Chapter

A Comprehensive Review on Hybrid and Electric Vehicle Energy Control and Management Strategies

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Abstract

We show a new technology to manage solid waste services through optimization methods (on sectoring, routing costs, and resources). This technology is called optimized planning and integrated logistics management (OPILM). It is being applied to Brazilian municipalities as it attends to their major natural features. The technology is formed by a framework of computational systems that uses optimization methods from sector arc routing and scheduling, fleet and staff scheduling, using also mobile smartphone apps. We present some of the results of real cases evaluated for residential refuse collection and selective waste collection in two Brazilian cities (Petrópolis/RJ and Bom Jesus dos Perdões/SP). The plan implementations achieved 17.9% from actual fixed and variable cost savings for sectors (vehicles and workers) and routes (time and distances) for residential refuse collection in Petrópolis/RJ. For the selective waste collection, we detail how we made our project to Bom Jesus dos Perdões/SP. We also present the returns considering costs involved in the management of the operational level and amortized by the investment required to use and apply the proposed technology for Petrópolis/SP.

Keywords: regenerative braking, energy management and control, driving cycles, hybrid electric vehicles, thermal management system

1. Introduction

The continuing falloff of fossil fuel reserves, in addition to strict emission rules around the world, has made even more critical the need for improved vehicular fuel economy [1–5]. Due to the worsening effect of climate greenhouse gasses and the limited fossil fuels, electric and hybrid electric vehicles (EHEVs) are carrying large responsibilities to freeze the drawback of defective environment and energy degradation in the recent years. Power management and control strategy is important innovation to boost the EHEV performances. Regeneration of electric energy from braking is the foremost important features of hybrid and electric vehicles. During braking, the motor can function as a generator to recover the vehicle's kinetic energy and potential energy to convert it into electrical energy, which can then be restored to the energy storage devices. Meanwhile, the motor will be controlled and will provide sufficient torque for braking.

Some research on the regenerative brake control approach has been published in the literature, although most of it is limited to flat driving cycles. Despite this, domestic and international researchers have done minimal research on downhill regenerative braking control. The ability to downsize the original internal combustion engine while fulfilling the power demand at the wheels in the case of HEV is the most popular of these benefits. This benefit is due to regenerative braking's capacity to transfer power to recharge the battery from both the internal combustion engine and the electric motor at the same time, resulting in lower fuel consumption and greater driving range [6–10]. The use of an electric drivetrain in a HEV allows kinetic braking energy to be recovered that would otherwise be lost owing to mechanical brakes in conventional vehicles. Accomplishing the aforementioned advantages in a real-time control method by coordinating the onboard power sources, it is a key to enhancing fuel efficiency and minimizing emissions. Various energy controls and management solutions have been advocated in the literature up to this point. This presentation presents a complete analysis of the literature, with a focus on offerings in the area of energy efficiency improvement control and management for electric and hybrid electric vehicles. Available research gaps and future works are also mentioned in this section of the discussion. The following is a list of the offerings in this chapter: First, strategies for HEV modeling, control, and management are briefly addressed in order to emphasize the relative relevance of each approach. Following that, two levels of HEV management and control strategies are examined in depth: HEV offline control strategies and HEV online control strategies. This in-depth analysis focuses on the control structure of the techniques under consideration, as well as their novelty and contributions to the achievement of several improvement goals, including but not limited to: reduced fuel consumption and emissions, charge sustenance, optimization of braking energy regeneration, and improved vehicle drivability. Finally, exploitable research gaps are identified and discussed within the research domain.

1.1 Approaches to HEV Modeling

In the current development of HEVs, there are at least three stages of computational modeling. The following are the stages:

- Detailed modeling is carried out during the HEV's research and development stages. Single powertrain components like an internal combustion engine and an electric motor are the focus of this type of modeling. This type of modeling aims to provide detailed information about the component being modeled's specific characteristics [11].

- Software-in-the loop (SIL) modeling occurs later in the HEV development cycle, but usually before any hardware is built. In the development of HEV control systems, SIL is now widely used [11].

