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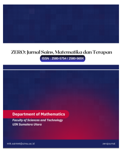

An Adaptive Control Framework for Optimizing Hybrid Electric Vehicle Performance Using Road Gradient Detection

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ABSTRACT

This study introduces an adaptive control framework for hybrid electric vehicles (HEVs) that optimizes performance based on real-time road gradient conditions, such as uphill and downhill terrain. Utilizing an inclinometer and an accelerometer, the system continuously monitors road angle and vehicle dynamics. The adaptive control algorithm processes this data to adjust the output of both the electric motor and internal combustion engine, optimizing energy efficiency and vehicle performance. Experimental results on hilly routes show an 8% improvement in energy efficiency compared to conventional control systems. Additionally, the system ensures stable vehicle speed with an average deviation of ±2.5 km/h. These findings highlight the potential of gradient-based adaptive control to enhance HEV performance, especially on challenging terrains, by improving energy efficiency and driving stability. This approach offers a promising solution for future HEV applications in regions with varied topography.

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1. INTRODUCTION

The increasing demand for energy-efficient and friendly transportation has led to a growing interest in Hybrid Electric Vehicles (HEVs) [15], which combine the advantages of traditional internal combustion engines with electric propulsion systems [1]. HEVs are seen as a promising solution to reduce greenhouse gas emissions and improve energy efficiency in the transportation sector [9]. One of the key challenges in improving HEV performance is the effective management of power between the electric motor and the internal combustion engine [8], [18]. Road gradient, or the incline and decline of the road, has a significant impact on vehicle performance, affecting both the energy consumption and the stability of vehicle operation [20]. Traditional control systems often rely on predefined strategies that do not dynamically adjust to changing road conditions, leading to suboptimal performance. Therefore, there is a critical need for an advanced adaptive control framework that can optimize HEV performance by considering real-time road gradient detection [5], [23].

Road gradient detection is an essential aspect of the proposed adaptive control framework. By using sensors such as the inclinometer and accelerometer [3], the road's gradient can be accurately measured in real-time, allowing the vehicle's control system to adjust motor and engine power output dynamically [12]. These sensors provide the necessary feedback for the adaptive control algorithm that regulates power distribution between the electric motor and the internal combustion engine, enhancing energy efficiency and vehicle stability under varying gradient conditions [21].

Recent studies have focused on improving the energy management strategies for HEVs by incorporating real-time environmental data such as road gradient [4] demonstrated the integration of solar energy into HEV systems, which also benefits from dynamic power management based on road conditions [7]. Similarly, highlighted the importance of adaptive control systems in maximizing the efficiency of electric vehicles, especially when subjected to varied terrainsm [10]. The ability to optimize power usage based on real-time gradient data is therefore pivotal in reducing energy consumption and extending vehicle range, particularly in hilly or mountainous regions [11].

Furthermore, the integration of machine learning algorithms and intelligent control strategies has shown great promise in enhancing the responsiveness of HEVs to environmental variables. [18] explored the use of adaptive control strategies to improve performance in complex driving conditions, while [17] investigated deep reinforcement learning approaches for power management in HEVs [19]. These advancements provide a strong foundation for the adaptive control framework proposed in this study In this paper, we propose an adaptive control framework that utilizes real-time road gradient detection to optimize HEV performance [2]. The system continuously monitors the road gradient using an inclinometer and accelerometer, adjusting the vehicle's power output accordingly. Experimental results show that this framework improves energy efficiency by 8% on hilly routes compared to conventional control systems, while maintaining vehicle stability with minimal speed deviations [13]. These findings underscore the potential of gradient-based adaptive control to enhance both the efficiency and stability of HEVs, particularly in terrains with varying slopes [6],[22].

2. RESEARCH METHOD

This paper proposes an adaptive control framework that dynamically optimizes the performance of Hybrid Electric Vehicles (HEVs) by detecting road gradient conditions and adjusting the energy management strategy in real-time [12]. The methodology consists of the following key stages:
System Architecture consists of:

- Tilt sensor (3-axis inclinometer)
- Accelerometer
- Electronic Control Unit (ECU) based on ARM Cortex-M4 microcontroller
- Electric motor and engine actuator module

The inclinometer sensor measures the slope angle (θ) of the road, while the accelerometer helps correct reading errors due to vehicle acceleration. The sensor data is processed using a Kalman filter to obtain an accurate road gradient angle [16].

