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Intelligent gear shifting in electric and hybrid vehicles: a CAN controller-based approach using SOC%

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ABSTRACT

The intelligent management of gear shifting in electric and hybrid vehicles (EVs and HEVs) is essential for optimizing energy efficiency, improving fuel economy, and enhancing driving comfort. Traditional gear shifting strategies, which are designed for internal combustion engine (ICE) vehicles, do not fully accommodate the unique dynamics of electric and hybrid powertrains. This paper proposes a novel approach for gear shifting in EVs and HEVs, integrating the state of charge (SOC%) of the battery as a critical input for decision-making. The proposed algorithm utilizes real-time data from the vehicle's controller area network (CAN), enabling seamless communication between the transmission control unit, battery management system, and powertrain control module. The algorithm adjusts gear shifting based on SOC%, vehicle speed, engine RPM, and throttle position, ensuring optimal use of the electric motor and internal combustion engine. At high SOC%, the algorithm prioritizes electric motor use to conserve fuel and extend battery life, while at lower SOC%, it switches to relying more on the combustion engine. The proposed method optimizes energy usage, enhances fuel efficiency, and prolongs battery life by adapting the shifting strategy to varying driving conditions.

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1. INTRODUCTION

As demand for more sustainable transportation solutions grows, hybrid electric vehicles (HEVs) and battery electric vehicles (EVs) have emerged as leading alternatives to traditional internal combustion engine (ICE) vehicles. These vehicles, powered by both electric motors and internal combustion engines, offer significant advantages in fuel efficiency, reduced emissions, and a smaller environmental footprint. With the increasing market share of EVs and HEVs, it is essential to develop advanced control systems that optimize vehicle performance, energy management, and driving comfort [1], [2]. A key area for improvement is optimizing gear shifting strategies, a critical component of the powertrain that directly influences energy efficiency and fuel economy. Traditional gear shifting mechanisms in ICE vehicles operate based on engine speed (RPM), throttle position, and vehicle load. These systems typically shift gears automatically or manually based on predefined parameters such as vehicle speed or engine load. However, these strategies do not account for the dual power sources in HEVs and EVs, where the electric motor and internal combustion engine operate under distinct performance characteristics. The electric motor provides high torque at low speeds, making it ideal for urban driving with frequent stops. Conversely, the internal combustion engine delivers additional power for high-speed driving or when the battery charge is low.

This dual powertrain introduces challenges in gear shifting, as EVs and HEVs require more sophisticated strategies than ICE vehicles [3]-[5]. State of charge (SOC%) plays a vital role in determining whether to use the electric motor or the combustion engine. SOC% reflects the amount of charge remaining in the battery and influences powertrain control. Traditional gear shifting strategies, which focus only on engine RPM and vehicle speed, are insufficient for EVs and HEVs. Adaptive algorithms, accounting for SOC%, vehicle speed, load, and throttle position, are necessary to optimize energy usage. For example, a high SOC% allows for prioritizing electric motor use to maximize efficiency, while a low SOC% triggers the internal combustion engine to conserve battery power and extend driving range. The need for intelligent, data-driven gear shifting systems is critical in HEVs and EVs. By utilizing real-time data from the controller area network (CAN), which facilitates communication between control units like the powertrain control unit (PCU), battery management system (BMS), and transmission control unit (TCU), the vehicle can make informed decisions about gear shifting. CAN enables real-time data exchange, ensuring efficient powertrain management. The proposed gear shifting algorithm uses SOC%, along with vehicle speed, engine RPM, and throttle position, to determine optimal gear shifts. This algorithm dynamically adjusts to varying SOC% levels, optimizing the vehicle's performance at all times.