- Hardware-in-the loop (HIL) modeling is done after the controllers have been manufactured and validated. At the detailed modeling stage of the development process, there are three common ways for HEV modeling: the kinematic or backward approach, the quasi-static or forward approach, and the dynamic approach [11].

1.2 Kinematic approach

The kinematic approach, as depicted in **Figure 1**, is a backward methodology in which the input variables are the vehicle's speed and the road's slope angle. This method calculates the engine speed using basic kinematic connections based on the wheel revolution speed and the total transmission ratio of the driveline. From the major vehicle characteristics, the tractive torque that needs to be applied to the wheels to drive the vehicle according to the selected speed range may be computed (e.g., vehicle mass, aerodynamic drag and rolling resistance).

To obtain an immediate fuel consumption or emissions rate estimate, the calculated engine torque and speed are combined with a statistical fuel consumption model [12]. The kinematic technique implies that the vehicle matches the goal performance; hence, the vehicle speed is purportedly known a priori [13]. As a result, the kinematic approach has the benefit of simplicity and cheap computational cost. The kinematic modeling method, also known as backward modeling, ensures that the driving speed profile is followed exactly. There are no guarantees that the given vehicle will be able to complete the specified speed trace because the power needed is immediately generated from the speed and not checked against the actual powertrain capabilities. A "fail-safe" component is usually included in the kinematic approach, which terminates the simulation if the required torque exceeds the maximum torque available (from the electric motor and engine). Another issue in this modeling technique is that it ignores engine thermal transient activity, which is seen after a cold start. Because transient situations are simplified into a series of stationary states, this modeling method is only useful for estimating vehicle fuel consumption and emissions in the first stages [11].

1.3 Quasi-static approach

Figure 2 depicts, the quasi-static technique of HEV modeling uses a driver model, usually a PID, which compares the desired speed of the vehicle (driving cycle speed) with the vehicle's real speed profile and then generates the power demand profile necessary to meet the target speed of the vehicle profile. The vehicle's differential motion equation is used to construct this profile of power demand [14]. After determining the engine's propulsion torque and speed, instantaneous consumption of fuel can be calculated using a statistical engine model, as stated in the kinematic or backward approach. The applicability and precision of the quasi-static modeling

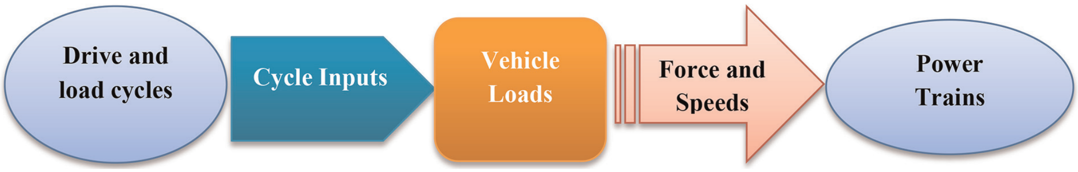


Figure 1.
Information flow in a kinematic or backward HEV model [11].

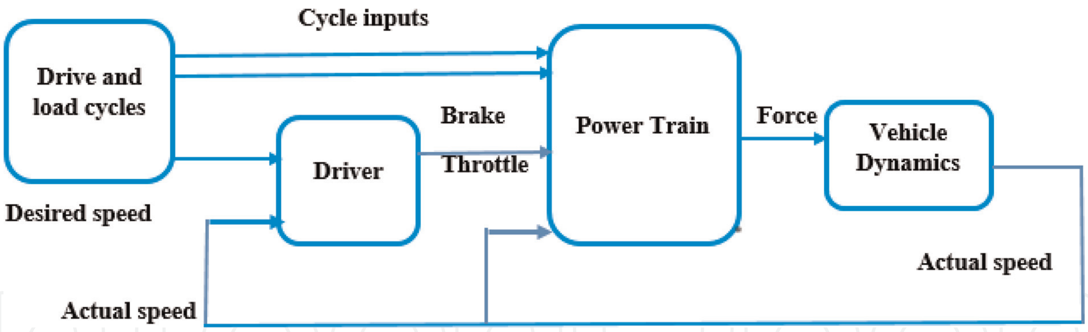


Figure 2.
Information flow in a quasi-static powertrain model [7, 11].

approach are highly dependent on the type of simulation models to be performed. When it comes to estimating the consumption of fuel and NOx of a car with a conventional powertrain, the quasi-static modeling approach delivers reasonable accuracy. Acceleration transients and related "turbo-lag" phenomena make a significant contribution to cycle cumulative emissions for pollutants like soot, demanding a more complex engine simulation model capable of adequately representing engine transient behavior [13].

