# ENERGY-AWARE ISA CONTROLLER FOR HYBRID AND ELECTRIC VEHICLES USING REAL-TIME GEOLOCATION AND SOC-BASED SPEED OPTIMIZATION

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**Keywords:**

Plug-in Hybrid Electric Vehicle (PHEV), Intelligent Speed Adaptation (ISA), Battery State-of-Charge (SOC), Microscopic Traffic Simulation, SUMO, Eco-driving


**Introduction:**

Road safety and energy efficiency are major challenges for India's rapidly growing transportation sector. Over-speeding remains a leading cause of road accidents and fatalities, particularly near sensitive zones such as schools, hospitals, and residential areas. Simultaneously, the growing penetration of Plug-in Hybrid Electric Vehicles (PHEVs) introduces new opportunities and challenges for intelligent speed management and energy optimisation. PHEVs depend critically on managing battery State-of-Charge (SOC) and fuel use for optimal performance, yet existing navigation and speed control systems do not accurately integrate Indian road speed limits or account for PHEV-specific energy dynamics.

Intelligent Speed Adaptation (ISA) systems combine real-time speed-limit data with vehicle speed control and have shown worldwide potential for improving road safety and promoting eco-driving benefits. However, Indian roads present unique challenges including inconsistent speed-limit data in OpenStreetMap (OSM), diverse terrain types (urban, highway, hilly), and complex traffic patterns. Current ISA systems are designed primarily for uniform road conditions and do not integrate hybrid vehicle energy models or consider regenerative braking opportunities on varied Indian terrain.

This project addresses these gaps through two complementary components: (i) a working hardware prototype implementing GPS-based automatic speed control using Arduino Nano, Neo-6M GPS, HC-05 Bluetooth, ultrasonic sensor, L293D motor driver, and LCD display; and (ii) a simulation-based HybridEcoISA framework evaluating an SOC-aware, slope-sensitive intelligent speed adaptation controller for PHEVs on realistic Indian road networks using SUMO v1.26 with TraCI. This is the first simulation study to quantify the effects of speed-limit integration on PHEV energy use specifically for Indian traffic and road conditions. The work was presented at ICDTE-2025, RV Institute of Technology and Management, Bengaluru (Springer proceedings, Paper ID: 450).

**Objectives:**

1. Design and build a working prototype for automatic GPS-based vehicle speed control using Arduino Nano, Neo-6M GPS, HC-05 Bluetooth, ultrasonic sensor, DC motor, and L293D motor driver; include horn restriction in no-horn zones and automatic headlight switching.
2. Integrate OSM road geometries with MoRTH speed-limit augmentation into a SUMO microscopic traffic simulation using realistic Indian urban, highway, and hilly road networks.
3. Model a representative PHEV with physics-based tractive power computation and battery SOC dynamics, including fuel-equivalent energy estimation per Equations (1)–(3).
4. Implement and compare three controllers: Baseline (SUMO Krauss driver), ASCS (strict speed-limit enforcer via TraCI), and HybridEcoISA (two-level SOC-aware + slope-aware heuristic).
5. Evaluate all controllers across three Indian road scenarios using 20 random seeds per scenario measuring energy consumption, SOC trajectories, speed violations, and travel time.
6. Demonstrate the novelty of bridging a physical GPS-based working model with a simulation-validated energy-aware ISA controller suitable for real-world ITS deployments in India.

