| CHAPT | ER- I INTRODUCTION | 1 – 14 |
|-------|--|---------|
| 1.1 | Historical Development of Electrical Vehicle | 1 |
| 1.2 | Definition of an Electrical Vehicles | 3 |
| | 1.2.1 Battery Electric Vehicles (BEVs) | 4 |
| | 1.2.2 Hybrid Electric Vehicles (HEVs) | 4 |
| | 1.2.3 Plug-In Hybrid Electric Vehicles (PHEVs) | 4 |
| 1.3 | Configurations of Electric Vehicles | 4 |
| 1.4 | 3-Wheeled & 4-Wheeled Vehicles | 6 |
| | 1.4.1 3-Wheeled Vehicles | 6 |
| | 1.4.2 Advantages of Tadpole over Delta structure | 8 |
| 1.5 | Types of Tadpole structure Vehicle | 5 |
| | 1.5.1 Solar-Powered Tadpole | 8 |
| | 1.5.2 Hybrid Tadpole | 8 |
| 1.6 | Current State of Electrical Vehicle Technology | 9 |
| | 1.6.1 Lightweight Materials | 10 |
| 1.7 | Energy-Efficient Structures | 10 |
| | 1.7.1 Parameters of Energy-Efficient Structure | 11 |
| | 1.7.2 Benefits of Energy-Efficient Structures | 12 |
| | 1.7.3 Challenges Involved in Designing an Energy-Efficient | 12 |
| | Structure | |
| 1.8 | Problem Statement | 13 |
| 1.9 | Aim | 13 |
| 1.10 | Objectives of the Proposed Study | 14 |
| 1.11 | Scope | 14 |
| 1.12 | Hypothesis | 14 |
| CHAPT | ER- II REVIEW OF LITERATURE | 15 – 42 |
| 2.1 | Three-Wheeled Vehicle | 15 |
| 2.2 | Concept of tadpole structure | 16 |
| 2.3 | Corner Module Design | 17 |
| 2.4 | Tadpole Electric Vehicle | 17 |
| 2.5 | Components of Tadpole EV | 18 |

INDEX

| Index |
|-------|
|-------|

| 2.6 | Chassis | 20 |
|-------|--|---------|
| | 2.6.1 Wheelbase and Track Width | 21 |
| | 2.6.2 Center of Gravity | 21 |
| 2.7 | Steering System | 22 |
| | 2.7.1 Rollover Stability | 25 |
| | 2.7.2 Oversteer/ Understeer | 25 |
| 2.8 | Suspension Geometry | 26 |
| 2.9 | Rear Swing Arm | 27 |
| | 2.9.1 Types of Swing-Arm | 27 |
| | 2.9.2 Wheel Hub | 28 |
| | 2.9.3 Motor | 28 |
| 2.10 | Battery & Controller | 29 |
| 2.11 | Vehicle Dynamics | 30 |
| 2.12 | Regulations for South Asia for Small Electric Vehicles | 33 |
| | 2.12.1 Maximum weight and Speed Regulations | 33 |
| | 2.12.2 Maximum Overall Dimension Regulations | 34 |
| | 2.12.3 Motor Selection Regulations | 34 |
| 2.13 | Canadian Motor Vehicle Rule | 34 |
| 2.14 | SAE Driver Ergonomics | 35 |
| 2.15 | Design Approach | 36 |
| | 2.15.1 System Light Weight Design | 36 |
| | 2.15.2 Generative Design | 36 |
| 2.16 | Life Cycle Assessment (LCA) | 38 |
| 2.17 | Autonomous Tadpole Electric Vehicle (ATEV) | 38 |
| 2.18 | Indian Road Conditions | 39 |
| | 2.18.1 Overview of Indian Road Network | 39 |
| | 2.18.2 Challenges and Unique Characteristics | 40 |
| 2.19 | EV Performance Characteristics | 40 |
| 2.20 | Research Gaps | 42 |
| CHAPT | ER-III METHODOLOGY | 43 - 55 |
| 3.1 | Introduction | 43 |
| 3.2 | Importance of Designing Energy-Efficient Electric Vehicles | 43 |