1.4 Dynamic modeling approach

The internal combustion engine behavior during transient conditions is also taken into account in the dynamic modeling technique, in addition to longitudinal vehicle dynamics. The engine's transient behavior is represented by a complete one-dimensional fluid dynamic model. In a dynamic modeling technique, an internal combustion engine engine's suction and discharge systems, for instance, are represented as a network of tubes connected by connections that reflect either physical joints between the tubes, such as area changes or volumes, or subsystems, namely the engine cylinder. A finite difference technique can then be used to find solutions to the equations governing mass, momentum, and energy flow for each element of the network. This enables highly dynamic events, such as rapid vehicle accelerations, to be correctly simulated. Dynamic modeling is often restricted to study areas requiring internal combustion engine development because it involves a substantial amount of time and calculation [15, 16]. The quasi-static technique is preferred for control development because it preserves the physical causality of the vehicle system and enables the use of the identical controller inputs/outputs in the simulator as well as on the real vehicle.

2. Power split configurations and HEV modes

HEVs have been shown to improve automotive fuel efficiency and emissions while meeting vehicle power demands, preserving vehicle performance, and offering a better driving experience [12]. Regardless of the HEV configuration in question, effective power distribution across the energy sources is required to achieve improved fuel efficiency and reduced emissions (ICE and electric motor). As part of this endeavor, several power split control systems have been suggested, evaluated, and applied to various HEV configurations. HEVs' power-split controller gets inputs from the global positioning system (GPS), including vehicle power demand, vehicle speed or acceleration, battery state of charge, current road load, and, on occasion, "intelligent" future traffic circumstances. A set of control decisions are contained in the controller outputs signal, which governs which of the following modes the HEV should operate in:

1. The regeneration mode (for kinetic energy recovery electric motor is used).
2. Charge with a trickle (for charging the battery engine power is used).
3. Only use the electric motor (electric motor operates alone).
4. Engine-only operation (ICE operates alone).
5. Assist function (electric motor and ICE operates).

2.1 HEV management and control strategies

Minimization of fuel consumption and emissions without compromising of vehicle performance, and battery state of charge are often the main control objectives of most HEV control strategies. As illustrated in the control strategy classification chart in **Figure 3**, HEV control techniques may be divided into two categories: online control strategies and offline control strategies. Although various papers and research publications have contributed to the compilation of reviews on HEV control tactics, this field of research is always expanding, and there is a need for an up-to-date review with the introduction of novel methodologies. This section's major goal is to highlight important research gaps in the field as well as contribute to the increasing list of review debates. On the basis of **Figure 3**, all HEV management and control solutions were discussed.

2.1.1 HEV offline energy management strategies

Control signals are determined using optimization-based control algorithms that minimize the sum of the goal function over time (global optimization) or minimize the objective function instantly (instantaneous optimization) (local optimization). Because the effectiveness of a global optimal control technique is solely dependent on a priori knowledge of the entire driving cycle, which is often difficult to determine in real time, global optimal techniques are often referred to as "non-causal," meaning they cannot be used in real time but can be used as a control benchmark against which all other causal real-time controllers can be compared. For optimal energy management of HEVs, global optimization approaches such as linear programming, dynamic programming, genetic algorithms, and others have been used.

2.1.2 Linear programming

The nonlinear fuel consumption model of an HEV is approximated and solved for a global optimal solution using linear programming [11]. Automotive energy management challenges have been effectively solved using linear programming.

