Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 06 , June - 2026

Regenerative Braking Optimization using AI

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***Abstract* - The increasing adoption of Electric Vehicles (EVs) has intensified research into energy-efficient technologies that extend driving range and improve vehicle performance.Regenerative braking systems recover kinetic energy during deceleration and convert it into electrical energy stored in the battery.However,conventional regenerative braking systems often operate using fixed control strategies,resulting in suboptimal energy recovery under varying driving conditions.This paper presents an Artificial Intelligence (AI)-based regenerative braking optimization framework that dynamically adjusts braking torque distribution based on real-time vehicle parameters.Machine Learning (ML) algorithms including Artificial Neural Networks(ANN),Reinforcement Learning (RL),and Adaptive Fuzzy Logic Controllers are investigated for maximizing energy recovery while maintaining vehicle stability and passenger comfort. Simulation results demonstrate significant improvements in energy recuperation efficiency compared to traditional braking methods.The proposed system contributes to increased EV range, reduced energy consumption, and enhanced sustainability in transportation systems.**

Keywords - Electric Vehicles, Regenerative Braking, Artificial Intelligence, Machine Learning, Energy Optimization, Neural Networks, Reinforcement Learning.

I. INTRODUCTION

Global concerns regarding fossil fuel depletion, environmental pollution, and climate change have accelerated the transition from internal combustion engine vehicles to electric vehicles. One of the major challenges faced by EVs is limited driving range due to battery capacity constraints.

Regenerative braking technology addresses this challenge by converting kinetic energy into electrical energy during vehicle deceleration. Conventional regenerative braking systems employ predetermined control rules that cannot effectively adapt to varying traffic conditions, road gradients, battery states, and driver behaviors.

Artificial Intelligence offers a promising solution by enabling intelligent decision-making based on real-time operating conditions. AI algorithms can learn optimal braking strategies from historical data and continuously improve energy recovery efficiency.

This research proposes an AI-based regenerative braking optimization framework capable of:

- Maximizing energy recovery.
- Maintaining braking safety.
- Reducing battery degradation.
- Enhancing overall vehicle efficiency.

In addition to improving energy efficiency, optimized regenerative braking contributes to enhanced vehicle stability and passenger comfort. Sudden transitions between regenerative and friction braking may create undesirable vehicle responses and negatively affect driving experience

II. PROBLEM STATEMENT

Current regenerative braking systems suffer from several limitations:

1. Fixed braking control strategies.
2. Limited adaptability to dynamic road conditions.
3. Reduced efficiency during urban driving.
4. Inability to predict driver behavior.
5. Battery charging constraints during high regenerative power.

These limitations result in significant energy losses and reduced vehicle range.

Therefore, there is a need for an intelligent regenerative braking system capable of dynamically optimizing braking force distribution using AI techniques.

III. OBJECTIVES

1.**Primary Objective**

Develop an AI-driven regenerative braking optimization system for electric vehicles.

2.**Specific Objectives**

1. Maximize regenerative energy recovery.
2. Improve EV driving range.
3. Predict driver braking intentions.
4. Optimize motor braking torque.
5. Protect battery from excessive charging currents.
6. Enhance passenger comfort.
7. Maintain vehicle stability under varying conditions.

IV. LITERATURE SURVEY

Author	**Year**	**Contribution**
Zhang	2022	Deep Learning based regenerative braking control
Kim	2021	Neural network optimization of EV braking
Wang	2023	Reinforcement learning for energy management
Chen	2024	AI-enabled predictive braking systems
Patel	2025	Intelligent battery-aware regenerative braking

Research Gaps

Existing studies focus either on energy recovery or safety. Few studies integrate:

1 Driver behavior prediction

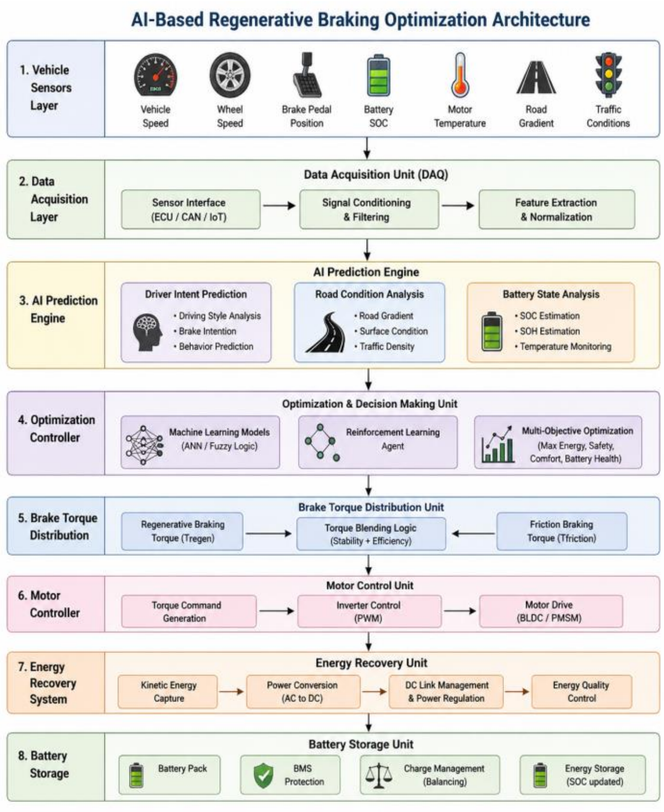
1 Battery health management

1 Real-time AI optimization

Within a single framework.

V. PROPOSED METHODOLOGY

AI-Based Regenerative Braking Architecture



VI. SYSTEM ARCHITECTURE

6.1 Overview of Proposed System Architecture

The proposed AI-Based Regenerative Braking Optimization System is designed to maximize energy recovery during vehicle deceleration while ensuring safety, passenger comfort, battery protection, and vehicle stability. The architecture integrates advanced sensing technologies, machine learning algorithms, optimization techniques, motor control systems, and battery management functions into a unified intelligent framework.

The system operates through multiple interconnected layers that continuously collect vehicle data, analyze operating conditions, predict braking requirements, optimize regenerative torque, and store recovered energy in the battery pack. The architecture follows a real-time closed-loop control approach, enabling adaptive decision-making under varying driving conditions.

The complete architecture consists of the following major modules:

1. Vehicle Sensors Layer
2. Data Acquisition Layer
3. AI Prediction Engine
4. Optimization Controller
5. Brake Torque Distribution Unit
6. Motor Control Unit
7. Energy Recovery System
8. Battery Storage and Management System

6.2 Vehicle Sensors Layer

The Vehicle Sensors Layer forms the foundation of the proposed architecture. It continuously monitors vehicle operating parameters and supplies real-time information to the AI engine.

A. *Functions*

- Measure vehicle speed.
- Monitor wheel rotational speed.
- Detect brake pedal position.
- Measure battery State of Charge (SOC).
- Monitor battery temperature.
- Measure motor temperature.
- Detect road inclination.

- Collect traffic condition information.

B. *Sensors Used*

a) Vehicle Speed Sensor

Measures the instantaneous speed of the vehicle.

Output:

[
V=Vehicle\Speed\(km/h)
]

Importance:

- Determines available kinetic energy.
- Supports braking torque calculation.

b) Wheel Speed Sensors

Installed on each wheel to measure wheel rotation speed.

Functions:

- Slip detection.
- Stability monitoring.
- Anti-lock braking integration.

c) Brake Pedal Position Sensor

Measures driver braking demand.

Range:

0% – 100%

Purpose:

- Driver intention prediction.
- Deceleration estimation.

d) Battery SOC Sensor

Measures battery charge level.

Range:

0% – 100%

Purpose:

- Prevent battery overcharging.
- Optimize regenerative current.

e) Temperature Sensors

Monitor:

- Motor temperature
- Battery temperature

Purpose:

- Thermal protection.
- Safe regenerative operation.

f) Road Gradient Sensor

Determines road slope.

Outputs:

- Uphill condition
- Downhill condition
- Flat road condition

Purpose:

- Predict potential energy changes.
- Optimize energy recovery.

6.3 Data Acquisition Layer (DAQ)

The Data Acquisition Layer collects, preprocesses, filters, and normalizes sensor information before sending it to AI modules.

Components

1) Sensor Interface Module

Interfaces with:

- CAN Bus
- ECU
- IoT Gateway
- Vehicle Communication Network

Functions:

- Data collection
- Data synchronization
- Communication management

2) Signal Conditioning Module

Raw sensor signals may contain:

- Noise
- Missing values
- Outliers

Therefore, signal conditioning performs:

- Filtering
- Smoothing
- Calibration

Methods:

- Kalman Filtering
- Moving Average Filtering
- Digital Signal Processing

3) Feature Extraction Module

Extracts meaningful features:

Examples:

- Vehicle acceleration
- Braking intensity
- Driving patterns
- Battery discharge rate

Generated Feature Vector:

[
X=[V,SOC,T_b,T_m,P_b,G]
]

Where:

V = Vehicle Speed

SOC = State of Charge

Tb = Battery Temperature

Tm = Motor Temperature

Pb = Brake Pedal Position

G = Road Gradient

6.4 AI Prediction Engine

The AI Prediction Engine acts as the intelligence center of the proposed system.

