

Low-Carbon Biofuel Combustion Technologies for Sustainable Hybrid Electric Passenger Vehicle Applications

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Abstract - Low-temperature combustion (LTC) is a process that can deliver the benefits of high thermal efficiency, low nitrogen oxides (NO_x) and particulate matter, as well as the high energy density and quick refueling times of the liquid-fuel process. It has the added advantage of being able to be integrated with hybrid electric vehicle (HEV) powertrains, where electrification allows operation only in the areas of stable and efficient LTC. This paper critically reviews homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), reactivity-controlled compression ignition (RCCI), and dual-mode strategies for passenger vehicles that use biofuel for hybrid operation. Key synthesis focus areas are fuel reactivity, preparation of the charge in the cylinder, combustion phasing, extension of the operating range, transient control, aftertreatment compatibility, hybrid topology, supervisory energy management, and well-to-wheel carbon performance. RCCI combustion regimes have been shown, in general, to allow greater combustion-phasing control and operation at higher load levels compared with highly premixed HCCI, and bioethanol, biodiesel, biogas, and higher alcohols can replace fossil carbon. Remaining challenges involve low-load incomplete combustion, pressure-rise limits at high load, cold-start and catalyst-temperature management, fuel-property variability, and life-cycle carbon uncertainty. The evidence thus supports fuel-engine-electric-drive design and supervisory control to avoid combustion instability and pollutant emissions, maintain a safe catalyst temperature and battery state of charge, and improve life-cycle carbon performance.

Keywords: Low-temperature combustion, biofuels, RCCI, hybrid electric vehicle, energy management, life-cycle emissions.

1. Introduction

The decarbonization of passenger transport must be associated with a decrease in fossil-carbon consumption, controlled emissions, and overall energy consumption. Although battery electric vehicles play a key role in the transition, hybrid electric vehicles (HEVs) are still needed where access to charging stations, battery costs and weight, grid carbon intensity, or variability in duty cycles prohibit complete electrification. The use of the internal combustion (IC) engine in an HEV enables the engine to be used as a controlled energy converter in addition to or instead of being the sole means of traction. The downsizing of engines, regenerative braking, electric launch, torque assistance, and load-point shifting can consequently focus engine operation towards high-efficiency areas. This flexibility is especially beneficial for low-temperature combustion (LTC) because of the potential for high efficiency at low engine-out emissions, which is typically achievable only in a limited speed-load regime [1]–[3].

LTC limits the simultaneous presence of locally fuel-rich areas and high combustion temperatures, which can lead to soot and thermal NO_x formation. This goal is achieved in many ways under the categories of homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and “reactivity-controlled compression

ignition” (RCCI) [1]–[2]. They have in common that they enable a reduction in NO_x and particulate matter (PM), with intensive exhaust aftertreatment providing part of this reduction. They also have limited combustion authority, since the phasing of ignition and heat release is a strong function of chemistry (chemical kinetics), mixture temperature, exhaust gas recirculation (EGR), residual gases, and fuel properties. Hence, lower loads, rapid transients, and cold starts are more challenging, and at high load, the maximum permissible pressure-rise rate can limit operation [3]–[5].

Biofuels affect the carbon balance and the combustion-control problem. As RCCI is a dual-fuel application, bioethanol and higher alcohols have the unique properties of high octane quality, high latent heat of vaporization, and low autoignition reactivity that make them potential candidates as low-reactivity fuels [6]–[7]. On the high-reactivity side, biodiesel can be used to introduce renewable inputs, but its use will necessitate special calibration of the injection system and mixture-control processes due to its higher viscosity, lower volatility, and feedstock composition [8]–[9]. Biogas can be used for dual-fuel LTC; however, methane slip and low-load combustion efficiency are special concerns [10]. Not only does the area in which the fuel is emitted influence total low-carbon performance, but, as these fuel-specific impacts highlight, it is impossible to rely on the amount of CO₂ emitted from the tailpipe to properly understand low-carbon performance. When performing life-cycle assessment (LCA) of LTC, the production of feedstocks, fuel processing, land use, electricity generation, battery production, and the vehicle's lifetime should all be taken into account [11]–[13].

This engineering problem thus becomes a coupled fuel-engine-powertrain problem. Unlike parallel and power-split designs, a series hybrid has a completely independent mechanical path, which means that a limited set of operating points can be used to run the engine; other architectures put the engine through a wider range of operating points. Supervisory energy management can coordinate engine start-stop events, change the combustion mode, and coordinate the allocation of fuel reactivity, battery state of charge (SOC), and catalyst temperature. Engine-modeled vehicle-level results have been shown to be significantly different from steady-state engine-map results for RCCI or ethanol-fueled advanced combustion with hybrid control [11], [14]–[16].