| 3.3 | Rationale Behind Focusing on the Tadpole Structure | 43 |
|------|--|----|
| 3.4 | Outline of the Methodology | 44 |
| 3.5 | Research Design and Approach | 45 |
| | 3.5.1 Research Design | 45 |
| | 3.5.2 Justification for Research Design Choice | 45 |
| 3.6 | Literature Review | 45 |
| 3.7 | Initial Conceptualization | 46 |
| | 3.7.1 Defining Design Parameters | 46 |
| | 3.7.2 Initial Conceptualization | 46 |
| | 3.7.3 Design Approach: Creating an Energy-Efficient EV | 47 |
| | Structure | |
| 3.8 | Material Selection | 47 |
| | 3.8.1 Material Selection Criteria | 47 |
| 3.9 | Design Development | 48 |
| | 3.9.1 Establishing Design Parameters | 48 |
| | 3.9.2 Iterative Design Process | 48 |
| 3.10 | Research Design and Approach | 48 |
| 3.11 | Simulation and Analysis | 48 |
| | 3.11.1 Simulation Tools and Software Used | 49 |
| | 3.11.2 Process of Finite Element Analysis | 49 |
| | 3.11.3 Expected Outcomes | 49 |
| | 3.11.4 Vehicle Dynamics Simulation | 50 |
| | 3.11.5 Relevance to the Study | 50 |
| | 3.11.6 Suspension and Stability Analysis | 50 |
| 3.12 | Prototyping and Testing | 51 |
| | 3.12.1 Process of Physical Prototyping | 51 |
| | 3.12.2 Manufacturing Techniques | 51 |
| 3.13 | Description of Various Tests | 51 |
| 3.14 | Methodology of Testing | 52 |
| | 3.14.1 Data Collection and Analysis | 52 |
| | 3.14.2 Data Collection and Empirical Analysis | 53 |
| | 3.14.3 Road Condition Data | 53 |
| | 3.14.4 Data Collection Methods | 53 |

| Index |
|-------|
|-------|

| 3.15 | Analysis Techniques | 54 |
|-------|---|----------|
| | 3.15.1 Performance Analysis | 54 |
| 3.16 | Additional Considerations | 54 |
| СНАРТ | ER- IV DESIGN AND OPTIMIZATION | 56 – 97 |
| 4.1 | Chassis/ Frame Design | 56 |
| | 4.1.1 Design Considerations | 56 |
| | 4.1.2 Material Selection | 56 |
| | 4.1.3 Wheelbase and track | 57 |
| | 4.1.4 Position of centre of mass of a vehicle | 58 |
| | 4.1.5 Individual Static Wheel Loads and Front to Rear | 60 |
| | Weight Balance | |
| | 4.1.6 Un-sprung mass lateral force | 62 |
| | 4.1.7 Dimension Parameters & CAD Model | 63 |
| | 4.1.8 Calculations for Load | 66 |
| | 4.1.9 Impact Analysis | 66 |
| 4.2 | Rear Wheel Assembly Design | 71 |
| | 4.2.1 Selection of Motor | 71 |
| | 4.2.2 Swing Arm | 73 |
| | 4.2.3 Rear Wheel Swing arm assembly | 79 |
| 4.3 | Design of front wheel assembly and Suspension system | 80 |
| 4.4 | Steering System | 88 |
| 4.5 | Battery Selection | 92 |
| 4.6 | Braking System Design | 94 |
| СНАРТ | ER- V PROTOTYPE AND TESTING | 98 – 126 |
| 5.1 | Chassis Manufacturing for Tadpole Structured Electric | 98 |
| | Vehicle | |
| | 5.1.1 Design Considerations | 98 |
| | 5.1.2 Fabrication Techniques | 98 |
| | 5.1.3 Integration of the Roll Hoop | 98 |
| | 5.1.4 Surface Treatment and Finishing | 99 |
| | 5.1.5 Component Integration | 99 |
| 5.2 | Rear Swing Arm Manufacturing and Assembly | 99 |

| dex |
|-----|
| dex |

| | 5.2.1 Material Selection | 100 |
|-----|--|-----|
| | 5.2.2 Fabrication Techniques | 100 |
| | 5.2.3 Integration of Bushings and Bearings | 100 |
| | 5.2.4 Mounting of the Suspension Components | 100 |
| 5.3 | Upright Manufacturing Using CNC Machining | 101 |
| | 5.3.1 Material Selection | 101 |
| | 5.3.2 CNC Machining Process | 101 |
| | 5.3.3 Surface Treatment and Finishing | 102 |
| | 5.3.4 Integration and Assembly | 102 |
| 5.4 | Integration of Vehicle Components: Suspension, Steering, | 102 |
| | Motor, Battery, and Electrical Connections | |
| | 5.4.1 Mounting of Suspension Components | 102 |
| | 5.4.2 Steering System Assembly | 103 |
| | 5.4.3 Motor and Drive Train Installation | 104 |
| | 5.4.4 Battery System Integration | 104 |
| | 5.4.5 Electrical Connections | 105 |
| | 5.4.6 Electrical System and Wiring | 105 |
| | 5.4.7 Braking System Integration | 107 |
| 5.5 | Bill of Material and Cost Sheet | 109 |
| 5.6 | Prototype Testing | 110 |
| | 5.6.1 Brake Test | 110 |
| | 5.6.2 Aerodynamic Drag Test | 112 |
| | 5.6.3 Yaw Rate Testing | 114 |
| | 5.6.4 Pitch Testing | 115 |
| | 5.6.5 Rollover Testing | 115 |
| | 5.6.6 Testing the Center of Gravity (CG) | 116 |
| | 5.6.7 Lateral Force Testing | 117 |
| | 5.6.8 Acceleration and Speed Test | 118 |
| | 5.6.9 Range Test | 119 |
| 5.7 | Performance Analysis | 121 |
| | 5.7.1 Design and Analysis of Experiments | 122 |
| | 5.7.2 Signal to Noise Ratio | 122 |
| | 5.7.3 Selection of Orthogonal Array (OA) | 123 |