2. HYBRID AND ELECTRIC VEHICLE POWERTRAIN

Figure 1 shows the gear shifting in electric and hybrid vehicles. The powertrain of HEVs and battery EVs is fundamentally different from traditional ICE vehicles [6]. While ICE vehicles rely solely on a combustion engine to power the vehicle, hybrid and electric vehicles utilize a combination of both electric motors and internal combustion engines. This dual power source approach is designed to maximize fuel efficiency, reduce emissions, and improve overall performance. The electric motor in HEVs and EVs is primarily responsible for providing high torque at low speeds. It is most effective during low-load conditions such as city driving, where frequent stops and low-speed driving occur. In these conditions, the electric motor allows for smoother acceleration and deceleration without consuming fuel. Additionally, during regenerative braking, the electric motor converts kinetic energy back into electrical energy, which is stored in the battery, enhancing the vehicle's overall efficiency.

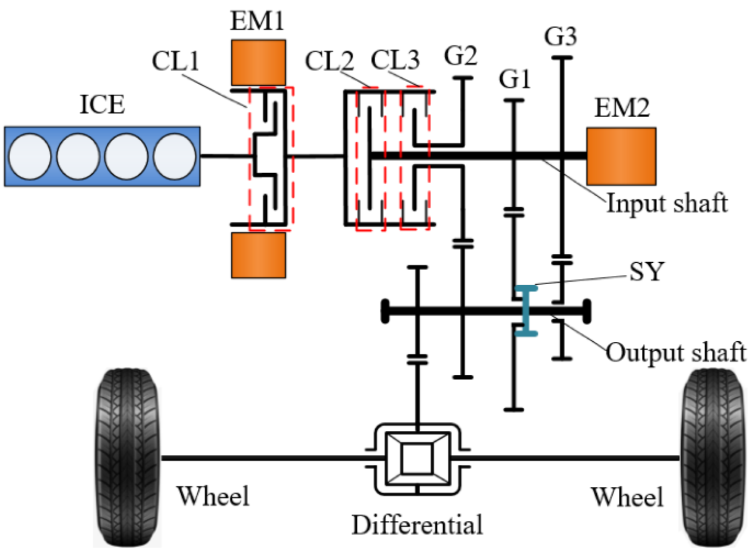

Figure 1. Gear shifting in electric and hybrid vehicles

2.1. Importance of SOC% in gear shifting

The SOC% is a key parameter in electric and hybrid vehicles, providing real-time information about the battery's charge level. The SOC% directly impacts how the vehicle's powertrain operates, influencing the balance between the electric motor and the internal combustion engine. The SOC% can be divided into three distinct ranges, each influencing the powertrain strategy:

i) High SOC% (80%-100%): When the SOC% is high, the battery is well-charged, and the electric motor should be prioritized for propulsion [7]. Using the electric motor in this range conserves fuel and maximizes energy efficiency, as the vehicle can rely on the clean, low-emission electric power. Additionally, when the SOC% is high, the system can shift to higher gears, allowing for smoother and more efficient operation in urban or low-speed conditions.
ii) Moderate SOC% (50%-80%): In this range, the vehicle can adopt a more balanced approach, utilizing both the electric motor and the internal combustion engine. The system can switch between power sources based on driving conditions, optimizing energy usage. For example, the electric motor can be used in city driving or during low-load conditions, while the ICE may be engaged during higher loads or for longer trips. The transmission system may adjust to more adaptive gears in this range to maintain performance and energy efficiency.
iii) Low SOC% (<50%): When the SOC% drops below 50%, the battery charge is considered low, and the vehicle should rely more heavily on the internal combustion engine to avoid excessive depletion of the battery. At this point, using the electric motor becomes less efficient, as the vehicle's range would be severely limited without recharging the battery. The system may also adjust the transmission to lower gears for more efficient operation, particularly during highway driving or when higher power output is required. By utilizing SOC% in the gear shifting strategy, an intelligent system ensures that the vehicle operates at its optimal efficiency in all conditions. This not only maximizes fuel efficiency but also helps extend the life of the battery by preventing deep discharges and maintaining an optimal charge level. Intelligent gear shifting based on SOC% allows the vehicle to make dynamic adjustments that optimize both energy usage and driving performance. By switching between the electric motor and ICE appropriately, the system can ensure that the vehicle remains energy-efficient while still offering the necessary performance for various driving conditions [8]-[10].