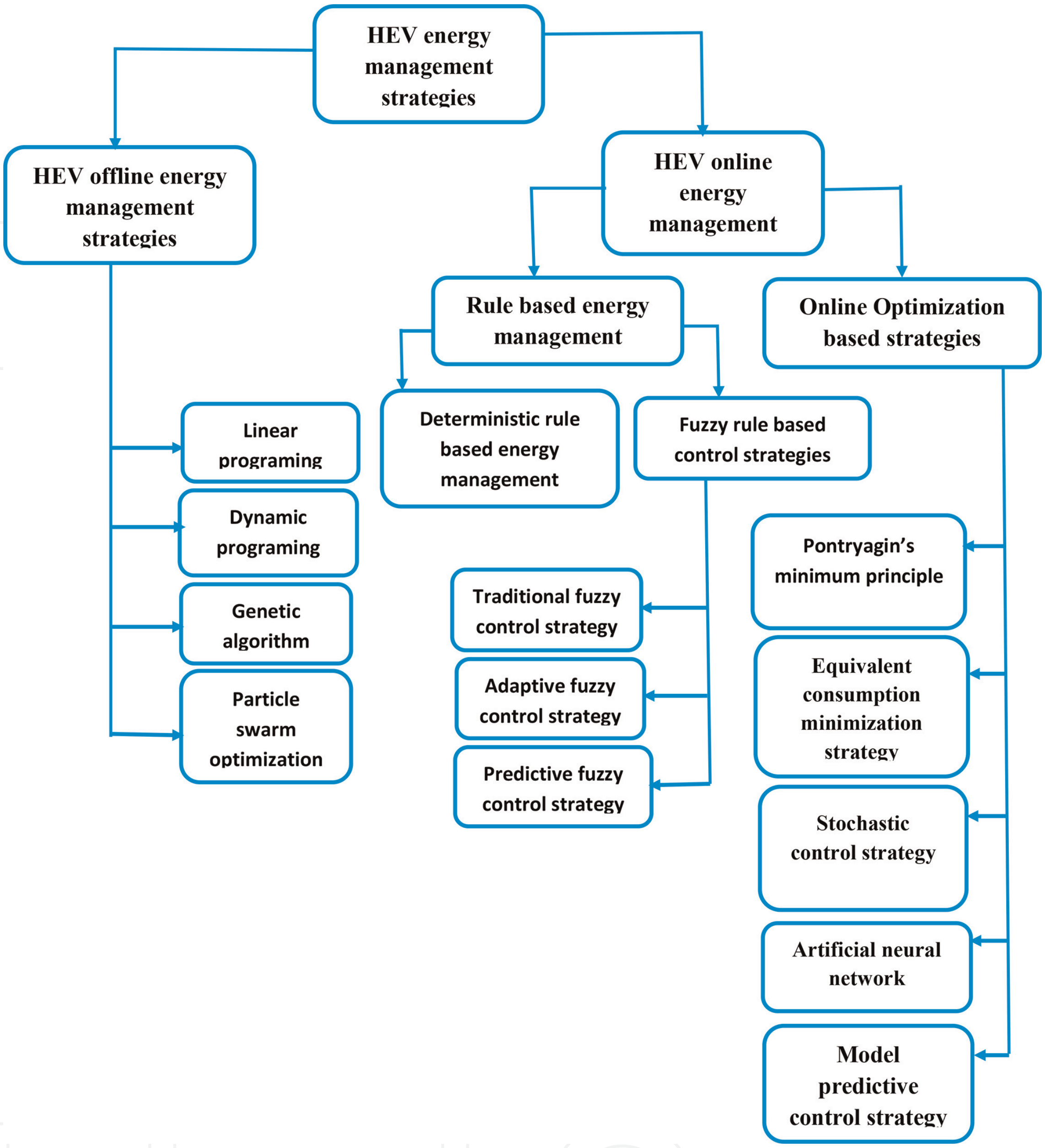


Figure 3.
HEV control strategy classification redrawn from [12].

2.1.3 Dynamic programming

The dynamic programming technique was invented by Richard Bellman and is used to determine optimal control policies through a multi-stage decision process. An ideal control policy, as described by Bellman, has the property that no matter what the prior decision (i.e., controls) was, the remaining decisions must comprise an optimal policy in terms of the state resulting from those previous decisions [17]. A discrete multi-stage optimization problem in which a decision based on the optimization criterion is taken from a finite set of decision variables at each time step is known as a dynamic programming algorithm. The backward recursive method and the forward dynamic programming methodology can both be used to implement Bellman's dynamic programming algorithm. The best sequence of control variables is found by working backward from the final state and selecting the path that minimizes the cost-to-go at each time step in the backward recursive technique (integral cost from that time step until the final state).