**Methodology:**

1. **Hardware Prototype:** Arduino Nano interfaces with Neo-6M GPS module (NMEA sentence parsing for latitude, longitude, speed at 1 Hz), HC-05 Bluetooth module (wireless monitoring and configuration), ultrasonic sensor (obstacle detection and emergency braking), L293D motor driver (PWM-based speed control), DC motor (traction), and I²C LCD display (zone status and speed feedback). A geofencing algorithm compares GPS coordinates with predefined restricted zones and automatically reduces motor PWM to enforce applicable speed limits without driver intervention. Integration tests on a scaled four-wheel chassis validated zone detection, speed enforcement, obstacle avoidance, and Bluetooth communication.
2. **Simulation Framework:** OSM road geometries for three Indian scenarios — Urban (Bengaluru city, bbox: 77.55°E–77.65°E, 12.9°N–12.98°N), Highway (Bengaluru ring road), and Hilly (Nandi Hills, 77.65°E–77.75°E, 13.3°N–13.4°N) — were imported and converted to SUMO net format using netconvert. MoRTH statutory speed tiers filled missing/inconsistent maxspeed attributes. Traffic demand was generated via origin-destination sampling. Each controller–scenario combination ran with 20 random seeds (statistical power >0.80). All experiments used SUMO v1.26, step-length 0.5 s, TraCI Python interface. Per-vehicle logs (speed, acceleration, slope, SOC, energy) recorded at every step.
3. **PHEV Energy Model — Equation (1):** $P_{req} = mav + 0.5\rho C_d A v^3 + mgC_r v + mgv\cdot\sin(\theta)$. Parameters: $m$=1600 kg, $C_d$=0.30, $A$=2.2 m², $C_r$=0.013, $\rho$=1.225 kg/m³, $g$=9.81 m/s². Battery: $E(t+\Delta t) = E(t) - P_{bat}\cdot\Delta t$; $SOC = E/E_{cap}$ ($E_{cap}$=8 kWh, $SOC_{init}$=0.8, $\eta$=0.95). Eq. (2): $E_{fuel} = P_{engine}\cdot\Delta t / \eta_{engine}$ ($\eta_{engine}$=0.35). Eq. (3): $E_{total} = E_{battery} + E_{fuel}$.
4. **HybridEcoISA Controller — Equations (4)–(6):** $V_{target} = V_{limit} - \Delta V_{SOC} - \Delta V_{slope}$. $\Delta V_{SOC}$: 8 km/h if SOC<0.68; 4 km/h if SOC<0.75; 0 otherwise. $\Delta V_{slope}$: −5 km/h

(controlled coasting) if slope<−1%; 0 otherwise. All controllers executed via TraCI every 0.5 s step. Evaluation: paired t-tests, 20 seeds, significance $p<0.05$.

**Result and Conclusion:**

Simulation results across all three Indian road scenarios show that HybridEcoISA consistently achieves the lowest total energy consumption, highest SOC preservation, and virtually eliminates speed violations, all with high statistical significance ($p=0.0000$):

| Scenario | Baseline (Wh) | ASCS (Wh) | HybridEcoISA (Wh) | Saving | p-value |
|---|---|---|---|---|---|
| Urban | 4352.1 | 4011.1 | 3976.0 | **8.6%** | 0.0000 |
| Highway | 4821.6 | 4366.1 | 4308.4 | **10.6%** | 0.0000 |
| Hilly | 3431.3 | 2730.7 | 2690.6 | **21.6%** | 0.0000 |

Speed violations were reduced by 99.6–100% across all scenarios. HybridEcoISA preserves higher battery SOC than both Baseline and ASCS by enabling regenerative braking through controlled downhill coasting. Travel time increased by only 3–5%, a reasonable trade-off given substantial improvement in energy efficiency and road safety. Hardware prototype validated GPS-based automatic zone detection and speed enforcement on a scaled test track. All results confirmed statistically significant across all scenarios ($p=0.0000$, paired t-test, 20 seeds).

**Project Outcome & Industry Relevance:**

HybridEcoISA achieves energy savings of 8.6–21.6% and near-complete violation elimination on Indian roads, matching or exceeding computationally intensive MPC and data-driven approaches at O(1) complexity — making it immediately deployable on existing embedded ECUs. The open-source simulation codebase (axhigowda.github.io/HybridEcoISA) provides a reproducible benchmark for future Indian ISA research. The work was presented at ICDTE-2025 (Springer, Paper ID: 450) and a full journal paper has been submitted to Transportation Research Part D: Transport and Environment (Elsevier, IF 7.3).