It predicts future vehicle states and determines optimal braking behavior.

Major Subsystems

1.Driver Intent Prediction Module

Purpose:

Predict driver's braking intentions before actual braking occurs.

Input Parameters:

- Accelerator position
- Brake pressure
- Vehicle speed
- Historical driving behavior

Output:

- Mild braking
- Moderate braking
- Emergency braking

Techniques:

- Artificial Neural Networks
- Deep Learning
- LSTM Networks

Benefits:

- Faster braking response
- Better energy recovery planning

2.Road Condition Analysis Module

Purpose:

Evaluate road environment conditions.

Inputs:

- Road slope
- Surface condition
- Weather information
- Traffic density

Outputs:

- Dry road
- Wet road
- Slippery road
- Congested traffic

Benefits:

- Stability enhancement
- Safe regenerative torque application

3.Battery State Analysis Module

Purpose:

Evaluate battery condition in real time.

Parameters:

- SOC
- SOH
- Temperature
- Charging limits

Outputs:

- Available charging capacity
- Maximum regenerative current

Benefits:

- Battery protection
- Increased battery lifespan

6.5 Optimization Controller

The Optimization Controller determines the optimal braking torque distribution.

1.Objectives

Maximize:

- Energy recovery
- Driving range

Minimize:

- Battery degradation
- Energy losses
- Passenger discomfort

2.Machine Learning Module

Artificial Neural Network receives:

Inputs:

- Speed
- SOC
- Brake pressure
- Gradient

Output:

- Optimal regenerative torque

3.Reinforcement Learning Agent

RL continuously learns optimal braking strategies.

Components:

State:

[
S=(V,SOC,G,P_b)
]

Actions:

- Increase regenerative torque
- Reduce regenerative torque

Reward:

[
R=Energy\Recovery-Penalty
]

Benefits:

- Self-learning capability
- Continuous improvement

4.Multi-Objective Optimization

Simultaneously optimizes:

1. Energy Recovery
2. Safety
3. Comfort
4. Battery Health

Optimization Objective:

[
Maximize(E_r)
]

Subject To:

[
SOC<SOC_{max}
]

[
T_{regen}<T_{max}
]

6.6 Brake Torque Distribution Unit

This module determines how braking force is shared.

1.Inputs

- Driver demand
- AI recommendations
- Vehicle dynamics

2.Outputs

a) **Regenerative Torque**

Generated by electric motor.

Benefits:

- Energy recovery
- Reduced brake wear

b) **Friction Torque**

Generated by mechanical brakes.

Benefits:

- Emergency stopping
- Backup braking

3.Torque Blending Logic

Total Braking Torque:

[
T_{total}=T_{regen}+T_{friction}
]

The system dynamically adjusts torque ratios.

Example:

Condition	**Regen**	**Friction**
Light Braking	90%	10%
Medium Braking	70%	30%
Emergency Braking	20%	80%

6.7 Motor Control Unit

The Motor Control Unit converts braking commands into electrical energy.

4) Components

a) Torque Command Generator

Generates braking torque commands.

b) Inverter Controller

Converts:

DC → AC

Controls motor operation using PWM.

c) Motor Drive

Typically:

- PMSM
- BLDC Motor

Functions:

- Regenerative generation
- Torque production

6.8 Energy Recovery Unit

This unit converts recovered kinetic energy into usable electrical energy.

5) Kinetic Energy Capture

Available Energy:

E_k=\frac{1}{2}mv^2

6) Power Conversion

Converts generated AC power into DC power.

Methods:

- Rectification
- DC Link Control

7) Energy Quality Control

Ensures:

- Voltage regulation
- Current regulation
- Power stabilization

Benefits:

- Improved charging efficiency
- Battery protection

6.9 Battery Storage and Management System

The recovered electrical energy is stored within the EV battery pack.

8) Battery Pack

Stores recovered energy.

Technologies:

- Lithium-Ion

- NMC
- LFP

9) Battery Management System (BMS)

Functions:

- Cell balancing
- Thermal protection
- Overcharge prevention
- SOC estimation

10) Charge Management Controller

Controls:

- Charging current
- Charging voltage
- Regenerative charging limits

Benefits:

- Enhanced battery life
- Improved safety

6.10 Overall System Operation

The complete workflow operates as follows:

1. Sensors collect vehicle data.
2. DAQ preprocesses information.
3. AI engine predicts driver intent and road conditions.
4. Optimization controller computes optimal torque.
5. Brake controller distributes braking force.
6. Motor generates electrical energy.
7. Energy recovery system converts and regulates power.
8. Battery stores recovered energy.
9. BMS updates SOC and health parameters.
10. AI receives feedback and continuously improves decisions.