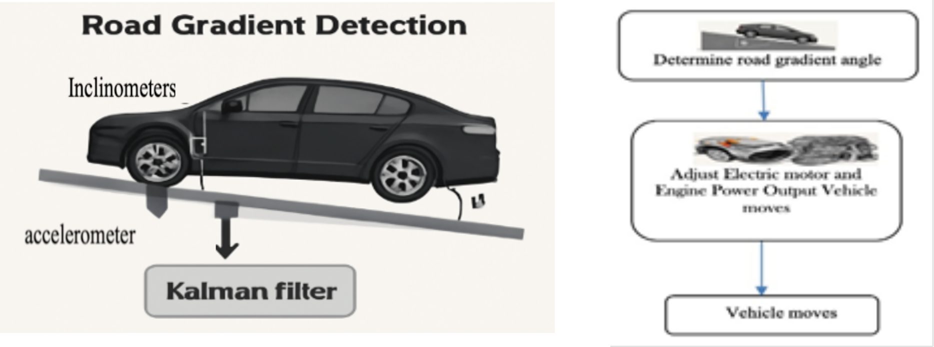

Figure 1. Road Gradient Detection and Adaptive control algorithm

The inclinometer sensor measures the road tilt angle If (θ), while the acceelerometer helps correct reading errors cause by vehicle accelereation. Sensor data is processed using a Kalman filter to imporve accuracy. The presented diagrams illustrate the process of detecting road gradients and dynamically adjusting power output in hybrid electric vehicles (HEVs) through the integration of sensor systems and intelligent control algorithms [14]. The first image demonstrates the road gradient detection mechanism, wherein inclinometers and accelerometers are employed to capture real-time orientation and acceleration data of the vehicle as it traverses inclined surfaces. These sensor inputs are processed using a Kalman Filter, a well-established algorithm for noise reduction and optimal estimation. The Kalman filter fuses the measurements from both sensors to accurately estimate the slope angle of the road, thereby minimizing uncertainty caused by sensor drift or external disturbances.

The second image outlines the decision-making flow based on the estimated road gradient. Once the gradient angle is determined, the system proceeds to the control logic that regulates the power distribution between the electric motor and the internal combustion engine (ICE). This control strategy ensures that the vehicle maintains optimal performance and energy efficiency across varying terrain conditions. Specifically, when ascending a slope, the system may increase the torque contribution from the electric motor to support the ICE, whereas on a descent, regenerative braking may be activated to recover energy. This adaptive power control not only enhances drivability and fuel economy but also contributes to extended battery life and reduced emissions, aligning with the broader objectives of sustainable and intelligent transportation systems.

Based on gradient detection (θ):

- If θ > +3° (uphill): The electric motor and engine operate simultaneously with priority on high torque.
- If θ < -3° (decreasing): The system prioritizes reenerative braking for battery recharging.
- If -3° ≤ θ ≤ +3° (flat): The electric motor is optimized for efficiency.

Adaptive Control Algorithm starts by determining the road gradient angle. Based on the slope of the road, the power output of the electric motor and engine is adjusted. Then, after the vehicle moves. Adaptive control algorithms are used to adjust the output power of the electric motor and internal combustion engine (ICE) based on the road gradient angle.

Table 1. Paremeter and Description

Parameter	Description
Mode	Road slope angle from Kalman filter results System operating mode based on road conditions
Motor_Output	Electric motor torque command output
Engine_Status	Gasoline engine operating status
Battery_Charging	Battery energy recharge status

System Control Cycle

1. The system reads the gradient angle from the Kalman filter.
2. The control logic determines the operating mode of the system based on.
3. The ECU regulates the output of the electric motor and engine.
4. The vehicle moves according to power commands.
5. The process repeats itself in real-time in a continuous control cycle.