Industry relevance spans: (i) PHEV OEMs designing energy management for the Indian market; (ii) city traffic authorities evaluating ISA deployment under NITI Aayog smart city and EV mandates; (iii) fleet operators seeking fuel cost reduction; and (iv) road safety organisations addressing over-speeding fatalities. The $CO_2$ savings of 0.34–0.86 kg per 100 km per vehicle translates to over 15,000 tonnes $CO_2$e per year for Bengaluru alone by 2030, supporting India's transport decarbonisation targets under FAME-III.

**Working Model vs. Simulation / Study:**

This project combines both a physical working model and a simulation study. The hardware prototype (Arduino Nano + Neo-6M GPS + HC-05 Bluetooth + L293D motor driver + ultrasonic sensor + LCD) implements ASCS-equivalent geofenced speed enforcement on a scaled four-wheeled chassis, demonstrating real-time GPS zone detection, automatic speed reduction on zone entry, obstacle avoidance, and Bluetooth wireless monitoring — all validated on a physical test track.

The simulation component (SUMO v1.26 + TraCI Python + OSM Bengaluru road networks) provides the energy analysis framework where HybridEcoISA runs across 180 total simulation runs (20 seeds per controller per scenario). The two components are complementary: the hardware proves practical deployability while the simulation quantifies energy and safety benefits at scale. Future work will connect both via hardware-in-the-loop (HiL) testing, transmitting HybridEcoISA speed targets to the Arduino prototype via Bluetooth at 9600 baud.

**Project Outcomes and Learnings:**

**Technical Outcomes:**

1. Functioning 4-wheel GPS-based automatic speed control prototype with zone detection latency <200 ms and ±5% speed accuracy.
2. OSM-to-SUMO pipeline with MoRTH speed-limit augmentation for three Indian road scenarios.
3. Three ISA controllers implemented and validated across 180 simulation runs (20 seeds each).
4. 8.6–21.6% energy savings and 99.6–100% violation reduction (p=0.0000, Cohen's d = 2.34–3.18).
5. Published at ICDTE-2025 (Springer, Paper ID: 450); journal submission to Elsevier TRD in progress.

**Learnings:**

1. SUMO microscopic simulation, TraCI Python API, OSM data pipelines, and PHEV physics modelling.
2. Embedded systems: Arduino, GPS (NMEA parsing), Bluetooth, PWM motor control, ultrasonic sensing.
3. Statistical experimental design: paired t-tests, 20-seed variance analysis, Cohen's d effect sizes.
4. Academic writing, peer review process, and international conference presentation at ICDTE-2025.

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**Future Scope:**

The future scope of this project includes:

1. Reinforcement Learning (RL) Controller: Replace the rule-based HybridEcoISA heuristic with a DQN or PPO agent trained in SUMO to learn optimal SOC-speed-slope policies beyond hand-tuned thresholds.
2. Hardware-in-the-Loop (HiL) Validation: Connect SUMO simulation outputs to the physical Arduino prototype via Bluetooth/serial to validate the energy model against real motor power measurements.
3. Multi-City Evaluation: Extend simulations to Chennai, Pune, and Delhi networks to demonstrate geographic generalisation of the controller under diverse Indian road conditions.
4. Battery Thermal Modelling: Incorporate temperature-dependent SOC dynamics and charge-sustaining/charge-depleting mode switching for higher fidelity PHEV simulation.
5. Fleet-Level Multi-Agent Deployment: Scale HybridEcoISA to coordinated multi-agent fleets using digital twin frameworks and multi-agent RL for city-wide traffic and energy optimisation.
6. Real-World Driving Data: Collect actual PHEV driving data on Bengaluru roads to validate and calibrate the simulation energy model against real measurements.