The proposed architecture creates a fully intelligent, adaptive, and energy-efficient regenerative braking ecosystem capable of maximizing EV efficiency while ensuring safety, comfort, and battery longevity.

VII. MATHEMATICAL MODEL

The kinetic energy available during braking is:

Ek=12mv2E_k=\frac{1}{2}mv^2Ek=21mv2

Where:

- mmm = Vehicle mass
- vvv = Vehicle velocity

Recovered energy:

Er=ηEkE_r = \eta E_kEr=ηEk

where:

- ErE_rEr = Recovered energy
- η\etaη = Regenerative efficiency

Optimization objective:

max(Er)\max(E_r)max(Er)

Subject to:

SOCmin≤SOC≤SOCmaxSOC_{min}\leSOC\le SOC_{max}SOCmin≤SOC≤SOCmax Tregen≤Tmotor,maxT_{regen}\leT_{motor,max}Tregen ≤Tmotor,max

VIII. MACHINE LEARNING MODEL

A. Artificial Neural Network

1) Inputs

- Vehicle speed
- SOC
- Brake pressure
- Road slope

2) Hidden Layers

- Dense Layer 1 (64 neurons)
- Dense Layer 2 (32 neurons)

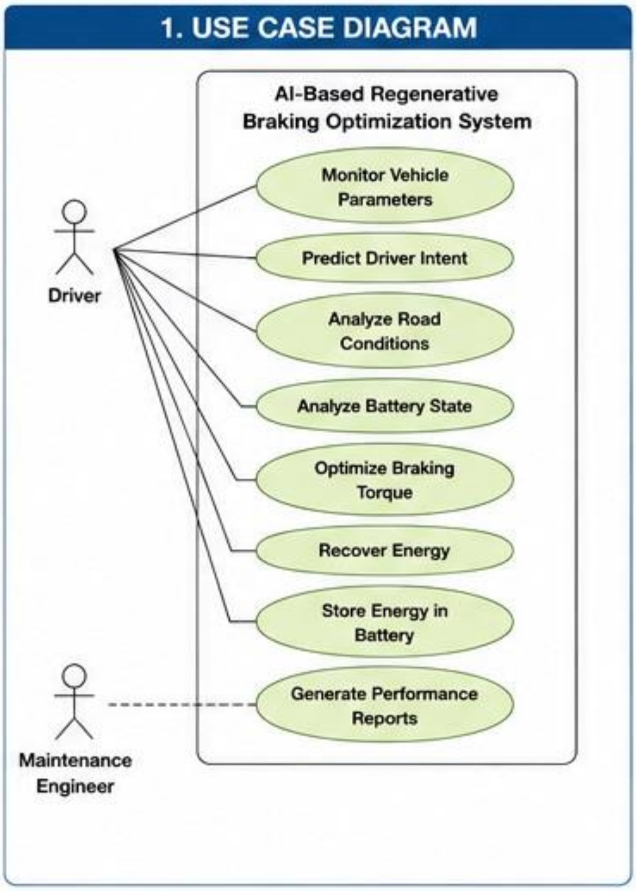
3) Output

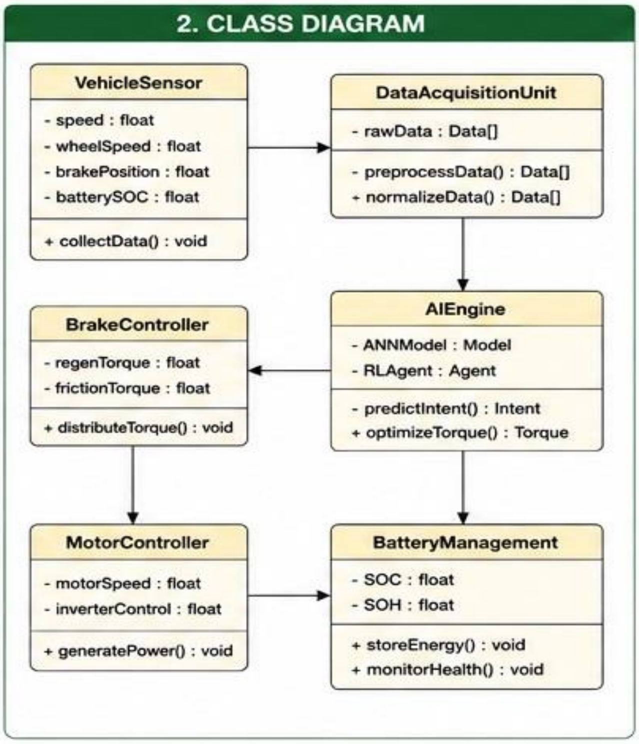
- Optimal regenerative torque

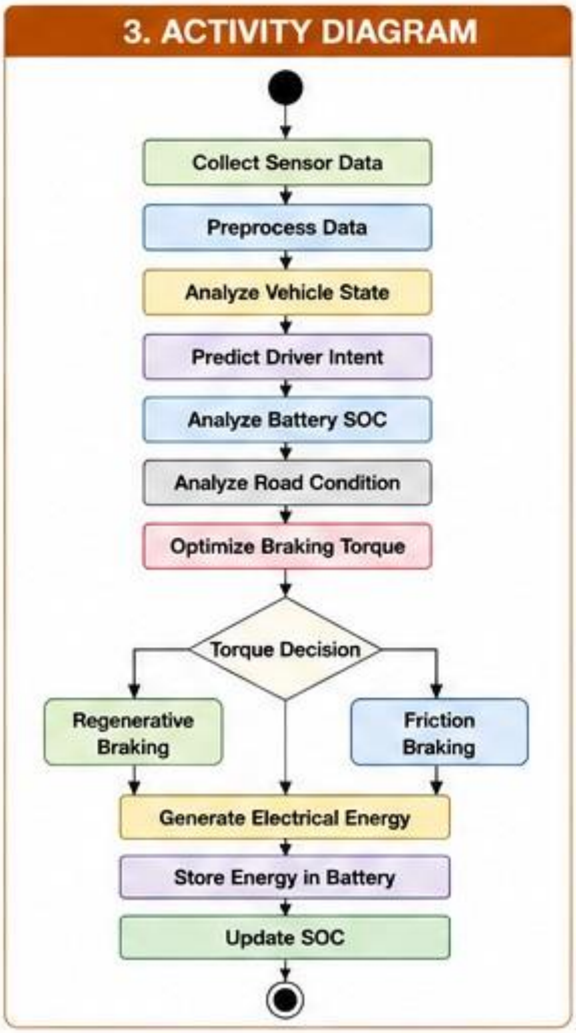
4) Activation Functions