The current research programme carried out in India in 2024 is also in the field of LTC, but addresses the problem at the system level and does not aim at isolated combustion-mode optimization [17]. Section 2 outlines the scope of this review and the approach to selecting the literature; Section 3 provides a description of the basic fundamentals related to thermodynamics, combustion, and hybrid-powertrain fundamentals; Section 4 describes and categorizes the major technical approaches; Section 5 compares the various technical approaches; Section 6 discusses practical implementation issues; Section 7 identifies gaps in the state of the art and associated research priorities; and Section 9 concludes the review.

2. Review Scope and Literature Selection

The review is focused on renewable-fuel LTC technologies that can be integrated with HEV or plug-in hybrid electric vehicle (PHEV) powertrains for light-duty passenger-vehicle applications. The main literature period is 2019–2026, with some foundational studies from 2015–2018 that are necessary for the concepts of HCCI, PCCI, RCCI, and hybrid-LTC where applicable. When bibliographic information was available and verified using bibliographic databases, publisher or journal web pages, or institutional repositories, these sources were given the highest priority.

The bulk of the evidence was obtained from peer-reviewed journal publications; SAE International and American Society of Mechanical Engineers (ASME) conference papers were used where they were relevant to drive cycles and/or vehicle integration. The search

terms were: low-temperature combustion, HCCI, PCCI, RCCI, bioethanol, biodiesel, biogas, hybrid electric vehicles, dedicated hybrid engine, energy management, drive cycle, and life-cycle assessment. Stationary-engine studies were retained only if they helped to explain fuel-reactivity effects, combustion limits, and emission mechanisms that are applicable to light-duty engines. Conventional biodiesel-combustion studies that did not consider LTC or hybrid integration were only briefly covered, and hydrogen and ammonia were treated only as limiting cases and not as main biofuel routes.

Evidence is synthesized by technical theme rather than by individual study. The main categories are charge preparation and reactivity control, renewable-fuel pairing, operating-range extension, hybrid architecture, and supervisory control. Reported numerical results are treated as study-specific because engine displacement, compression ratio, injection hardware, EGR, test cycle, battery configuration, and system boundaries differ substantially across the literature; no meta-analytic normalization is attempted. This distinction is important because an apparent steady-state advantage can diminish after catalyst light-off, mode-transition penalties, battery energy use, upstream fuel emissions, and real-driving conditions are included [3], [11], [14]–[16].

3. Technical Background

The efficiency objective of an LTC engine can be expressed by brake thermal efficiency (BTE):

$$\eta_b = \frac{P_b}{\dot{m}_f LHV} \quad (1)$$

In Equation (1), η_b denotes brake thermal efficiency, P_b denotes brake power, $\dot{m}_f$ denotes the fuel mass-flow rate, and LHV denotes the lower heating value. Energy-normalized efficiency is essential for comparing biofuel substitution because oxygenated fuels commonly have a lower LHV than petroleum fuels. BTE must also be interpreted together with combustion efficiency, pumping work, heat-transfer losses, and mechanical efficiency, since LTC calibration can shift losses among these mechanisms. Dilution (by EGR) can prevent NOx formation and prevent heat transfer, but high EGR rates and high boost requirements can lead to greater gas-exchange work, and low-load operation can lead to greater incomplete-combustion losses. The efficiency, in this sense, should accordingly also be measured at the programmed operating points and include the electrical conversion path in the hybrid application in addition to the maximum BTE of an engine map measured in isolation.

The difference between the various modes is mainly in the way of preparing the mixture and phasing ignition. HCCI combustion is highly premixed, and the charge is rather homogeneous, leading to the suppression of soot and NOx, but with combustion phasing dependent only on intake temperature, EGR, compression ratio, valve phasing, residual gases, and fuel chemistry. PCCI continues to have direct-injection control, but is also able to progress and/or split injection to create higher levels of premixing to enhance phasing control, at the cost of wall wetting, over-mixing, and injection-timing sensitivity. Reactivity stratification is the intentional formation of a charge with a high-reactivity fuel (HRF) introduced by means such as direct injection or port fuel injection, and a low-reactivity fuel (LRF) introduced, again, by port fuel injection. The LRF energy fraction can be expressed as

$$X_{LRF} = \frac{\dot{m}_{LRF} LHV_{LRF}}{\dot{m}_{LRF} LHV_{LRF} + \dot{m}_{HRF} LHV_{HRF}} \quad (2)$$