2.2. Role of CAN bus in hybrid and electric vehicles

In modern hybrid and electric vehicles, the need for real-time communication between various control units is essential for efficient powertrain management. This communication is facilitated by the CAN bus, a robust and widely used vehicle communication protocol that allows the exchange of data between different electronic control units (ECUs). These ECUs include the PCU, BMS, TCU, and other components critical for the vehicle’s operation. The CAN bus acts as the backbone of data transfer within the vehicle, enabling various components to communicate and share critical information that is essential for making real-time decisions about powertrain operation [11]-[15]. By connecting the key systems in the vehicle, the CAN bus ensures that the gear shifting algorithm can access and respond to data inputs such as: i) SOC%: The vehicle’s battery state of charge, providing vital information for determining whether to rely on the electric motor or internal combustion engine. ii) Vehicle speed: Essential for determining when to shift gears and how to balance power distribution between the electric motor and ICE. iii) Engine RPM: Provides information about engine load, which helps determine whether the electric motor or ICE should be used. Table 1 presents the EVs vs HEVs regarding gear shifting. This table explained features of EV and HEVS.

Table 1. EVs vs HEVs regarding gear shifting

Feature/aspect	Electric vehicles (EVs)	Hybrid electric vehicles (HEVs)
Primary power source	Electric motor only	A combination of an ICE and an electric motor
Transmission type	Mostly single-speed	Typically, a multi-speed automatic or e-CVT
Need for gear shifting	Not applicable (in most models)	Required to manage ICE performance
Torque characteristics	High torque available at low RPM – no need for shifting	ICE needs gear shifting for efficient torque and speed control
Complexity of drivetrain	Simpler (due to no gearbox)	More complex (due to the integration of ICE and electric drive)
Examples	Tesla Model 3, Nissan Leaf (single-speed)	Toyota Prius, Honda Insight (gear shifting involved)
Performance considerations	Some high-end EVs may use 2-speed (e.g., Porsche Taycan)	Gear shifting helps optimize ICE efficiency and emissions
Maintenance requirements	Lower (no clutch or gear shifting parts)	Higher (transmission components require maintenance)

3. METHODOLOGY

3.1. Algorithm design for SOC%-based gear shifting

The design of an efficient SOC%-based gear shifting algorithm is essential to optimize the energy management and driving experience in hybrid and electric vehicles. The algorithm uses key vehicle parameters such as SOC%, vehicle speed, engine RPM, and throttle position to make real-time decisions about gear shifts. Each of these inputs influences how the powertrain should operate, balancing the use of the electric motor and ICE [16]-[20]. The core objective of this algorithm is to maintain maximum energy efficiency while ensuring that the vehicle's performance is never compromised. The design approach considers the following input variables: SOC%: The percentage of battery charge remaining, which determines the available energy and thus influences the powertrain decision. Vehicle Speed: The current speed of the vehicle, which plays a crucial role in determining whether higher or lower gears should be engaged. Engine RPM: The rotation speed of the engine, which is critical for ensuring that both the electric motor and the ICE operate within their optimal RPM range to avoid excessive wear or inefficiency. Throttle Position: Indicates how much the driver is pressing the accelerator pedal. A higher throttle position implies a demand for more power, which may require the engagement of the internal combustion engine.

The algorithm operates in three primary states based on the SOC%, each dictating different behavior for the gear shifting process. The design is as follows:

i) High SOC% (>80%):

When the battery charge is high, the system prioritizes electric motor usage to maximize energy efficiency and minimize fuel consumption. The algorithm adapts by: Prioritizing electric motor use: The system ensures that the electric motor is the primary source of propulsion, shifting gears early to maintain a lower engine RPM, which helps conserve battery energy. Upshifting earlier: Since the electric motor is more efficient at lower engine speeds, the system will shift up at lower RPMs, optimizing both battery use and vehicle performance.

ii) Medium SOC% (50%-80%):

