A novel acceleration-based mode selection approach in mild hybrid vehicles

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Abstract. When the regulations were first formulated in 2008, one of the potential way’s automakers were supposed to meet the goal of 95g CO2/km by 2020/21 was the hybridization of vehicles. Market participants and customers are becoming more interested in electric vehicles. Infrastructure, high-power device complexity, driving distance and requirements for protection all seem to be obstacles that will take longer than anticipated to integrate, followed by fuel cell vehicles, which will be the new significant thing, particularly in the commercial vehicle segment. As an outcome, hybrid vehicles with 48V architecture are perceived as the forerunners of complete electrification. It outperforms traditional in terms of fuel efficiency and high voltage hybrids in terms of price and time-to-market. Evaluating a control approach for torque management between the motor and engine and mode change decision, namely, from electric to the hybrid mode or likewise, is a major challenge for automotive service providers for hybrid electric cars. Each of these dynamics will directly affect fuel efficiency and manoeuvrability, notably during mode transition. Research work presented and examines a new idea for improved driving dynamics on a P3 mild gasoline car in Modified Indian Driving Cycle (MiDC) 1ST stage (urban) under system constraints such as sustaining 12V battery voltage, lower battery 48V SOC, and so on. The novel method that has been implemented is focused on two techniques. I. A modified Adaptive Equivalent fuel consumption minimization strategy for the engine's and the motor's power distribution, and II) A rules-based mode change decision.

Keywords: Mild hybrid vehicle, recuperation, fuel efficiency, 48V.

1. Introduction
Reducing CO2 emissions and importance to boost the adoption of the emission-free system is crucial to evade climate emergencies. A decade earlier, the European union settled on a 95 grams of carbon dioxide per kilometre goal for 2020/2021 was meant to be as a stepping stone to reducing car emissions, crucial to decarbonizing transport. There has been an increase in EVs and full hybrids in recent times, but to date, progress has been minimal, constrained by the availability of supply and choice of models. In 2018, Toyota and Lexus achieved a market share of 56% hybrids and Hyundai-Kia 4.5%; no other manufacturer has chosen to supply more than 1% in recent years. The average hybrid emissions are around 93 gCO2/km in 2018 compared to the average gasoline of 125 gCO2/km and diesel of 121.5 gCO2/km [1]. So far, Toyota has preferred strong hybrids, and very few players have been influential in the mild-hybrid segment, especially P0 topology.
Automotive industries have also come up with entirely new concepts like fuel cell, electric vehicle, strong hybrid, other alternative fuel, etc., to meet the emission standards and sustain future competition. All such technologies resulted in high costs and more time to market. A decade ago, significant OEMs introduced 42V hybrid cars[2] (ex: Toyota had developed the first-ever 42-volt hybrid system). Still, at that time, it was not cost-effective compared to functional benefits, and the importance of a high voltage system was neglected, and later 42V revolution died down. Owing to the need for more onboard electrical power from 12V loads, cabling techniques, and automatic controls, it's laying the groundwork for systems with greater voltage once again. The 48V systems operate closer to the 60V maximum point of lethal electric shock risk, delivering its maximum possible power without such expensive protection or specialized cabling connections that really are 10 times more expensive than lesser voltage devices. [3]. Most of the accessory loads connected to the engine via the FEAD system can be converted to electrical loads starting with steering pump, brake vacuum pump, oil, water pump, electric turbo assist, etc., which could yield better fuel benefit[4].

The various architectures of parallel hybrids vehicles include P0 - engine - motor fixed by a belt ratio usually 3, P1 - motor positioned on the engine crankshaft, P2 - motor sandwiched between engine and gearbox, P3 - motor attached to the gearbox shaft via speed reducer, and P4 - both axles driven independently by electric motor and engine. Many OEMs have already launched P0 vehicles but facing challenges w.r.t Cost vs. Fuel benefit since it yields significantly less fuel benefit and would not be eligible for customer-pleasing rewards. Motor mounted post gearbox has the edge over P2 since OEMs face a tough challenge with the machine's packaging between ICE and transmission system due to space constraints in the sedan/hatchback vehicle segment. P4 calls for a modified powertrain, and currently, OEM's not keen on this topology due to the high cost and complexity of handling different sources to drive the wheels [5].