In Equation (2), X_{LRF} denotes the LRF energy fraction; $\dot{m}_{LRF}$ and $\dot{m}_{HRF}$ denote the LRF and HRF mass-flow rates, respectively; and LHV_{LRF} and LHV_{HRF} denote their corresponding lower heating values. X_{LRF} is one of the main RCCI calibration variables, as it affects the ignition delay, spatial reactivity gradients, heat-release rate, and emissions. These pairing

opportunities that utilize renewable resources, including ethanol-biodiesel, other alcohol-biodiesel options, and biogas with a diesel-like or biodiesel pilot, can then deliver fossil-carbon substitution and combustion-phasing control [9]–[10], [18]–[20]. In practical control, the crank angle at 50% accumulated heat release (CA50) and the maximum pressure-rise rate should not exceed acceptable limits, and the cyclic fluctuations should not be too large. The second control layer is possible with hybridization, which allows the distribution of demanded traction power between the electric path and the engine. Wheel-Equivalent Power Balance: Considering a parallel powertrain architecture, a simplified wheel-equivalent power balance is

$$P_{\text{dem}}(t) = P_{\text{ICE}}(t) + P_{\text{EM}}(t) - P_{\text{loss}}(t) \quad (3)$$

In Equation (3), P_{dem} denotes demanded traction power, P_{ICE} denotes the engine contribution, P_{EM} denotes the electric-machine contribution, P_{loss} denotes driveline losses, and t denotes time. This gives the energy management system (EMS) direct access to a method to protect the LTC engine from transients or mode changes that are too rapid for the LTC engine to stabilize, or to keep the LTC engine out of unstable operating areas. Series architectures carry this decoupling even further, as they do not have any mechanical links between the engine and the wheels, but they suffer from extra electrical-conversion losses due to the generator, inverter, battery, and traction motor [21]–[22]. An example of an LTC hybrid setup is shown in Figure 1. Vehicle-level decarbonization cannot be inferred from engine efficiency alone, so a life-cycle metric is also needed. A well-to-wheel-plus-manufacturing (W2W+) metric is a simplified representation of:

$$E_{\text{CO}_2\text{e}} = \frac{[E_{\text{manuf}} + \int (\dot{m}_f \text{CI}_f + P_{\text{grid}} \text{CI}_{\text{grid}}) dt]}{D} \quad (4)$$

In Equation (4), $E_{\text{CO}_2\text{e}}$ denotes the well-to-wheel-plus-manufacturing CO₂-equivalent emissions; E_{manuf} denotes vehicle-manufacturing CO₂-equivalent emissions; $\dot{m}_f$ denotes the fuel mass-flow rate; CI_f denotes fuel carbon intensity; P_{grid} denotes grid power; CI_{grid} denotes electricity carbon intensity; t denotes time; and D denotes lifetime distance. Hence, the same hybrid will yield varying climate outcomes with varying biofuel feedstocks, mixes of electric-energy sources, and their usage. Electricity-related terms in non-plug-in HEVs mainly depend on manufacturing and auxiliary-energy assumptions, while plug-in HEVs (PHEVs) need specific consideration of grid charging. The statement of a credible comparison should therefore include the definition of a functional unit, assumptions for battery replacement, the pathway for fuel production, a source profile for the electricity generated, and a profile for the biofuel co-products produced. As long as there are no fixed boundaries, low tailpipe CO₂ cannot be equated with low life-cycle carbon performance.

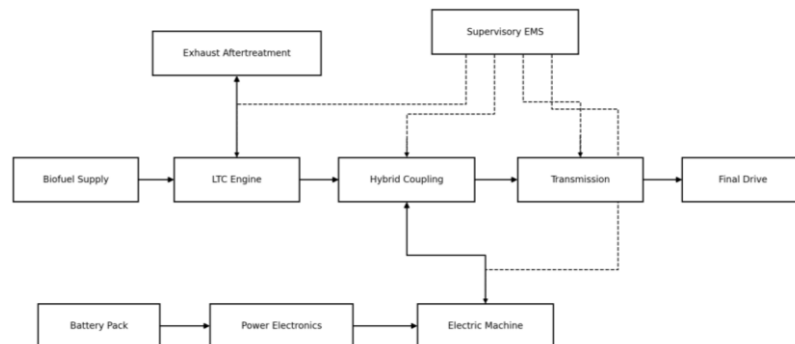


Figure 1. Representative biofuel-powered LTC hybrid electric passenger-vehicle architecture

