The track should be long enough to safely achieve the target speeds and allow for braking. Ensure the vehicle is in a standard condition, with all fluids at optimal levels and tires properly inflated. Remove any unnecessary weight that could affect performance. Set up precise timing equipment at predefined intervals along the track to measure acceleration times accurately. GPS-based data loggers used for high accuracy.

- **Test Execution:** From a standstill, accelerate the vehicle as quickly as possible to the target speed (e.g., 60 Kmph). Record the time taken to reach each significant speed interval (e.g., 0-30 Kmph, 0-60 Kmph). Continue to accelerate the vehicle beyond the initial target speed to determine its top speed. Ensure this is done under controlled conditions, considering the vehicle’s safety limits. Perform several runs to ensure consistency and accuracy of the results. Account for variables such as wind direction, track conditions, and driver input.
- **Parameters Measured:**
  1. Acceleration Times: Specific times to accelerate from 0 to various speeds (e.g., 30 Kmph, 60 Kmph). These times are indicators of the vehicle’s responsiveness and power output.
  2. Top Speed: The maximum speed the vehicle can achieve on the track. Important for assessing the vehicle's performance capabilities and motor power limit.

Table 5.9 : Acceleration Test Results

Test Run No.	0 to 20 kmph (sec)	0 to 40 kmph (sec)	Top Speed Achieved (kmph)
1	3.2	6.5	58
2	3.1	6.4	57
3	3.0	6.3	59
4	3.2	6.6	60
5	3.1	6.5	58
Average	**3.1**	**6.5**	**58**

5.6.9 Range Test

To evaluate the vehicle's fuel efficiency and overall range. This test aims to determine how economically a vehicle consumes fuel under various conditions and the maximum distance it can travel on a full tank or charge.[100]

- **Procedure:** Use standardized driving cycles like the EPA cycle, which simulate urban, highway, and mixed driving conditions. Alternatively, conduct tests under real-world driving conditions, including city traffic, highways, and varying speeds. Ensure the vehicle is in a typical operating state, with regular maintenance performed. The is battery fully charged. Equip the vehicle withenergy monitors, GPS and data logging systems to accurately track distance and driving conditions.

- **Test Execution:**

1. Urban Driving Cycle:
    - Simulate city driving with frequent stops, lower average speeds, and idling periods.
    - Measure the energy use over a predefined urban route.
2. Highway Driving Cycle:
    - Simulate highway driving with steady higher speeds and minimal stops.
    - Record the energy consumption over a set highway distance.
3. Mixed Driving Cycle:
    - Combine elements of both urban and highway driving.
    - Useful for assessing the vehicle's overall efficiency in typical usage scenarios.
4. Range Test:
    - For assessing the total range, continue driving the vehicle until the battery is depleted.
    - Record the total distance traveled under the test conditions.

Parameters Measured:

- Energy Consumption
    - o The amount of kWh consumed per Km for electric vehicles.
    - o Key for evaluating vehicle efficiency and comparing it to standards or other vehicles.
- Total Range:
    - o The maximum distance the vehicle can travel on a a full battery charge.
    - o Critical for understanding the practicality and usability of the vehicle in real-world conditions.

Table 5.10 : Different Mode and Range Results

Test Run No.	Driving Cycle Type	Energy Consumption (kWh/100 Km)	Total Range (km)	Observations
1	Efficiency Mode	1.8	185	Efficient in stop-go traffic
2	Cruise Mode	2.5	130	Balanced urban/highway drive
3	Normal Mode	2.2	150	Longer range at steady speed

5.7 Performance Analysis

In this section, we delve into the findings from the Taguchi and regression analyses conducted on the vehicle prototype developed. This study aimed to unravel the impact of three critical variables - weight, camber, and tire width - on the vehicle's range. Understanding the influence of these factors is crucial for optimizing vehicle design, particularly in the context of enhancing battery efficiency and overall performance.