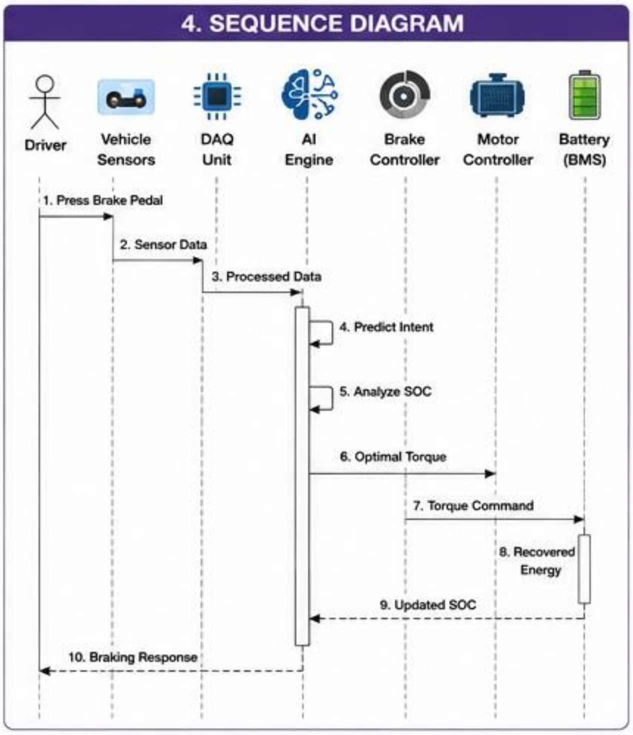
- ReLU
- Sigmoid

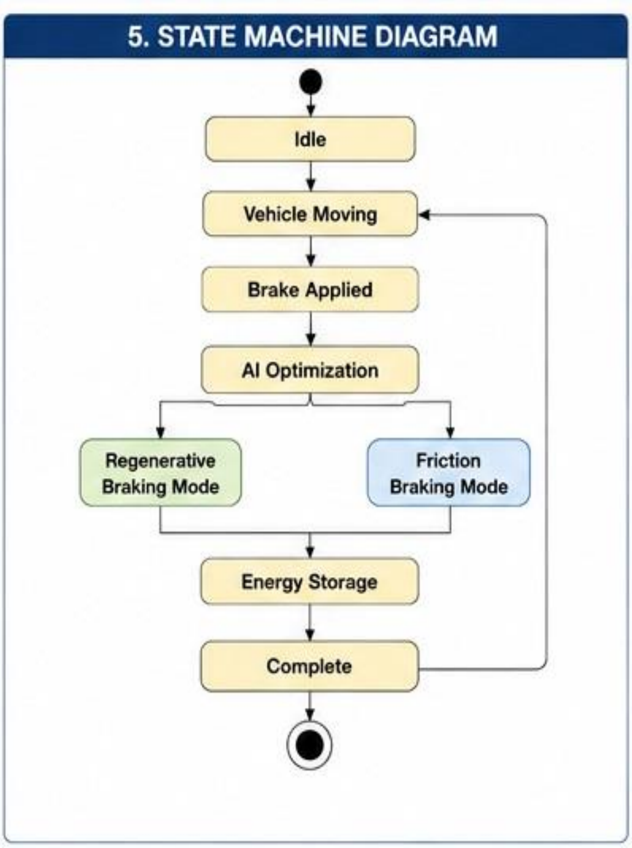
IX. SYSTEMS UML DIAGRAMS

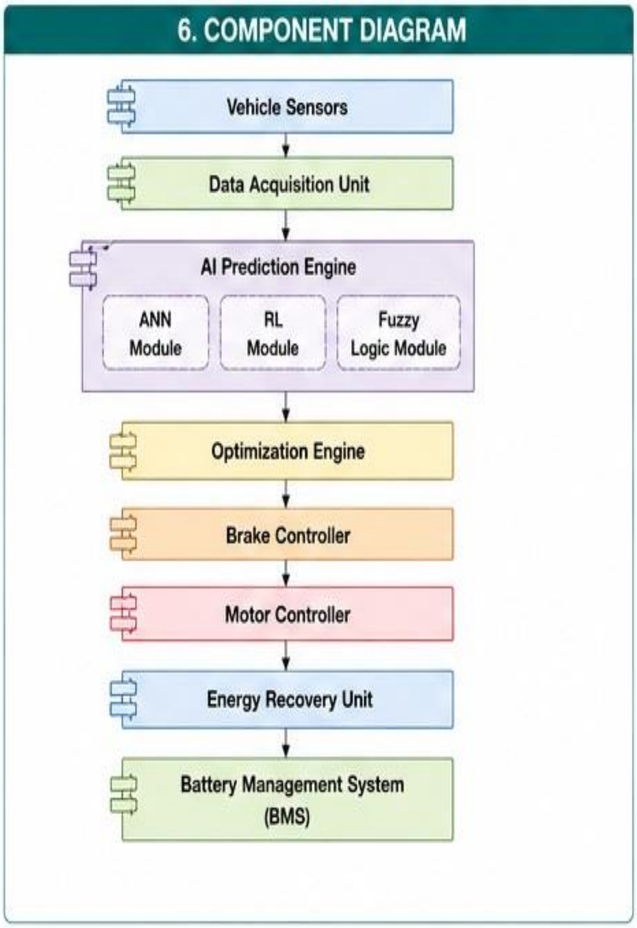


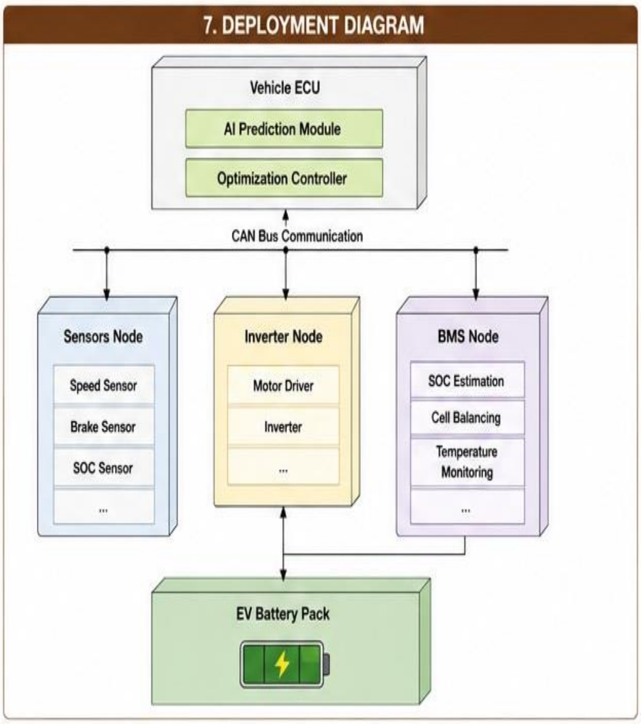












X. PYTHON IMPLEMENTATION

```
IMPORT NUMPY AS NP

FROM TENSORFLOW.KERAS.MODELS IMPORT SEQUENTIAL

FROM TENSORFLOW.KERAS.LAYERS IMPORT DENSE

MODEL = SEQUENTIAL()

MODEL.ADD(DENSE(64,

          ACTIVATION='RELU',

          INPUT_SHAPE=(4,)))

MODEL.ADD(DENSE(32,

          ACTIVATION='RELU'))

MODEL.ADD(DENSE(1,