4. Evolution and Classification of Existing Approaches

4.1 Premixed single-fuel LTC: HCCI and PCCI

Premixed single-fuel LTC developed around lean, highly premixed mixtures established before the principal heat-release event. When HCCI is performed with a sufficiently lean and

cool mixture, it will generate low emissions of soot and NO_x, but it does not have a spark-ignition or main-injection event that directly controls the start of combustion. Transient phasing is complicated by changes in the charge temperature, the amount of gas left behind, and the reaction mechanisms. At high load, the heat-release rate and pressure rise are limitations, while at low-load operation, the limitations are misfire, incomplete oxidation, and high hydrocarbon (HC) and carbon monoxide (CO) emissions [1]–[2]. However, full-map HCCI is challenging to apply in a normal passenger car, but could be achievable by limiting engine operation to a small and favourable operating space through hybridization.

PCCI offers more influence on the phasing of direct injection (early or split injection) without sacrificing a high rate of premixing. Its controllable range is wider than that of HCCI, but excessively early injection leads to increased wall impingement, a risk of lubricant dilution, and sensitivity to mixture preparation. At the laboratory level, renewable PCCI studies have shown that they can achieve simultaneous reductions in both NO_x and soot emissions under controlled conditions, but energy-consumption benefits are not consistently derived, and penalties in HC/CO emissions can occur [23]. PCCI is therefore most appealing when used in a multi-mode combustion system and not as an unrestricted 'full-map' system.

4.2 Reactivity-stratified LTC: RCCI

RCCI introduces additional control over combustion phasing through a combination of fuel-reactivity contrast and injection timing [4]. Early demonstration projects were based on mixtures of gasoline and diesel, though later projects started using ethanol, butanol, biodiesel, biogas, and other renewable fuel sources [3], [8], [24]. RCCI is able to span a wider range of loads than highly homogeneous HCCI due to spatial gradients in ignition timing achieved by direct injection of the HRF. For the tested engine, the greatest possible coverage of light-duty operation and BTE for RCCI were reported in a light-duty comparison [5] and are still dependent on geometry, hardware, and calibration. Spray behavior and chemical reactivity change when switching to biofuels as a result.

Ethanol and higher alcohols are good LRF candidates because the high-octane quality of these fuels helps to prevent premature autoignition, while evaporative cooling also counteracts premature autoignition, but excessive premixing causes weak low-load oxidation [6], [19]. Biodiesel can be used as a substitute for part or all of the diesel-like HRF, which increases the renewable portion but changes the viscosity, atomization, and ignition characteristics and thus the injection strategy. Renewable-fraction analyses in the ethanol-biodiesel system reveal a strong coupling between renewable fraction and HRF injection phasing, and independent optimization of these parameters is not useful [20]. The evidence points to a wider view of fuel composition, namely as a variable to manage combustion processes as well as a variable to account for carbon.

4.3 Gaseous and multi-component renewable RCCI

RCCI goes beyond the use of liquid oxygenates with gaseous and multi-component fuels. The idea of biogas-based RCCI is to provide an intake-supplied low-reactivity gaseous charge that can be ignited by a small high-reactivity fuel pilot, and twin-injector systems offer further calibration possibilities [10]. Methane slip is the main issue at the system level. Optimising the use of renewable gases is therefore directly connected to hybrid thermal management during frequent engine stops because adequate oxidation of renewable gases requires the catalyst temperature to be maintained.

The benefits offered by multi-component fuels such as isopropanol-butanol-ethanol blends with biodiesel, in terms of further flexibility in the control of fuel volatility, octane number, cetane number, and oxygen content, need to be considered against the issues of fuel standardisation, cold-start performance, material compatibility, fuel storage, and fuel supply.

A fuel pair is therefore expected to meet combustion-control requirements as well as have an acceptable low upstream carbon intensity, be renewable and scalable, be able to operate in a cold environment, and be compatible with infrastructure. Low engine-out NO_x does not necessarily ensure overall viability.

4.4 Dual-mode engines and dedicated hybrid engines

No single LTC mode provides optimal performance across the complete engine map. Thus, in beneficial low- and medium-load modes, dual-mode engines take advantage of RCCI or another LTC method, but switch to conventional compression ignition, spark ignition, or another stable mode during warm-up and high-load operation. Though this method does not involve severe constraints on pressure rise and misfires, there may be penalties in fuel consumption and emissions during mode switching [3], [14]. These changes between the combustion systems' operating modes can be mitigated by electrification, either in terms of the frequency with which the modes of operation are used or in terms of the magnitude of the transitions. This can be carried further by using dedicated hybrid engines (DHEs), which are designed to run in the smaller operating envelope that hybridization allows.