The current paper focuses on developing a control system for a P3-AMT hybrid system. It can perform features like Hybrid torque-assist during launch, electric drive/creep/launch, clutch start and other clutch transients, optimal torque split

**Figure 1.** Trends in sales of alternatively fueled cars.[1]
between motor and ICE along with optimal gear selection, Idle and start-stop coasting, and recuperation[6][7].

Figure 2. Different hybrid architectures[5]

2. Overview of the systems

2.1 Vehicle configuration

Figure 3 explains the CAN and Vehicle design of the P3 mild gasoline car. It is composed of 3 controllers, the first is the engine control unit(ECU), which is liable for engine functions and communication of the 48V modules. Hybrid control unit(HCU) is in charge of hybrid operation, while transmission control unit(TCU) is in charge of clutch and gear actuation. The CAN protocol is used by all 3 control units to communicate. 12V and 48V are the two voltage levels available in this car. Besides the installation of a brake sensor capable of providing the pedal pressed distance as well an electronic brake vacuum pump that could assist with stopping during the electric drive, the majority of the 12V system is preserved. 48V system is newly introduced into the vehicle includes 48V Battery to supply power to the motor and power converter unit to maintain the 12V system stable and store the energy during recuperation phase. The motor can assist the engine and act as a generator to keep the energy back to the battery. The power control unit is responsible for converting the energy from the 12V system to a 48V system and vice versa. All three 48V components will come with their control unit and communicates with ECU via CAN. Table 1 list the significant specification of the powertrain.

| Table 1. P3-mild Hybrid vehicle configuration. |
|-----------------------------------------------|
| Engine | Class | 1.2L Port fuel injection |
|        | Maximum power | 62kW @ 5500RPM |
|        | Maximum Torque | 110Nm @ 3500RPM |
| Transmission | Class | Automated manual transmission system | Five gear |
| Motor | Class | Permanent magnet synchronous motor |
|        | Maximum power | 10kW |
|        | Maximum torque | 53Nm |
| PCU | Class | Power converter unit |
|        | Maximum power | 1.8kW |
| 48V Battery | Class | Lithium |
|        | Maximum power | 0.33kWh |


3. Software system configuration

3.1 Supervision system layout

Figure 4 explains the Software working principle of P3 mild hybrid system. 48V battery limits are the master to decide the Motor torque limits to make sure that the 48V battery's limits of safety are not exceeded during boosting or charging phases. PCU is responsible for boost operation (12V → 48V) and buck (48V → 12V)[8]. Boosting is only done when the 48V device is first turned on. After that, it only operates in buck state by default to ensure the 12V battery charge is kept up with the highest priority. 48V components have their control unit and communicate with ECU via CAN. ECU coordinates the driver demands considering the system limits. TCU is responsible for deciding the gear based on vehicle speed, driver demand, etc., and clutch actuation. HCU considers the driver demand based on which torque split between ICE and Motor is done based on simplified A-ECMS, derived according to Pontryagin's Minimum strategy [9].
Figure 4. Software control flow of mild hybrid P3 system.