In this range, a hybrid approach is adopted, utilizing both the electric motor and the internal combustion engine. This balanced strategy allows the system to adjust to varying driving conditions: Hybrid operation: The algorithm will engage the electric motor during low-speed conditions (e.g., city driving) or when throttle demand is low, while switching to the ICE during higher-speed or higher-load conditions. Dynamic gear shifting: The system uses real-time data on vehicle speed and throttle position to determine when to engage the electric motor and when to activate the ICE. This allows for smoother transitions between power sources, optimizing both battery life and fuel consumption.

iii) Low SOC% (<50%):

When the battery charge is low, the system prioritizes the ICE to prevent excessive battery depletion. The gear shifting behaviour under low SOC% is adjusted as follows: ICE priority: The system relies more heavily on the internal combustion engine to conserve battery power. In this mode, the electric motor is used minimally, and the ICE takes over to ensure that the vehicle continues to operate efficiently. Optimal engine RPM: The algorithm ensures that the ICE operates within its optimal RPM range to avoid unnecessary fuel consumption and wear. Lower gears are often engaged in this condition to provide more power at lower speeds, especially when additional torque is required.

The following steps outline the fundamental logic of the gear shifting process: High SOC% (>80%): Prioritize electric motor usage. Ensure gear shifts occur at lower RPMs. Early upshifting to maximize electric motor efficiency. Medium SOC% (50%-80%): Use both the electric motor and ICE. Adjust gear shifts based on vehicle speed and throttle position. Engage ICE at higher speeds or with increased throttle demand. Low SOC% (<50%): Prioritize ICE operation to conserve battery. Ensure gear shifts maintain optimal engine efficiency. Use lower gears when necessary to ensure smooth and efficient power delivery.

3.2. Gear shift decision logic

The gear shift decision-making process is based on several defined conditions that determine when to upshift or downshift gears, ensuring that the vehicle operates in the most efficient way. These conditions rely on vehicle speed, engine RPM, and SOC%, as explained:

- Shift up condition: The system will shift to a higher gear if: Vehicle speed exceeds a threshold: At higher speeds, the engine can operate more efficiently at lower RPMs, allowing for a higher gear to be engaged.
- Engine RPM is below a defined maximum RPM: To maintain efficiency, the engine should not exceed a certain RPM. If the RPM is too low, the system can shift up to reduce fuel consumption and improve overall performance's% is above a threshold. When the SOC% is high, there is sufficient battery power to prioritize electric motor usage, allowing the system to shift to higher gears and conserve energy.

The decision logic is executed dynamically in real time, adjusting based on changing driving conditions such as acceleration, deceleration, and changes in road gradient. The SOC%-based gear shifting algorithm is shown in Figure 2.

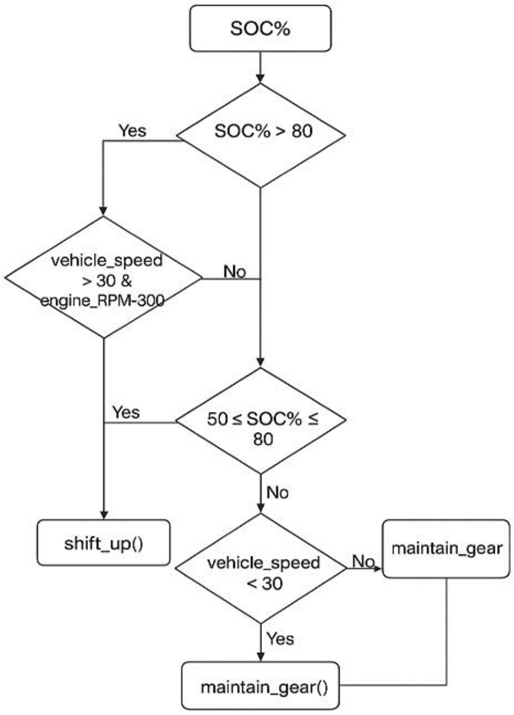

Figure 2. Pseudo-code for SOC%-based gear shifting algorithm

4. CALCULATIONS

In this section, we explore the impact of the SOC%-based gear shifting algorithm on the vehicle's fuel efficiency, battery efficiency, and engine RPM during gear transitions [21]-[25]. The goal is to understand how the SOC% influences energy consumption and to calculate how the algorithm's decisions contribute to the overall performance of the hybrid or electric vehicles.