The use of electrically supplied transient torque allows calibration with a higher compression ratio, higher dilution, an optimized combustion system, and advanced combustion strategies within a narrower operating envelope. Advanced-combustion studies fueled by ethanol also suggest that material differences can be achieved in vehicle-level greenhouse gas (GHG) performance by employing supervisory control [16]. The results here also indicate that integrated design to satisfy the combustion map, electric-machine rating, windowed battery energy, and renewable-fuel strategy is a more appropriate alternative to sequential optimization of individual subsystems.

4.5 Hybrid topology and supervisory control

Hybrid topology determines how strongly the powertrain can exploit the limited operating range of LTC. The most extreme decoupling of the operating point is offered by a series hybrid, as wheel speed can be varied over a wide range while the engine continues to operate at a few efficient points with a generator. RCCI series-hybrid studies indicate that this can reduce the requirement for full-map combustion capability [21]; however, the benefit may be offset by losses in generator or inverter, battery, and traction-motor efficiencies. Parallel P2 systems do not require the addition of a clutch, but require electric torque assistance and require their EMS to handle a larger set of engine loads and to orchestrate more frequent mode changes [14]. PHEVs use grid energy and usually larger batteries; carbon performance depends on charging behavior and electricity carbon intensity [11].

Supervisory control has evolved from rule-based scheduling to the equivalent consumption minimization strategy (ECMS), dynamic programming (DP), model predictive control (MPC), fuzzy control, and reinforcement learning (RL). Adaptive ECMS has been tested for RCCI hybrids [14]–[15], and hierarchical preview-based control has been used to eliminate unnecessary transitions between the two modes in PHEV systems consisting of dual-mode dedicated hybrid engines. Furthermore, the results of multi-objective biofuel-hybrid optimization indicate that component sizing and calibration are interdependent decisions [25]. Thus, an effective control hierarchy connects fast combustion regulation with mode and thermal management and combines, at the vehicle level, control of energy use, battery SOC, and operating-point selection.

5. Comparative Analysis

The comparison of the key LTC-hybrid study methods is provided in Table 1 according to renewable-fuel pathway, control variables, operating range, emission tendencies, hybrid suitability, and dominant limitation. A single efficiency value is not emphasized in the

comparison due to the use of different engines, loads, and test conditions for the reported BTE, indicated thermal efficiency, emissions, and fuel-consumption figures.

Table 1. Comparison of key LTC-hybrid study methods

Approach	Renewable-fuel pathway	Control variables	Operating range	Emissions tendency	Hybrid suitability	Principal limitation
HCCI	Ethanol or alcohol blends	Intake temperature; EGR; valve timing; compression ratio; equivalence ratio	Narrow; strongest at selected low-medium loads	Low NOx/soot; HC/CO can be high at low load	High in series/range-extender operation	Weak direct phasing authority; high-load pressure rise [1]–[2]
PCCI	Biodiesel alcohol; oxygenated diesel blends	Early/split injection; EGR; boost; injection pressure	Wider than HCCI but hardware-sensitive	Low soot/NOx possible; wall-wetting and HC/CO penalties	Moderate-high	Spray-wall interaction; narrow calibration window [23]
RCCI	Ethanol-biodiesel; alcohol-biodiesel; biogas-biodiesel/diesel	LRF energy share; HRF timing/quantity; EGR; boost; intake temperature	Broadest LTC range among main premixed concepts	Strong NOx/soot reduction; low-load HC/CO remain problematic	Very high	Dual-fuel hardware; transient phasing; pressure-rise constraints [3], [8], [10], [18]–[20]
Dual-mode RCCI/conventional	Renewable LRF with diesel/biodiesel HRF	Mode boundary; torque reserve; injection and air-path control	Broad/full map through mode switching	Low emissions in LTC transition possible	High in parallel/P2 HEV	Switching complexity; catalyst thermal management [14]–[15]
Biofuel DHE / advanced compression ignition	Ethanol-rich fuels; flex-fuel blends	High dilution; compression ratio; ignition strategy; EMS set-points	Narrowed around best-efficiency island	Low CO ₂ potential; regulated emissions depend on mode/aftertreatment	Very high	Requires vehicle-engine co-design and robust transient control [16], [22], [25]

Table 1 indicates that for a hybrid powertrain, the dominant design criterion for the standby engine is not necessarily one that provides a large operating range for the engine alone. When the increase in efficiency that results from avoiding less favorable engine points is offset by a loss in electrical-conversion efficiency, a series hybrid can take advantage of a narrow HCCI or RCCI operating island. The engine may, however, need a wider RCCI or "dual-mode" region in the case of a parallel hybrid where the engine is mechanically tethered to the driveline. The choice of the LTC approach thus must depend on the architecture [14], [21]–[22].