3.2 Improvement of Fuel Economy performance

In P3 mild hybrid system, the mode can be categorized as Engine, Hybrid and Electric[10]. Combustion engine runs during both Engine and Hybrid mode. Still, motor helps the vehicle movement in hybrid mode, resulting in lesser fuel consumption and better drivability since motor response time is faster. In Hybrid mode for a given driver demand, the fuel economy performance is mainly governed by selecting enhanced working points of motor, engine and thermal efficiency of 48V battery. In Engine mode, fuel is the ultimate source of power. Hence, energy depleted from the 48V battery has to be charged again and vice versa, which means that by charging 48V battery, the operating points of the engine can be shifted to better operating points and use the charged electrical energy efficiently where the engine operating points are poor by which overall system efficiency is improved. Hence, it is possible to consider using energy charge storage as virtual fuel consumption (positive or negative). A weighing factor $z$ usually denotes this virtual specific fuel consumption. At each instantaneous time (i.e., at each instantaneous speeds (ICE, motor operating points), the torque split is decided by meeting the total load (driver demand), does not exceed the component limits is considered, and the best operating point where the power consumed by ICE ad motor is least consumption is calculated. As shown in Fig.5,6 operating point of the ICE is moved to improved points in the MIDC 1st phase by 48V battery charging and switching the engine off at low speeds where engine efficiency is inferior [11].
Figure 5. Base vehicle engine working points in MIDC 1ST Phase.

Figure 6. P3 Mild hybrid engine working points in MIDC 1ST Phase.

At low speed, Motor efficiency is far better when compared to engine. The overall system performance is greatly optimized since it is linked after the gearbox (powertrain losses include a gearbox, clutch and crankshaft will be excluded in electric phase except for differential losses). Similarly, energy can be recovered effectively in recuperation mode, i.e., losses owing to powertrain components with the exception of differential losses. P0, P1 topologies cannot avoid the powertrain losses, while P2 cannot prevent the differential and transmission losses [12][13].

3.3 Fuel Economy performance improvement by changing the operating mode

To improve the conventional system's fuel economy, it is by improving the overall energy transfer to the wheel, i.e., enhancing the efficiency of the powertrain components, thermal efficiency of the engine, and proper handling of 12V loads. The engine's thermal efficiency is improved by running the engine at its best operating/efficiency regions. Recuperate available kinetic energy as much as possible and use the free power to drive the wheels instead of wasting it in the form of heat. Hence, we could avoid the powertrain losses (except the differential losses) and engine low operating points by switching off the engine driving the wheels by motor.

Figure 7 shows the overview of switching between the Electric, Hybrid, and Engine mode. At flat surfaces where accelerations are constant, the vehicle is driven pure electrically. When the battery's SOC is less or the driver request exceeds the motor's capacity, the engine is automatically started. Engine can be started with either a starter or a clutch, but at low speeds, the likelihood of a
starter start is greater than a clutch start. The clutch start would result in better drivability without any jerks since the wheel side clutch’s kinetic energy could start the engine with one pulse contact with engine side clutch could add better fuel benefit. As per the below-mentioned results, during the electric drive, the Battery SOC will be depleted. Once the engine is started, it performs the load point shift to re-energize the 48-volt battery using the machine by which could avoid running at the engine’s poor working points and assist engine in driving the wheels in hybrid mode. During the overrun or braking phase’s kinetic/free energy available in the vehicle is converted and stored in the 48V battery, which can be used to drive the wheels, by which the system's overall efficiency could be improved[14][15].

Figure 7. Operating modes in MIDC 1ST Phase (Urban).

4. P3 48V Hybrid AMT Control Strategy
The control strategy is developed based on two approaches I) Rule-based and II) modified A-ECMS approach. The rule-based system is used only for mode change, i.e., from ICE mode to EV mode and vice versa, and the A-ECMS approach is used during only Hybrid and ICE mode. In modified A-ECMS, at each instant, the power distribution between the ICE and the 48V battery, satisfying the driver demand and respecting the global constraints (e.g., start and end SOC of the 48V battery is minimal) and local restrictions (e.g., Battery safety limits should not be breached in the driving cycle)[16][17].

4.1 Rule base approach
Figure 8 explains when to shut off and start the engine and includes the decision to open or close the clutch. This approach makes sure constant acceleration phases the vehicle is driven purely by motor subjective to battery limits. Whenever there is no driver demand, the engine is shut off. The motor is used as a braking system to recuperate as much as possible and maintained in E drive only at low speeds without switching on the engine, which frequent engine starts can be eliminated. Engine start is triggered if the vehicle reaches desired speed or if driver requests exceeds the motor capacity, or if the state of charge of the battery is lesser than calibrated value.