4.1. Fuel efficiency (L/100 km)

Fuel efficiency is a critical measure of a vehicle's performance, especially for HEVs that switch between electric power and ICE power depending on SOC% and other parameters. It is calculated using (1).

$$Fuel\ Efficiency\ \left(\frac{L}{100}Km\right) = \left(\frac{Fuel\ Consumed\ (L)}{Distance\ Travelled\ (km)}\right) \times 100 \quad (1)$$

Where Fuel consumed (L) is the amount of fuel used by the internal combustion engine during the journey, and distance travelled (km) is the total distance the vehicle has covered. Impact of SOC%-based gear shifting on fuel efficiency:

i) High SOC% (>80%):

At high SOC%, the electric motor is primarily used, leading to minimal or no fuel consumption from the ICE. Since fuel consumption in this range is almost negligible, the fuel efficiency is at its highest. The vehicle relies on the electric motor, which is much more energy-efficient compared to combustion engines, especially in low-load urban driving conditions. Fuel efficiency in this mode is near its optimal, typically close to 0 L/100 km for short-distance city driving where the electric motor is primarily in use.

ii) Medium SOC% (50%-80%):

In this range, both the electric motor and the ICE are used, and the fuel efficiency is dependent on the exact ratio of electric motor and ICE usage. As the SOC% decreases within this range, more reliance is placed on the ICE for higher-speed or high-load conditions. The algorithm dynamically adjusts the power sources, aiming to balance fuel consumption and battery usage. For example, in conditions where the vehicle requires more power (e.g., accelerating to highway speeds), the ICE may be used more, which results in lower fuel efficiency compared to when the electric motor is more engaged.

iii) Low SOC% (<50%):

When the SOC% drops below 50%, the system prioritizes the use of the internal combustion engine to avoid battery depletion. As a result, the vehicle's fuel efficiency is lower because the ICE is generally less efficient than the electric motor. The algorithm shifts gears based on vehicle speed, throttle position, and engine

RPM to ensure that the ICE operates within an optimal range to maintain performance without consuming excessive fuel.

Example calculation for fuel efficiency: Let’s consider a scenario where a vehicle travels 100 km under varying SOC% conditions.

- High SOC% (>80%)

The vehicle operates mostly on the electric motor. Fuel consumed (L) = 0 L (since no combustion engine is used).

$$Fuel\ Efficiency\ \left(\frac{L}{100}Km\right) = \left(\frac{0}{100}\right) \times 100 = \frac{0L}{100}Km \tag{2}$$

- Medium SOC% (50%-80%)

The vehicle uses both the electric motor and the ICE. Let’s assume 10 L of fuel is consumed over 100 km of travel. The corresponding fuel consumption can be calculated using (3).

$$Fuel\ Efficiency\ \left(\frac{L}{100}Km\right) = \left(\frac{10}{100}\right) \times 100 = \frac{10L}{100}Km \tag{3}$$

- Low SOC% (<50%)

The vehicle relies mostly on the ICE, consuming 20 L of fuel over 100 km. The corresponding fuel consumption is calculated as defined in (4).

$$Fuel\ Efficiency\ \left(\frac{L}{100}Km\right) = \left(\frac{20}{100}\right) \times 100 = \frac{20L}{100}Km. \tag{4}$$

- Battery efficiency

Battery efficiency refers to the percentage of battery energy used per distance traveled, which is a critical measure for evaluating the energy conservation of electric and hybrid vehicles. The battery efficiency is calculated using (5).

$$Battery\ Efficiency\ (\%) = \left(\frac{Battery\ Discharge\ (Wh)}{Distance\ Travelled\ (Km)}\right) \times 100 \tag{5}$$

Where battery discharge (Wh) represents the amount of energy drawn from the battery during the trip, and distance travelled (km) is the total distance covered by the vehicle.