RCCI offers the best evidence among the concepts considered for achieving a combination of renewable low-reactivity fuels with low engine-out NO_x and soot. Bioethanol is especially well suited for use as an LRF because of its high octane number, which corresponds to low autoignition reactivity and provides a large reactivity separation from diesel-like HRFs [6]–[7]. There is potential to increase the renewable-fuel fraction from the biodiesel side, but combustion stability and emissions will change because of the different spray and ignition properties of biodiesel compared with gasoline or fuel vapor, and the resulting combustion behavior will be strongly influenced by the injection timing (injection-phasing control) of the RCCI method, particularly in the case of ethanol-biodiesel RCCI [20]. There is still a focus on low-load ignition and injection timing, as HC and CO due to incomplete oxidation may be more limiting than soot or NO_x at light load.

Vehicle-level trends under steady-state operation can also differ from those of engine-domain steady state because the redistribution of operation occurs through supervisory control and component sizing. This emissions-oriented adaptive ECMS (in one simulated parallel full hybrid of RCCI/conventional dual-mode operation) achieved savings in fuel consumption of 12%, engine-out NO_x emissions of 75%, and soot of 82% compared with this study's baseline [14]. Again, these are case-dependent, but they indicate the effect of supervisory control. An ethanol-fueled advanced-combustion PHEV study also found CO₂ reductions that were highly dependent on the ethanol fraction, from 28% to 75% as the ethanol proportion increased from E20 to E100; control optimization also showed additional benefits [16].

Furthermore, more recent plug-in-hybrid assessments confirm a need to compare with other LTC concepts using the same vehicle mass and accessory load, final-drive ratio, battery SOC boundary conditions, and drive cycle [26]–[27].

Sustainability comparisons also require explicit separation of tank-to-wheel, well-to-wheel, and cradle-to-grave metrics. Low upstream carbon intensity can favor biofuel HEVs, whereas land-use assumptions, fertilizer demand, processing energy, transport, and co-product allocation can materially change the result. LCA studies of bioethanol/biogas hybrids and Indian passenger vehicles show that electricity mix, fuel pathway, and methodological boundaries can change the relative ranking of HEVs, PHEVs, battery electric vehicles, and conventional vehicles [12]–[13]. Low tailpipe CO₂ therefore does not by itself establish a low-carbon outcome.

After treatment adds a further system-level trade-off. Lower engine-out NO_x and soot can reduce selective catalytic reduction and particulate-filter loading, but the lower exhaust temperatures associated with LTC can limit oxidation of HC, CO, and methane. Frequent engine-off periods can cool catalysts, while active catalyst heating consumes fuel or electrical energy and may move the engine away from its preferred LTC region. Comparative studies should therefore supplement BTE and brake-specific engine-out emissions with cumulative cold-start emissions, thermal-management energy, mode-transition penalties, catalyst-temperature history, and combustion efficiency. These measures are necessary for consistent comparison of series, parallel, and plug-in hybrid configurations.

6. Applications and Practical Implementation

The most realistic near-term configuration in passenger cars involves downsizing the engine for LTC use and embedding it in a capable hybrid or PHEV, as opposed to stand-alone engine(s) that will presumably maintain LTC throughout the map. For that purpose, a representative parallel configuration is shown in Figure 1, which connects the renewable-fuel supply, LTC engine, electric machine, battery, power electronics, transmission, aftertreatment, and supervisory EMS. A series range extender shares all the physical components and includes additional electrical conversion, but the physical path from the engine to the wheel is eliminated, resulting in more operating points from which to choose.

Fuel-system design is directly affected by the choice of fueling strategies. Thus, ethanol-biodiesel RCCI can involve dedicated fuel storage, port injection of the LRF, direct injection of the HRF, and fuel-quality sensing or adaptive estimation. Flex-fuel operation can be used to enhance infrastructure compatibility, but the calibration will need to consider all aspects that change with ethanol content, volatility, and cold-start behavior. Durability and compatibility of seals and filters, oxidation stability, deposits, and injector coking have to be assessed for biodiesel applications. Biogas requires pressure storage and metering and adequate oxidation-catalyst capacity to control methane slip.