2.1.4 Genetic algorithm

The genetic algorithm (GA) is a heuristic search algorithm for developing optimization solutions. Darwin's theory of evolution inspired this branch of artificial intelligence. GA starts with a population of preliminary solutions (chromosomes) to find the best solution to a problem. Each population's solutions are picked based on their suitability for forming new and enhanced versions. As a result, the most suited solutions have a better chance of growing than those that are less suitable. The method is performed indefinitely until the desired optimization conditions are met. The genetic algorithm is a reliable and practical global optimization method with a large search space that may be used to solve complex engineering optimization problems with nonlinear, multimodal, and non-convex objective functions.

2.1.5 Particle swarm optimization

Dr. Eberhart and Dr. Kennedy created particle swarm optimization (PSO) in 1995 [18, 19]. This method is based on the social behavior of flocking birds, which optimizes a problem by iteratively trying to enhance a candidate solution in terms of a specific quality metric. Particles in PSO travel about a search space, directed by the search space's best known positions as well as the swarm's best known position. When better sites are located, the swarm particles will move. PSO is a meta-heuristic method for searching a large number of candidate solutions. PSO does not require the optimization problem to be differentiable, despite its non-causal character, and is thus well suited to optimization problems with some degree of noise or irregularity. In HEVs, particle swarm optimization has proven to be effective.

2.2 HEV online energy management strategies

HEV online control strategies, in contrast to HEV offline control strategies, are causal and implementable in real time. Heuristic control rules (rule-based control strategies) or an instantaneous optimization of a stated objective function can be used to create HEV online control techniques (online optimization-based strategies).

2.2.1 Rule-based energy management strategies

The most typical method of establishing real-time supervisory control in a HEV is using a rule-based control scheme. The control rules are frequently based on heuristics, engineering intelligence, or mathematical models, and they are designed to allow the ICE to function at high-efficiency levels while still allowing for energy recovery via regenerative braking. The development of rule-based HEV control approaches is typically divided into two stages: the formulation of appropriate powertrain control rules and the calibration of the strategy, which is commonly accomplished through simulations on a vehicle model. In most cases, rule-based control approaches fail to guarantee the optimality of the solution or to fulfill the required final integral constraint (charge sustainability). To correct this, the control rules must ensure that the integral constraint state of charge (SOC) remains between the lower and upper boundaries as specified. There is no standard approach to forming control rules in rule-based control strategies, and there is no way to know a priori whether a certain set of rules is adequate for a given application. However, the control rules could be designed deep and complex enough to handle any exceptional event that might occur [20].

The fundamental benefit of rule-based HEV control approaches is their simplicity, which makes them very simple to comprehend and execute on actual cars [11]. Rule-based control techniques have monopolized the production vehicle industry due to their minimal computational demand, natural adaptability to online-applications, high dependability, and reasonable fuel consumption outcomes. Despite their extensive use, rule-based HEV management systems still face considerable obstacles. Due to the lengthy rule definition and calibration process, developing a rule-based HEV management approach typically necessitates a significant amount of time and investment in competent labor. This scenario is exacerbated by the necessity to change the rules for each new driving circumstance and engine, raising concerns about the robustness of rule-based HEV control schemes. Furthermore, current research investigations reveal that rule-based HEV control approaches offer lower but acceptable fuel consumption results when compared to optimization methods. Deterministic rule-based control strategy and fuzzy rule-based control strategy are two types of rule-based controllers [11].