Impact of SOC%-based gear shifting on battery efficiency:

i) High SOC% (>80%): At high SOC%, the battery is fully charged, and the vehicle relies primarily on the electric motor. This maximizes the efficiency of the battery, as the system avoids draining the battery unnecessarily by using the ICE. Battery Efficiency is high since the electric motor is highly efficient in urban or low-load conditions.
ii) Medium SOC% (50%-80%): As the SOC% drops, the system balances between the electric motor and the ICE, leading to a decrease in battery efficiency. In this range, the algorithm may switch between using the electric motor and the ICE depending on the driving conditions. The battery discharge rate may be higher during acceleration or at higher speeds, reducing the overall efficiency.
iii) Low SOC% (<50%): When the battery charge is low, the system relies more on the ICE, and battery efficiency drops significantly. The electric motor is used only for short bursts of power or during low-speed conditions, while the ICE provides most of the power, resulting in lower battery consumption.

Example calculation for battery efficiency:

- High SOC% (>80%): assume the battery discharges 15 kWh over 100 km.

$$Battery\ Efficiency\ (\%) = \left(\frac{15000}{100}\right) = 150\ Wh\ per\ KM = 15\% \tag{6}$$

- Medium SOC% (50%-80%): assume the battery discharges 18 kWh over 100 km.

$$Battery\ Efficiency\ (\%) = \left(\frac{18000}{100}\right) = 180\ Wh\ per\ KM = 18\% \tag{7}$$

- Low SOC% (<50%): assume the battery discharges 25 kWh over 100 km.

$$Battery\ Efficiency\ (\%) = \left(\frac{25000}{100}\right) = 250\ Wh\ per\ KM = 25\% \tag{8}$$

Engine RPM and gear transitions: The engine RPM at which gear shifts occur plays a critical role in ensuring both vehicle performance and fuel efficiency. For both the electric motor and the ICE, RPM directly influences power output and operational efficiency. Electric motor power curve: Electric motors typically deliver maximum torque at low RPMs, making them highly suitable for low-speed driving conditions, such as city traffic and initial acceleration. ICE power curve: In contrast, the ICE performs optimally within a specific RPM range, where it can generate sufficient power while maintaining fuel efficiency. Generally, the ideal operating range lies between 2000 RPM and 3500 RPM, balancing performance and fuel consumption effectively.

5. CONCLUSION

In this paper, we have proposed an SOC%-based gear shifting algorithm aimed at optimizing the performance and energy efficiency of hybrid and electric vehicles (HEVs and EVs). By integrating SOC% into the gear shifting decision process, the proposed algorithm offers a more adaptive approach to gear selection, improving fuel and battery efficiency in various driving conditions. The methodology outlined in this study shows how the gear shifting logic can dynamically adjust to different SOC% levels, prioritizing electric motor usage at high SOC%, balancing both power sources at moderate SOC%, and relying more on the internal combustion engine at low SOC%. This strategy not only conserves fuel and battery power but also ensures smooth transitions between the electric motor and the ICE, enhancing the overall driving experience. The calculations provided in this paper demonstrate the significant impact of SOC%-based shifting on both fuel efficiency and battery efficiency. As the SOC% decreases, the system adjusts its gear shifting strategy to minimize battery depletion and maximize fuel usage. Additionally, the system optimizes engine RPM, ensuring that the engine operates within its most efficient range, preventing unnecessary fuel consumption and engine strain. By leveraging the capabilities of the CAN, the proposed algorithm can access real-time data from various vehicle components, enabling precise decision-making for gear shifts. Further exploration will focus on intelligent gear shifting in electric and hybrid vehicles using a CAN controller-based approach integrated with SOC% monitoring to enhance performance and energy efficiency.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Vadthya Jagan	✓		✓	✓			✓			✓	✓		✓	✓
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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest to disclose.

DATA AVAILABILITY

The data availability is not applicable to this paper as no new data were created or analyzed in this study.

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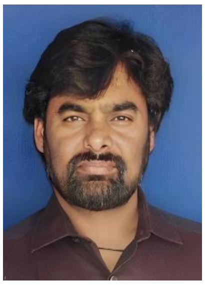

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