EMS should use efficiency, battery SOC, catalyst temperature, demanded power, thermal constraints, and the available combustion mode to plan engine operation. Through electric launch and regenerative braking, this RCCI mode of operation can be avoided, as the surpluses and shortages of engine power can be reserved for charging the battery, and low loads can be safely mapped onto an RCCI operating island that is stable enough under moderate-load regimes to benefit from such flexibility. In the case of quick demand shifts, electric torque fill allows for slower EGR, boost, and fuel-reactivity modifications. Achieving this balance between start-stop decisions, catalyst cooling, and cold-start penalties, and maintaining drivability through combustion-mode transitions, requires the same supervisory layer. Production feasibility covers more than control calibration.

Two fuel systems, evaporative-emission management, crash safety, on-board diagnostics, refueling logistics, and regional fuel availability can be packaging issues that determine whether a concept that works well in the lab can be adopted in practice. Development should therefore move from steady-state mapping towards hardware-in-the-loop (HWitL), engine-in-the-loop (EitL), chassis-dynamometer (CD), and real-drive evaluation (RDE). Validation should cover ambient-temperature variation, fuel-property variability, multiple start-up events, battery ageing, component degradation, and catalyst thermal history. Although biodiesel-HEV experiments have already been conducted [20] and RCCI vehicle studies have been carried out [23], [28] to prove technical feasibility, further durability data and validation of tailpipe emissions under full regulation are still required before production readiness can be confirmed.

7. Major Challenges and Research Gaps

A critical area continues to be transient combustion control—a large amount of the available calibration evidence is for steady-state operation, while passenger vehicles are constantly switching between low and high torque and between start and stop. RCCI phasing can fluctuate over a few cycles because of variations in intake temperature, residual fraction, rail pressure, and fuel properties. Although progress has been made in the development of control-oriented models, validation remains limited across aging, altitude, ambient-temperature changes, and renewable-fuel variability [3]. With low-load operation, there is a related thermal issue: with hybridization, engine-off points can be avoided; however, some or all engine-off periods can lead to decreases in wall and catalyst temperatures and increases in HC, CH₄, and CO during subsequent operation, leading to higher overall emissions. Steady engine-out maps are still used in many vehicle simulations, and these thermal transients have been underrepresented.

Further expansion of the LTC area is prevented at high load by the maximum pressure-rise rate, ringing, and peak cylinder-pressure limitations. Combustion stability can be improved either by increasing the HRF contribution or by decreasing the premixed fraction; however, this moves combustion towards diffusion-controlled burning. The boundary can be expanded with more boost and more EGR, but the additional work done by the turbocharger increases thermal loading and air-path lag. Thus, dual-mode operation is a viable option, although its transient emissions are still not as fully described as those produced during steady-state operation.

There is also an additional calibration dimension because of fuel-property variability. Ignition chemistry and fuel delivery may be affected by changes in ethanol-water content, biodiesel feedstock and cetane quality, viscosity, distillation characteristics, or the percentage of methane in biogas. These changes cannot be fully accounted for in useful validations using fixed calibration maps for realistic representations of fuel types over vehicle lifetimes. At higher fractions of renewable fuels, it may be necessary to use fuel-quality sensing, adaptive estimation, or closed-loop combustion feedback, but, once again, long-duration validation is somewhat sparse. There is likewise little durability information available on biodiesel-related deposits and lubricant contamination, injector fouling, alcohol-material compatibility, acid formation, repeated exposure to high pressure-rise rates, and operation of an aftertreatment system at low temperature. Some test campaigns have been limited to a single cylinder, which does not provide vehicle-level durability information, and longer aging tests are required to explain interactions between contaminants in renewable vehicle fuels, lubricants, oxidation catalysts, and particulate filters.

One methodological gap identified was carbon accounting, where different studies regularly use various indicators—tank-to-wheel CO₂, cradle-to-grave impacts, or well-to-

wheel GHG emissions. However, the results regarding biofuels are extremely dependent on feedstock, land-use estimates, co-product allocation, processing energy, and transport [12]–[13]. Low-carbon LTC can thus only be meaningfully compared with PHEVs or battery electric vehicles if the basic functional unit and carbon-intensity input are consistent. Moreover, a production constraint is not always taken into account in optimization studies. All of these—real-time computation, diagnostics, fault management, drivability, noise, vibration, and harshness (NVH), thermal management, catalyst monitoring, regulatory compliance, sensor cost, and calibration burden—have to be addressed at the same time. The overall research gap is thus the lack of constraint-complete demonstrators that link combustion improvements at lab scale with passenger-vehicle use in the real world and are ready for regulation.