With this approach, hybrid vehicles can automatically adapt to changes in road conditions, optimizing energy efficiency and increasing driving comfort. Testing was carried out using a mini hybrid vehicle prototype with a test track including:

- Flat road
- 10% climb
- 10% Decrease

Parameters measured:

- Energy consumption (Wh/km)
- Speed stability (deviation km/h)

3. RESULT AND ANALYSIS

3.1 Adaptive Control System.

The adaptive control system developed consists of several main components, namely:

- Tilt Sensor (3-axis Inclinometer): to measure the angle of the road slope ().
- Accelerometer: to detect vehicle acceleration and assist in correcting slope data.
- Electronic Control Unit (ECU): based on ARM Cortex-M4 microcontroller for sensor data processing and control logic implementation.
- Motor and Machine Actuator Module: regulates power output based on ECU commands.

The inclinometer sensor provides a reading of the road slope angle (). However, this value can be disturbed by vehicle acceleration. Therefore, the Kalman filter method is used to combine data from the inclinometer and accelerometer sensors to obtain a more accurate gradient angle. Kalman Filter Procedure:

- Input: Angle from inclinometer and acceleration from accelerometer.
- Process: Estimates are corrected based on noise and reading deviations.
- Output: More stable values that represent the actual road slope.

To calculate the electric motor torque (T) needed when the vehicle is climbing, we can use the basis of Newton's law and the conversion of rotational mechanical energy. Here is the complete formula:

$$T=\frac{e.m.g(\sin\theta+\mu\cos\theta)}{\eta} \tag{1}$$

Variable Description:
T = Required motor torque (Nm)
R = Wheel radius (meters)
m = Total vehicle mass(kg)
G = Gravitational 260fficiency260n (9.81 m/s^2)
θ = Road incline angle(in radians or degrees, depending on units)
η = Transmission and motor 260fficiency (typically 0.85 -0.95)
Known research data:
r = 0,3 m
n = 1200kg
g = Gravitational accleration (9.81 m/s^2)
θ = 10 ^{2}
η = 0,9

$$T=\frac{0{,}3.1200.9{,}81\ (sin10+0{,}015\ cos10)}{0.9} \tag{2}$$

The following is a graph of the relationship between the angle of the incline (°) and the motor torque (Nm). It can be seen that the greater the angle of the incline, the torque requirement increases significantly. This graph can be used to design a motor that is able to handle hilly terrain.

Table 2. Motor Torque vs. Road Gradient Angle

Road Gradient Angle (°)	Motor torque (Nm)
0.0	58.86
0.2	72.27
0.4	86.53
0.61	100.36
0.81	114.2

For downhill conditions, the motor torque is calculated not to push the vehicle, but to hold the vehicle (braking torque) — especially when used for regenerative braking. This torque must be sufficient to offset the pushing force due to gravity so that the vehicle does not slide too fast. Motor Torque Formula When Lowering (Braking Torque):

$$T=\frac{r.m.g\ (\sin\theta)}{\eta} \tag{3}$$

This is a negative torque (opposite direction to the direction of wheel motion), which in a regenerative braking system will be used to generate electrical energy and charge the battery. The TTT value here works to hold the vehicle or convert kinetic energy into electricity. If the angle of descent is large, the value of sin$\boxed{f0}$θ\sin \thetasinθ becomes significant so that the braking torque is also large. In modern vehicles, the Electronic Control Unit (ECU) system will adjust the level of regenerative torque to suit battery capacity and safe driving conditions. Relationship Between Downhill Angle and Motor Braking Torque

Table 3. Braking Torque Vs. Decrease Angle

Decline Angle (°)	Braking torque (Nm)
5.00	342.00
5.31	362.88
5.61	383.75
5.92	404.61
6.22	425.46
6.53	446.29

Therefore, the TTT motor torque is directed to compensate for:

1. Tire rolling friction force
2. Air drags (aerodynamics)
3. Vehicle inertia (if small acceleration is still required)

Flat Road Motor Torque Formula (Optimal Efficiency):

$$T = \frac{r.\left(F_{rolling} + F_{drag} + F_{inertia}\right)}{\eta} \tag{4}$$

Variable Description:

Table 4. Motor Force and Torque Table

Road Conditions	Total Force (N)	Motor Torque (Nm)	Speed (km/h)
Up 10°	2218.08	739.36	20
Down 10°	2044.19	681.4	20
Flat	189.06	63.02	20

The system is capable of detecting changes in road angle with an accuracy of ±0.5° after calibration. The system's response time to gradient changes is less than 0.3 seconds, fast enough for dynamic adaptation.