The Taguchi method, a robust statistical tool, was employed to determine the effect of design parameters on performance characteristics. This technique is pivotal in engineering applications, particularly in optimizing product design and manufacturing processes. It simplifies the complex interplay of multiple variables into a comprehensible format, enabling designers to pinpoint influential factors and their optimal levels. In our study, the focus was on understanding which of the three variables - weight, camber, and tire width - most significantly affects the vehicle's range.

Complementing the Taguchi analysis, a regression analysis was also performed. Regression analysis, a fundamental statistical tool, helps in understanding the relationship between dependent and independent variables. In our case, it was utilized to develop a predictive model for the vehicle's range based on weight, camber, and tire width. Such models are instrumental in forecasting performance outcomes under various scenarios, thereby guiding design decisions.

Both analyses are central to this study as they provide a comprehensive understanding of how each variable influences the vehicle's range. The insights gained from these analyses are not only crucial for this specific model but also have broader implications in the field of automotive engineering. They contribute to the evolving knowledge base on vehicle efficiency and are pertinent in the context of escalating environmental concerns and the push for sustainable automotive technologies.

5.7.1 Design and Analysis of Experiments

Experimental design is a robust statistical technique used to ascertain the unknown characteristics of the operational parameters in a given experiment and to analyze and simulate the interplay between the components involved. The conventional experimental design methodologies are excessively intricate and not user-friendly. Moreover, an extensive array of experiments must be conducted as the quantity of operating parameters escalates. Hence, it is imperative to identify and examine the causes responsible for variances in a controlled laboratory setting. These investigations fall within the realm of offline quality enhancement. [101]

5.7.2 Signal to Noise Ratio

In order to assess the quality characteristics of a product or process parameters, the Taguchi approach employs the signal-to-noise ratio (S/N ratio). It is also known as a statistical performance indicator. The signal-to-noise ratio is defined as the ratio between the mean (signal) and the standard deviation (noise). Regardless of the category of quality characteristics, selecting process parameters with the greatest signal-to-noise ratio consistently yields the highest quality, while minimizing fluctuation. The Taguchi technique generally employs three standard signal-to-noise (S/N) ratios.

- Reduced size is preferable.
- Nominal is the superior choice.
- Greater size yields superior results.

LB is selected as the chosen approach for this investigation, with the aim of maximizing the effectiveness of the cooling tower. Here, n is the total number of measurements taken during the experiments, including the parameters being measured. A graph is created to display the average efficacy mean and S/N ratios for each parameter at various levels. According to the signal-to-noise ratio (S/N ratio), a bigger value is considered better (LB), as it corresponds to higher efficacy values. [101]

5.7.3 Selection of Orthogonal Array (OA)

The Taguchi method utilizes an orthogonal array for experimental analysis. The orthogonal array is employed to decrease the quantity of trials conducted to analyze quality criteria. The optimal OA is chosen based on the overall number of degrees of freedom needed. The degrees of freedom (DOF) can be determined by considering the number of components, the number of levels for each factor, and the number of interactions. The research work does not take into account the interaction effect between the process parameters. The degrees of freedom for a system with three levels is 2, which is calculated by subtracting 1 from the number of levels. The total degrees of freedom (DOF) needed for three elements with three levels each is 6, which can be calculated as 3 multiplied by the difference between 3 and 1, resulting in 6. In the Taguchi method, the total degrees of freedom (DOF) of the selected orthogonal array (OA) must be greater than or equal to the total DOF needed for the experiment. Therefore, the L9 OA with eight degrees of freedom is chosen for this study. [101]

Table 5.11: Parameters and their Values

Level	Weight (N)	Camber Angle (Degree)	Tire Width (mm)
1	2400	0	90
2	2600	1	100
3	2800	2	110

The combination of parameters for experimentation is acquired by utilizing the Taguchi L9 array and setting the level to 3 in the Minitab software. The table provided is labeled as Table 4.2.