8. Future Research Directions

Future development should begin with integrated fuel-engine-powertrain co-design. Fuel reactivity, renewable fraction, injector architecture, compression ratio, EGR capability, electric-machine rating, battery energy window, and hybrid topology should be optimised simultaneously and not successively. Changes in the merit of any of the above subsystems can be traded off against changes in others, and trade-offs in multiobjective optimization should include fuel energy use, tailpipe NO_x and PM, unburned HC or CO, catalyst temperature, battery degradation, and life-cycle CO₂-equivalent emissions.

Adaptive combustion control is a second priority. It can be a combination of cylinder-pressure sensing, ion-current sensing, virtual-pressure estimation, and fast exhaust measurements, and all four methods can be combined in closed-loop regulation of combustion phasing, indicated mean effective pressure, and maximum pressure-rise rate. Physics-informed or uncertainty-aware data-driven models may decrease the calibration burden while maintaining safety. Then, online adjustment of LRF share and HRF injection timing could be used to accommodate changes in ethanol concentration, biodiesel quality, and ambient conditions.

This should be followed by thermally aware energy management. The thermal states of catalysts and engines should be considered explicit states and/or constraints in supervisory control, rather than secondary corrections. Prediction of engine-off interval (EIO) benefits can be used as a guidance function for route, traffic, and road-grade preview to assist predictive controllers in determining whether restart-energy and catalyst-temperature penalties can be offset by the benefits of EIO. When using biogas and alcohol-rich LTC, the temperature of the oxidation catalyst directly affects the control of methane, HC, and CO; this requirement is particularly important.

Harmonization of LCA boundaries is also needed in renewable-fuel pathways. Vehicle efficiency and vehicle life-cycle carbon intensity should be reported with transparent electricity- and fuel-production emission factors and sensitivity analysis. Regional variation in the grid, biofuel feedstock, biodiesel availability, the compatibility of blending E20 and E100, and characteristics of the urban duty cycle should be treated explicitly, as transferring assumptions from Europe or North America can lead to errors in the results for India [13], [17]. Validation of the combustion models should be established in a step-by-step process from single-cylinder combustion screening to multi-cylinder transient mapping, hybrid-powertrain or engine-in-the-loop testing, chassis-dynamometer testing, and on-road testing for validation. Fuel blends should be tested over the full temperature ranges, at altitude, under multiple start-stop conditions, and in aftertreatment systems after exposure to roadside conditions and aging. Deposits should be covered under durability programs, including injector deposits, fuel-system material compatibility, lubricant condition, piston and ring

deposits, and catalyst aging. These strengths can then be applied to the optimal operating ranges of the respective architectures: HCCI-type operation at very narrow operating points, RCCI at potentially larger hybrid operating ranges, ethanol-rich dedicated hybrid engines at a very specific (or reduced) high-efficiency operating range, and dual-mode engines at a broader operating range. This research goal does not, therefore, imply that one LTC mode is universally better than all the others, but rather aims to provide a detailed operating envelope and conditions of use for each LTC strategy in order to gain a vehicle-level benefit that is reproduced with every use.

9. Conclusion

Thus, biofuel-based LTC can play a part in the low-carbon hybrid passenger transport system only if combustion, electrification, biofuel production (if applicable), aftertreatment (if required), and supervisory control are considered together as a coupled system. HCCI and PCCI are examples of low-emission premixed combustion, but are limited with respect to phasing control and operating range. RCCI allows more control with reactivity stratification and is a good approach for renewable-fuel blends, such as ethanol–biodiesel or biogas with a high-reactivity pilot, albeit requiring more devices (dual-fuel hardware) and more tuning (transient control). By using electric torque to absorb very fast transients in the design problem and by shifting engine operation onto stable, efficient LTC zones, hybridization enables the use of electric torque in a more effective manner. In the series design, there is maximum decoupling of the operating points with higher electrical-conversion losses, while the parallel/P2 design features direct mechanical ripple transmission with a wider combustion/mode-management range. The evidence considered indicates that steady-state engine performance is only an adequate measure for testing a low-carbon LTC hybrid. Vehicle-level fuel consumption and emissions are affected by the design of the controllers, the size of the components, the historical state of the catalysts, fuel properties (in the case of renewables), charging conditions, and system boundaries. Thus, a first step towards a credible development target is a closed-loop, fuel-adaptive, thermally aware LTC hybrid powertrain verified with a real-driving test and assessed using transparent life-cycle carbon accounting. Successful demonstration of this ability would give a better foundation for more reliably judging whether biofuel-LTC hybrids can offer a long-lasting and local decarbonisation benefit beyond engine-out test behaviour, which is often beneficial in a laboratory setting.

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