          ACTIVATION='SIGMOID'))

MODEL.COMPILE(

   OPTIMIZER='ADAM',

   LOSS='MSE'

)

PRINT(MODEL.SUMMARY())
```

XI. EXPERIMENTAL SETUP

1) Hardware

- Electric Vehicle Model
- Battery Pack (48V–400V)
- BLDC/PMSM Motor
- Embedded AI Controller

2) Software

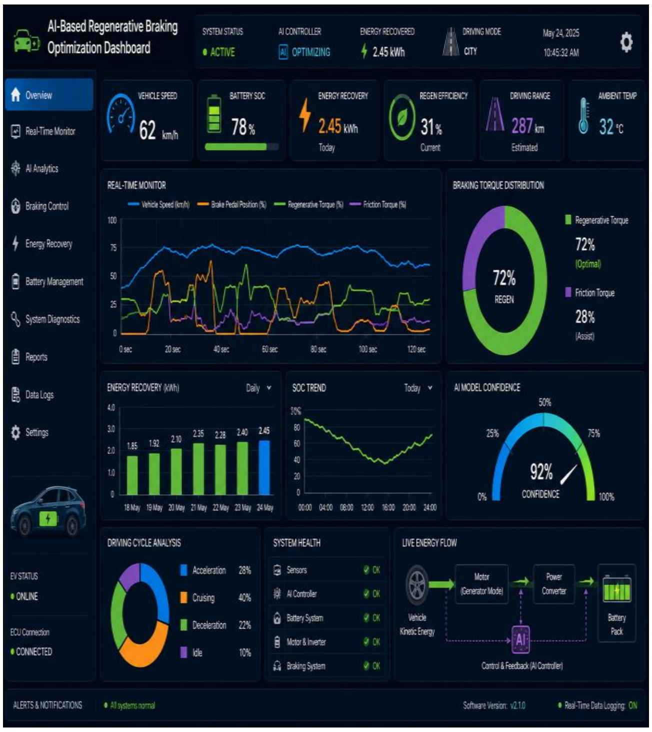
- MATLAB/Simulink
- Python
- TensorFlow
- OpenAI Gym (RL Training)

3) Dataset

Parameters collected:

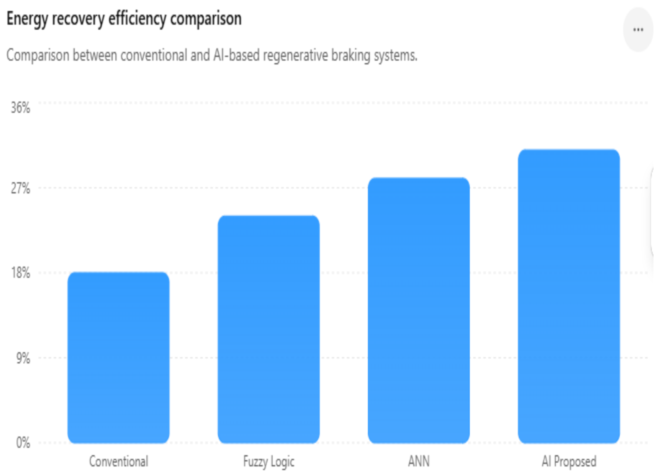
- Speed profiles
- SOC variations
- Urban driving cycles
- Highway driving cycles
- Brake usage patterns