Figure 9 explains the two different rule-based approaches considered for mode decision I. Rule 1 Vehicle startup/launches are performed in electric mode until vehicle speed reaches a defined calibration value II. Rule Vehicle performs electric drive during constant acceleration phases. It is
observed that the motor's electrical energy during the stable accelerations phase is less since the vehicle already has enough moment of inertia. Hence, in a given driving cycle, energy recuperated during deceleration could be more than energy spent during the electric drive, resulting in a better fuel economy. Maximum power consumed in the rule 1 approach is around 18kW and later is 14kW. Such a rule-based strategy also favors drivability concerns during the mode shift and possibility to perform engine start via clutch is very high since the vehicle side clutch already has enough energy to pass on the energy to engine side clutch by one pulse faster closing of the clutch. During the launches, the probability of starter start is very high, resulting in noise vibration harshness issues and the loss of accelerations during the starter start.

![Flowchart](image)

**Figure 8.** Rule-based Approach for mode decision.
4.2 Simplified Adaptive Strategy for minimizing equivalent consumption

The main aim of the process is to keep the gap between the battery’s start and end SOC as minimal as possible. Since all energy comes from fuel and energy captured during the braking/drag phases, the 48V battery can only serve as an energy accumulator. Energy depleted from the battery must be filled up at some point later using the engine’s power or by the available free energy in the system during recuperation phases [18][19].

Pontryagin’s minimum principle can be used to calculate equivalent fuel consumption:

\[ Peqv(t) = Pfuel(t) + z(t) \cdot Pbatt(t). \]

The optimal energy management problem's objective aims to find control \( u(t) \) that leads to depreciation of the fuel used up, \( m_f \), during a trip with length \( t_f \) (beginning at \( t_0 = 0 \)). This is the same as lowering the integral performance index to a minimum.

\[ J = \int_{t_0}^{t_f} m_f (u(t), t) \, dt, \]

where \( m_f \) [g/sec] is the used fuel’s mass flow rate.
Constraints relating to motor, engine’s physical restraints, and most significantly keeping the battery SOC within the parameters defined affect performance index deprecation. A collection of global and local constraints on the state and control variables are used to form the equation.

The global constraint is that final SOC value \( x(t_f) \) should meet a predetermined value \( x_{target} \) i.e.,

\[
x(t_f) - x_{target} = \Delta x \approx 0
\]

(2)

The local constraint is considered as the minimum and maximum limits of motor torque, engine torque, and 48V battery SOC at any given time.

\[
SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}}
\]

(3)

\[
T_{x_{\text{min}}} \leq T_x(t) \leq T_{x_{\text{max}}}
\]

(4)

Local constraint:

\[
T_{\text{eng}_{\text{min}}} \leq T_{\text{eng}}(t) \leq T_{\text{eng}_{\text{max}}}
\]

(5)

\[
T_{\text{EM}_{\text{min}}} \leq T_{\text{EM}}(t) \leq T_{\text{EM}_{\text{max}}}
\]

(6)

\[
SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{max}}
\]

(7)

\( T_{EM} \) is Torque of motor, \( T_{\text{eng}} \) is Torque of engine.

\[
T_{\text{EMop}_{\text{min}}} = \min(T_{\text{EMmax}}, \max(T_{\text{EMmin}}, (T_{\text{Drv}} - T_{\text{eng}_{\text{max}}}))
\]

(8)

\[
T_{\text{EMop}_{\text{max}}} = \max(T_{\text{EMmin}}, \max(T_{\text{EMmax}}, (T_{\text{Drv}} - T_{\text{eng}_{\text{min}}}))
\]

(9)