2.2.2 Deterministic rule-based control strategy

The rules for the deterministic rule-based control method are determined using the engine's fuel economy or emissions map. The rules are frequently implemented using pre-computed look-up tables. The concept of a hybrid optimum line for a parallel HEV with continuously variable transmission (CVT) was introduced by Kim et al. [21], who used a deterministic rule-based control technique. The best values of CVT gear ratio, motor torque, and engine throttle were effectively determined and applied in real time using this method. The electric assist control approach is one of the most widely used deterministic rule-based HEV control strategies. The ICE is employed as the sole source of power in this technique, and the electric motor is only used to provide additional power when the vehicle requires it. Another type of deterministic rule-based control is thermostat control technique. The electric motor and ICE are employed to generate the electrical energy that powers the car in this manner. By simply turning on/off the internal combustion engine, the battery state of charge is always maintained between specified high and low values. The thermostatic control technique was employed by Jalil et al. [22] to turn the engine on/off based on the battery state of charge profile. When compared to a deterministic rule-based control technique, the obtained outcomes were shown to be considerably sub-optimal. The following rules apply to several of the most extensively used rule-based control systems [13]:

1. When the vehicle's power demand falls below a specified threshold, the vehicle operates solely as an electric vehicle (EV), with the electric motor supplying the whole power requirement. This rule is usually applied to prevent the engine from operating at low-efficiency levels. The applicability of this rule, however, is contingent on the size of the HEV's electric engine and batteries.

2. When the vehicle power demand exceeds the maximum engine power, the electric motor is engaged for power-assist.

3. During regenerative braking, the electric motor charges the battery.

4. When the battery SOC falls below the defined minimum value, the ICE is activated to generate extra torque.

2.2.3 Fuzzy rule-based control strategy

Rule-based controllers are the forerunners of fuzzy rule controllers. In the fuzzification and defuzzification process, the linguistic representation of the control inputs is turned into a numerical representation with membership function in a fuzzy rule controller. The fuzzy rule-based control strategy's underlying logic is a type of multivalued logic derived from fuzzy set theory, which is designed to deal with reasoning that is approximate rather than precise. The relative simplicity of fuzzy rule controllers allows for tuning and adaption as needed, hence increasing the degree of control flexibility. Because of its nonlinear structure, it is very useful in complicated systems like modern powertrains. The battery level of charge, desired ICE torque, and intended mode are often inputs to fuzzy rule controllers, which output the ICE operating point. Driver command, battery SOC, and motor/generator speeds were treated as fuzzy sets for the creation of a fuzzy rule-based control strategy considered by [23, 24]. A power notification system was added to the fuzzy control framework, allowing the engine to operate in its high-efficiency region. In most cases, the electric motor compensates for the gap in power demand and ICE power. Traditional fuzzy control strategy, adaptive fuzzy control strategy, and predictive fuzzy control strategy are some of the current varieties of fuzzy rule-based control [13].

2.2.4 Traditional fuzzy control strategy

Traditional fuzzy control is frequently used to improve fuzzy efficiency, allowing the ICE to run more efficiently. This is accomplished by load balancing, which involves using the electric motor to push the engine to operate in its most efficient region (low engine speed, high engine torque) while maintaining the battery charge level. In a parallel HEV, Sulaiman et al. [25] presented a fuzzy logic controller to optimize fuel usage. The proposed strategy is centered on improving the efficiency of the vehicle's most important components, such as the internal combustion engine, electric motor, and battery.

2.2.5 Adaptive fuzzy control strategy

Fuzzy control that adapts because it potentiates simultaneous optimization of fuel efficiency and emissions, strategy is becoming increasingly popular in automotive applications on HEV. Because fuel efficiency and emissions are frequently at odds, an optimal solution cannot be found that meets all of the goals. However, utilizing the weighted-sum approach, where appropriate weights are modified over different driving situations for fuel efficiency and emissions, a sub-optimal solution is possible. The weights are relative, reflecting the importance of the particular objectives (fuel usage, NOx, CO, and HC emissions) [13]. As a result, adaptive fuzzy controllers can control specific objectives by modifying the weights given to them.

2.2.6 Predictive fuzzy control strategy

Prior information about a planned driving trip is used by a predictive fuzzy controller. This information is frequently obtained *via* a global positioning system (GPS), which provides information on the kind of impediments that the vehicle is likely to encounter, such as heavy traffic and a steep incline, among other things. Vehicle speed, speed state in the look-ahead window, and elevation of sampled places along a specified route are all common inputs to the predictive controller. The predictive fuzzy controller calculates the optimal ICE torque contribution for each vehicle speed based on the available history of vehicle motion and the speculation of its possible future motion, and outputs a normalized signal in the order of 1 to +1, indicating whether the battery should be charged or discharged. Fuzzy controllers have drawn a lot of interest from heuristic control professionals in the research and automobile industries due to their simplicity and robustness.