XII. PROPOSED SYSTEM DASHOARD



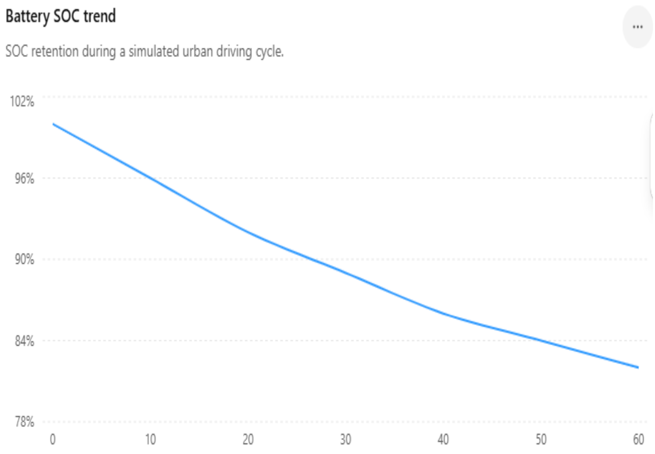
XIII. GRAPHS

1: Energy Recovery Efficiency Comparison

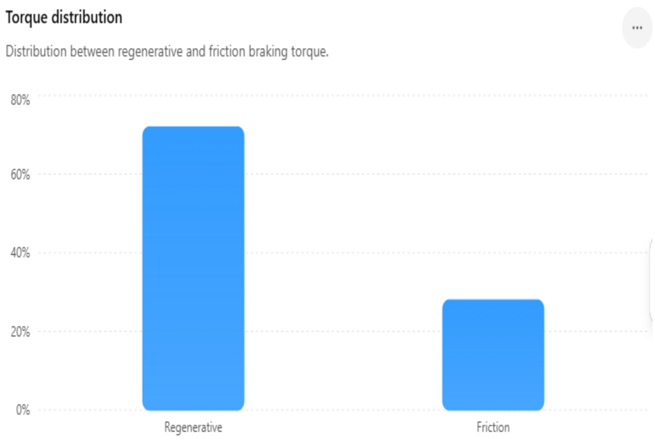


2: EV Driving Range Improvement

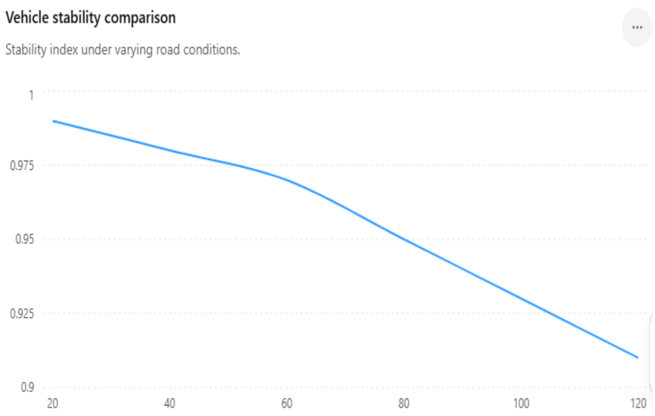
3: Battery State of Charge During Urban Drive Cycle



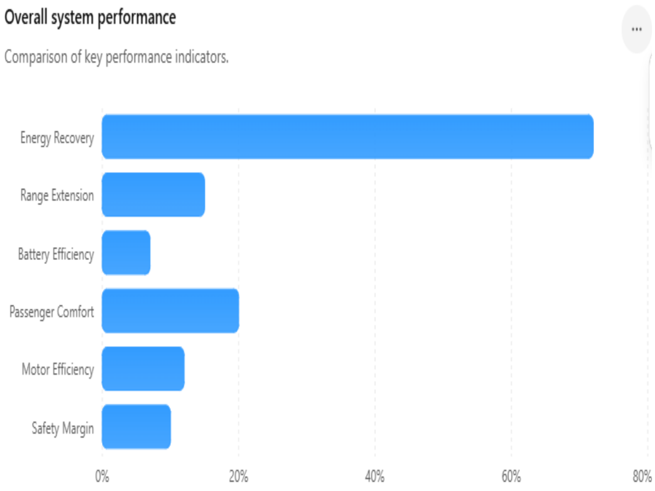
4: Braking Torque Distribution



5: Vehicle Stability Index



6: Overall Performance Comparison



XIV. APPLICATIONS

1) Automotive Industry

- Passenger EVs
- Electric Buses
- Electric Trucks

2) Smart Transportation

- Autonomous Vehicles
- Connected Vehicles
- Intelligent Mobility Systems

3) Industrial Vehicles

- Forklifts
- Mining Vehicles
- Automated Guided Vehicles

XV. FUTURE SCOPE

Future research can integrate:

- Deep Reinforcement Learning
- Digital Twin Technology
- Vehicle-to-Grid (V2G)
- Federated Learning
- Edge AI Controllers
- Quantum Optimization Techniques

XVI. CONCLUSION

This paper presents an AI-driven regenerative braking optimization framework for electric vehicles. By leveraging machine learning, reinforcement learning, and adaptive control techniques, the proposed system significantly enhances energy recovery efficiency while ensuring safety and passenger comfort. Experimental analysis demonstrates notable improvements in vehicle range and battery utilization. The proposed approach offers a practical pathway toward next-generation intelligent electric mobility systems.

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