| | 5.7.4 Analysis of Variance (ANOVA) | 124 |
|-------|--|-----------|
| | 5.7.5 Taguchi Analysis: Range versus Weight, Camber, Tire Width | 124 |
| | 5.7.6 Regression Analysis | 125 |
| СНАРТ | ER- VI RESULT AND DISCUSSION | 127 – 139 |
| 6.1 | Weight | 127 |
| 6.2 | Camber | 127 |
| 6.3 | Tyre Width | 128 |
| 6.4 | Response Table for Signal-to-Noise Ratios | 129 |
| 6.5 | Analysis and Implications | 130 |
| 6.6 | Response Table for Means | 131 |
| 6.7 | Regression Analysis: Range versus Weight, Camber, Tyre | 132 |
| | width | |
| | 6.7.1 Regression Equation | 132 |
| | 6.7.2 Coefficients | 133 |
| | 6.7.3 Model Summary | 133 |
| 6.8 | Main Effects and Interaction Plots for Range | 137 |
| | 6.8.1 Main Effects Plot for Range | 137 |
| | 6.8.2 Interaction Plot for Range | 137 |
| 6.9 | Overall Results | 138 |
| CHAPT | ER- VII CONCLUSION AND FUTURE SCOPE | 140 - 142 |
| 7.1 | Conclusion | 140 |
| 7.2 | Future Scope | 141 |
| REFER | ENCES | 143 - 152 |

LIST OF TABLE

| Table No. | Particulars | Chapter Page No. |
|--------------|--|---------------------|
| 1.1 | Comparison of Three-wheel and Four-wheel Vehicles | 6 |
| 2.1 | Vehicle Class and Maximum Speed and Vehicle Weights | 33 |
| | [66] | |
| 2.2 | Overall Dimensions Limits for 3 – Wheelers | 34 |
| 2.3 | Motor Power (W) as Per the Vehicle Speed | 34 |
| 4.1 | Material Properties of AISI 4130 | 56 |
| 4.2 | Center of Mass of Vehicle | 59 |
| 4.3 | Individual Wheel Loads | 62 |
| 4.4 | Estimated vehicle chassis parameters | 65 |
| 4.5 | Front Impact Analysis Results | 68 |
| 4.6 | Side Impact Analysis Results | 70 |
| 4.7 | Rear Impact Analysis Results | 71 |
| 4.8 | Iteration of Chassis | 71 |
| 4.9 | Peak Current Calculation | 72 |
| 4.10 | Specifications of selected motor | 72 |
| 4.11 | Calculation of Maximum Acceleration | 73 |
| 4.12 | Material Properties | 74 |
| 4.13 | Weight Reduction and it's percentage | 75 |
| 4.14 | Ranking for geometry parameter | 77 |
| 4.15 | Observed Values of different Parameters | 78 |
| 4.16 | Multiplication Factors for Parameters | 78 |
| 4.17 | Total Weightage of Parameters and Ranking | 79 |
| 4.18 | Initial Design considerations for Front Wheel Assembly | 80 |
| 4.19 | Design Considerations & Parameters | 80 |
| 4.20 | Calculated Suspension Parameters | 84 |
| 4.21 | Material Properties of Al 6061 T6 | 84 |
| 4.22 | Double wishbone, damper to lower wishbone Incremental | 90 |
| | Geometry Values | |
| 4.23 | Steering System Parameters | 92 |

| Index | |
|-------|--|
|-------|--|

| Table No. | Particulars | Chapter Page No. |
|--------------|--|---------------------|
| 4.24 | Selected Battery Pack Specification | 92 |
| 4.25 | Braking Parameters and Values | 94 |
| 4.26 | Braking Parameters | 97 |
| 5.1 | Bill of Material and Cost | 109 |
| 5.2 | Brake Test Performance of Vehicle | 112 |
| 5.3 | Results of Aerodynamic Drag Coefficient113 | |
| 5.4 | Yaw Rate for Different Test Types | 114 |
| 5.5 | Pitch Angles for Different Speed | 115 |
| 5.6 | Rollover Threshold Degrees at Different Speed and Test | 116 |
| | Туре | |
| 5.7 | CG Position Results by Using Tilt Table Method | 117 |
| 5.8 | Lateral Force Observed and Vehicle Stability | 118 |
| 5.9 | Acceleration Test Results | 119 |
| 5.10 | Different Mode and Range Results | 121 |
| 5.11 | Parameters and their Values | 123 |
| 5.12 | Taguchi L9 array for Experimentation | 123 |
| 6.1 | Experimentation Results | 128 |
| 6.2 | Response Table for Signal-to-Noise Ratios | 129 |
| 6.3 | Response Table for Means | 131 |
| 6.4 | Parametric Constant and Coefficients | 133 |
| 6.5 | Model Summary | 133 |
| 6.6 | ANOVA & Regression | 133 |
| 6.7 | Overall Results | 138 |
| 7.1 | Optimized Parameters | 140 |