Table 5.12 : Taguchi L9 array for Experimentation

Sr. No.	Weight (N)	Camber (Degree)	Tire Width (mm)
1	2400	0	90
2	2400	1	100

Sr. No.	Weight (N)	Camber (Degree)	Tire Width (mm)
3	2400	2	110
4	2600	0	100
5	2600	1	110
6	2600	2	90
7	2800	0	110
8	2800	1	90
9	2800	2	100

5.7.4 Analysis of Variance (ANOVA)

ANOVA is a highly prevalent strategy for identifying significant factors that influence a response and quantifying their impact. The primary cause of non-reproducibility in cooling tower performance is the lack of control over the test facility and the operating conditions of the cooling tower. The F-test in ANOVA refers to the ratio between the variance of the process parameter and the error variance. It assesses if the parameter has a substantial impact on the quality attributes. This procedure involves comparing the F-test statistic of the parameter with the critical value (F0.05) at a significance level of 5%. If the F-test value exceeds the critical value of F0.05, the process parameter is deemed to be statistically significant. It is evident that all factors are significant. The user's text is enclosed in tags.

5.7.5 Taguchi Analysis: Range versus Weight, Camber, Tire Width

The Taguchi analysis in this study offers critical insights into how weight, camber, and tire width influence the range of the vehicle. This methodical approach employs a systematic and efficient plan for experimentation, which is particularly advantageous in settings where multiple variables are at play.

The central premise of the Taguchi method is its focus on the concept of the signal-to-noise (S/N) ratio. This ratio is a measure of the robustness of the system's performance characteristic. In our context, it was used to assess which of the three variables - weight, camber, and tire width - most robustly impacts the vehicle's range. The analysis revealed that the weight had the most significant effect, followed by tire width and camber. This finding is crucial as it underscores the importance of weight in vehicle design, particularly in its role in influencing the range.

The Taguchi method's emphasis on 'larger-the-better' for the S/N ratio aligns perfectly with the goal of maximizing the vehicle's range. By ranking the variables based on their delta values, the method provides a clear hierarchy of their impact levels. The analysis thus guides designers and engineers in prioritizing their focus on weight reduction strategies, as it emerged as the top-ranked factor.

Moreover, the Taguchi method's ability to handle complex interactions between design parameters makes it an invaluable tool in automotive engineering. Its application in this study not only enhanced the understanding of individual variable impacts but also provided insights into their collective influence on the vehicle's range. This comprehensive understanding is essential for making informed design decisions that can lead to significant improvements in vehicle performance and efficiency.

5.7.6 Regression Analysis

The regression analysis conducted as part of this study serves as a cornerstone for developing a predictive model for the vehicle's range. This statistical approach is instrumental in quantifying the relationship between dependent and independent variables, which, in this case, are the range and the factors of weight, camber, and tire width, respectively.

The regression model derived from the analysis encapsulates the intricate relationship between the range and the three variables. It suggests a negative correlation, indicating that an increase in weight, camber, and tire width tends to decrease the range of the vehicle. This inverse relationship is particularly pronounced for weight, as highlighted by its coefficient and P-Value in the model. The model thus serves as a quantitative tool, enabling predictions about how changes in these variables can affect the vehicle's range. Such predictive capability is invaluable in the design phase, where various scenarios can be simulated to assess their impact on performance.

However, the model's moderate R-squared value and its lack of statistical significance at conventional levels indicate that it may not fully capture the complexity of the relationships between these variables and the vehicle's range. This suggests that other factors, not included in the model, might also have a significant impact. The moderate predictive power of the model implies that while it provides useful insights, it should be used with caution, and its predictions should be validated against real-world data.

The regression analysis contributes significantly to our understanding of how weight, camber, and tyre width interact to influence the vehicle's range. Although the model has limitations in its predictive power, it offers a foundational framework that can be built upon with further research. Incorporating additional variables and refining the model can lead to more accurate predictions, ultimately aiding in the design of more efficient and high-performing vehicles.[101]

Perimeter
2.21 km

Area
975,076 ft²

Fig. 47 : Track Selected for Testing