\( T_{\text{EMop}_{\text{min}}} \) is the minimum motor desired torque, \( T_{\text{EMop}_{\text{max}}} \) is the maximum motor desired torque, \( T_{\text{EMmax}} \) is actual maximum motor torque, \( T_{\text{EMmin}} \) is actual minimum motor torque, \( T_{\text{Drv}} \) is driver demand torque, \( T_{\text{eng}_{\text{max}}} \) is engine maximum torque and \( T_{\text{eng}_{\text{min}}} \) is engine minimum torque.

\[
T_{\text{Step},\text{EM}} = \frac{T_{\text{EMop}_{\text{max}}}-T_{\text{EMop}_{\text{min}}}}{\text{Discrete points}}
\]

(10)

\( T_{\text{Step},\text{EM}} \) is the discretized torque of the motor.

\[
T_{\text{EMloop}} = T_{\text{EMmin}} + T_{\text{Step},\text{EM}}
\]

(11)

\( T_{\text{EMloop}} \) is the motor torque derived for each iteration.

\[
T_{\text{engloop}} = T_{\text{Drv}} + T_{\text{EMloop}}
\]

(12)

\( T_{\text{engloop}} \) is the engine torque derived for each iteration.

The following equation should be used to measure power based on fuel consumption:

\[
P_{\text{fuel}} = Q_{lhvmf}(T_{\text{eng}}, \omega_{\text{eng}}) \quad \text{Fuel lower heating value}
\]

(13)

The following equation should be used to measure battery power:

\[
P_{\text{batt}} = P_{\text{em}}(T_{\text{mot}}, \omega_{\text{mot}}) + P_{\text{battLoss}}
\]

(14)

The battery’s loss power can be determined using the equation below:

\[
P_{\text{battLoss}} = (P_{\text{em}})^2 * \left[ R / (V_{\text{OC}})^2 \right]
\]

(15)

The resistance through the battery terminals is \( R \), and the battery’s open-circuit voltage is \( V_{\text{OC}} \).
4.3 Adaptation focused on SOC feedback
This principle's main objective is to change the equivalence factor dynamically at each instant based only on SOC variation. It always tries to maintain its current value around the target value. This approach is robust, easy to implement, and computationally cheap. Better output is achieved by properly calibrating the gain parameters used in the adaptation rule. The equivalence factor varies during charging and discharging the 48V battery. The main objective is to determine whether electrical energy or fuel energy is costly at the present time [20][21][22].

\[
Z(t) = Z_0 + kP(SOCTarget - SOC(t)) + KI \int_0^t (SOCTarget - SOC(\tau)) d\tau
\]  \hspace{1cm} (16)

5. Actual vehicle results
The below-mentioned results show that a developed control strategy can achieve by keeping the local constraints, i.e., the Battery Power limits (Figure 13) and motor power and torque limits (Figure 14) are within limits respecting its temperatures.
Figure 12. Motor Powers in MIDC 1st phase (urban).

Figure 13. 48V Battery Powers in MIDC 1st phase (urban).

6. Conclusion
A novel control technique was designed for the P3 mild gasoline vehicle with a 10kW motor primarily based on MIDC 1st phase (urban). The following conclusions can be drawn as mentioned below:

I) In generator mode, the engine's operating point shifted, increasing the engine's thermal efficiency.
II) In electric mode, the overall efficiency of energy transfer is improved by driving the wheels and capturing the recuperation energy.

III) In hybrid mode, motor assists will enhance driving dynamics and efficiency of the engine.

IV) Considering the system limitations, the integration of all electronic control units allowed for the maintenance of acceptable driving efficiency.

Future research should focus on the optimal control technique’s mode change and gear determination, which may result in better fuel savings, but given the number of engine starts due to mode shift and feeling, derivability efficiency will be a difficult barrier.

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ABBREVIATIONS
PCU – Power conversion unit
SOC – State of charge
ICE – Internal combustion engine
ECU – Electronic control unit
ECMS - Equivalent consumption minimization strategy
HCU – Hybrid control unit
TCU – Transmission control unit
MIDC – Modified Indian driving cycle
OEM - Original equipment manufacturer
CO₂ - Carbon dioxide
AMT – Automatic manual transmission

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