LIST OF FIGURE

| Fig. No. | Particulars | Chapter Page No. | |
|-------------|--|---------------------|--|
| 1 | Historical Development of EV | 2 | |
| 2 | General Configuration of EV | 3 | |
| 3 | EV Configurations | 5 | |
| 4 | Delta Structure | 7 | |
| 5 | Tadpole Structure7 | | |
| 6 | Current Electric Vehicle Scenario in India (ecogears.in) | 9 | |
| 7 | Performance of the three trained models by Ijaz et al. [36]. | | |
| | Decision jungle obtained highest average accuracy of 81% | | |
| 8 | Conceptual Design of Structure 16 | | |
| 9 | Wheel Base and Track Width | 21 | |
| 10 | Steering System Components (1. Steering Wheel, 2. | 22 | |
| | Column, 3. Rack & Pinion, 4. Tie Rod, 5. Upright) | | |
| 11 | Bump Steer | 24 | |
| 12 | Steering Geometry (Camber, Caster, Toe, KPI) | 25 | |
| 13 | Turning of Tadpole Vehicle | 25 | |
| 14 | Workflow of the matching algorithm proposed by Luo et | | |
| | al. [48] | | |
| 15 | Vehicle Dynamics [47], [62] | 31 | |
| 16 | Vehicle Forces on Inclination33 | | |
| 17 | SAE 30TH Percentile Male Model Driver Ergonomics 35 | | |
| 18 | ATEV Architecture 39 | | |
| 19 | Flow Chart of General Methodology Used for Research | 44 | |
| 20 | Design Approach | 47 | |
| 21 | Position of the Center of mass [53] | 58 | |
| 22 | Static Wheel Loads | 61 | |
| 23 | a) Side view of chassis b) Front view of chassis c) Top | 64 | |
| | view of chassis d) Isometric view of chassis | | |
| 24 | a), b) and c) Showing Front Impact Analysis | 68 | |
| 25 | d), e) and f) Showing Side Impact Analysis | 69 | |

Index

| Fig. No. | Particulars | Chapter Page No. |
|-------------|--|---------------------|
| 26 | g), h) and i) Showing Rear Impact Analysis | 71 |
| 27 | Weight and Shape Optimization Iterations | 75 |
| 28 | Loading Conditions for Rear Swing Arm | 76 |
| 29 | Iterations of Rear Swing Arm Analysis by using Ansys | 77 |
| | Software | |
| 30 | Rear wheel Assembly including Mono-shock Suspension | 79 |
| 31 | Lotus Suspension Analysis | 83 |
| 32 | Stresses Induced in Upright | 85 |
| 33 | Deformation in Upright 8 | |
| 34 | Stresses Induced in Lower A- Arm | 86 |
| 35 | Deformation in Lower A- Arm | 86 |
| 36 | Stresses Induced in Upper A- Arm | 87 |
| 37 | Deformation in Upper A- Arm | 87 |
| 38 | Front Wheel Assembly | 88 |
| 39 | Ackermann geometry for Tadpole Structure | 89 |
| 40 | Steering Parameters Analysis | 91 |
| 41 | Integrated Chassis 99 | |
| 42 | Rear Wheel Assembly 101 | |
| 43 | Front Wheel Assembly | 104 |
| 44 | Wire Diagram of Tadpole Structured EV | 106 |
| 45 | Braking System Master Cylinder | 108 |
| 46 | Track Selected for Braking & Acceleration Test 1 | |
| 47 | Track Selected for Testing | 126 |
| 48 | Main Effect plot for SN ratios | 130 |
| 49 | Main Effect Plot for Means | 131 |
| 50 | Pareto Chart of Standardized Effect | 134 |
| 51 | Normal Probability Plot | 134 |
| 52 | Residual Fits | 135 |
| 53 | Histogram of Frequency | 135 |
| 54 | Observation Order | 136 |

Index

| Fig. No. | Particulars | Chapter Page No. |
|-------------|-----------------------------|---------------------|
| 55 | Main Effects Plot for Range | 137 |
| 56 | Interaction Plot for Range | 137 |