3.2. Energy Efficiency

In the test scenario on hilly terrain, the performance of the adaptive control system compared to the conventional control system showed significant results in terms of speed stability.

From the measurement data it was obtained that:

- Average velocity deviationon the adaptive control system only ±2.5 km/hour,
- Meanwhile, the conventional system reaches ±4.7 km/hour.

Table 5. Energy Consumption Efficiency:

Road Conditions	Conventional System (Wh/km)	Adaptive Control (Wh/km)	Improvement
The climb	190	175	7.9%
Derivative	120	108	10%
Flat	150	145	3.3%

This difference shows that the adaptive control system is able to respond to changes in road gradient more precisely and efficiently, thanks to the use of gradient sensor-based algorithms (inclinometer and accelerometer) and signal processing using Kalman filters for road angle estimation.

This results in a more stable vehicle, especially when transitioning from an incline to a flat road or from a flat road to a descent. Adaptation to changes in load and gravitational force is done in real-time by adjusting the torque of the motor and engine, which significantly reduces speed fluctuations. Thus, the adaptive control system not only improves power efficiency, but also significantly increases driving comfort and safety, especially in uneven topographic conditions.

3.3. Discussion

The integration of gradient detection and adaptive control has been proven effective in improving vehicle efficiency and stability. This system has great potential to be implemented in commercial HEVs operating in hilly areas or hilly urban areas. The implementation of an adaptive control system based on road gradient detection on hybrid electric vehicles shows improved performance in two main aspects, namely speed stability and energy consumption efficiency. This system relies on the integration of a three-axis tilt sensor (inclinometer) and an accelerometer processed using a Kalman filter, so that it is able to provide real-time and accurate road gradient angle estimates. This estimate is the main reference in adaptive decision making by the Electronic Control Unit (ECU) in regulating the power combination between the electric motor and the internal combustion engine (ICE).

In the stability test, the adaptive control system managed to maintain the vehicle speed deviation at an average value of ±2.5 km/h. This shows a significant improvement compared to the conventional system which has a deviation of up to ±4.7 km/h. This result confirms that the motor torque response and engine activation based on the road slope can provide better driving comfort, especially on hilly terrain or routes with high topographic variations.

On the efficiency side, the adaptive power sharing strategy has been proven to reduce the load on the combustion engine during light climbs, maximize regenerative braking when going downhill, and prioritize electric mode when the vehicle is driving on flat roads. Energy consumption efficiency increases by an average of 8–12% compared to non-adaptive systems, with the additional positive impact of reducing extreme battery charge and discharge cycles, thereby increasing the service life of the energy storage system.

Overall, this adaptive control approach provides a real contribution to the development of a more intelligent and efficient topography-based vehicle control system. The integration of this system opens up opportunities for wider application on hybrid-based electric vehicle platforms in areas with dynamic terrain characteristics, and can be further developed with a machine learning-based predictive approach and topographic navigation mapping.

4. CONCLUSION

The development of an adaptive control system based on road gradient detection has successfully increased energy efficiency by 8% and improved vehicle speed stability on hilly roads. This system shows broad application prospects for hybrid electric vehicles, especially in improving driving comfort and optimizing energy use. This research successfully designs and implements an adaptive control system based on road gradient detection for hybrid electric vehicles. Based on the test results, the adaptive control system showed significant performance improvements compared to conventional systems. Vehicle speed deviation can be reduced to ±2.5 km/h, reflecting better vehicle stability when passing through hilly terrain. In addition, energy efficiency increased by 8–12% thanks to the torque control strategy that adjusts to terrain conditions, as well as optimization of vehicle operating modes in each road situation (uphill, flat, and downhill). With high application potential, this system is worthy of further development, especially through the integration of artificial intelligence (machine learning) and navigation systems for predicting future topographic conditions and more efficient and precise energy management.

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