2.3 Online optimization-based strategies

Online optimization-based solutions break down global optimization problems into a series of smaller problems, lowering the amount of time and effort required to solve them. This eliminates the requirement for future driving data, allowing for real-time implementation. Local optimization procedures have gained the most research interest in HEV management, although producing marginally sub-optimal results when compared to global optimization strategies. The most widely used strategies are ECMS (Equivalent Consumption Minimization Strategy) [26] and PMP (Pontryagin's Minimum Principle) [3, 21]. Artificial neural networks, particle swarm optimization (PSO), and model predictive control (MPC) are some of the other online optimization-based methodologies now being investigated.

2.3.1 Pontryagin's minimum principle

Pontryagin's minimal principle (PMP) is a specific instance of the Euler-Lagrange equation of the calculus of variations, which was formulated in 1956 by Russian mathematician Lev Pontryagin and his students. The optimal solution to the global optimization issue must satisfy the criterion of optimality, according to the principle. The performance of the PMP controller was shown to be particularly sensitive to the estimated co-state value after studying the state of energy evolution for various co-state values. The model-based PMP control technique was discovered to compel the vehicle to deplete the battery for a co-state value larger than 10, and then transition to a charge-sustaining mode when the lower SOE (State of Energy) bound is achieved. Likewise, when the co-state value is 6, the model-based PMP technique allows the battery to be progressively reduced during the cycle, reaching the lower SOE boundary only at the end of the driving pattern and avoiding any charge maintaining activities. This process, known as blended mode, enables the achievement of the lowest possible vehicle fuel usage throughout a set of driving cycles. According to the findings of Stockar et al. [27], PMP is a shooting approach for solving a boundary value optimization issue. As a result, the optimal control technique that emerges is non-causal and cannot be executed in real time.

2.3.2 Equivalent consumption minimization strategy

The Equivalent Consumption Minimization Strategy (ECMS), which was first devised based on the heuristic assumption that the energy consumed to operate a vehicle over a driving cycle ultimately comes from the engine, is a more easily implementable local optimization strategy. As a result, the hybrid system just acts as a buffer for energy [13]. The instantaneous minimization of a cost index, which is the sum of a number of operation metrics weighted by equivalence factors, is the basis for this technique. Engine fuel cost and battery fuel cost are two often utilized metrics in ECMS HEV regulation. It can be implemented online because it does not require prior knowledge of driving patterns. The optimum power split is biased using a nonlinear penalty function of the battery state of charge divergence from its goal value to impose the global constraint of charge-sustaining operation.

2.3.3 Stochastic control strategy

For the power management of a series HEV, a stochastic model predictive control (SMPC) framework was created. The driver's power demand was simulated as a Markov chain, evaluated over numerous driving cycles, and utilized to generate SMPC control law scenarios. When compared to deterministic receding horizon control techniques, simulation results reveal that the SMPC solution drives engine, motor, and battery operations in a causal, time-invariant, state-feedback manner, resulting in enhanced fuel economy and vehicle performance.

2.3.4 Model predictive control strategy

Over a finite horizon, model predictive control is the solution to a basic optimal control problem. It is done online with the help of a model that predicts the impact of control on the system output. It works by calculating the optimal control for the prediction horizon in real time but only applying the first element; the prediction horizon is then shifted forward at the next time step. MPC's operation is based on high model accuracy and prior knowledge of reference trajectories, both of which are not directly possible in-vehicle applications. When combined with a navigation system, however, MPC has been proven by Salman et al. [28] to be an effective real-time predictive optimum control technique.

2.3.5 Artificial neural network (ANN)

An artificial neural network (ANN) is a computing system composed of a number of simple, highly interconnected processing components that process data based on their dynamic state responses to external inputs. Mc Culloh and Pitts created the ANN concept in 1943, and Hebb enhanced it in 1949 by adding the first learning rule. By modifying weights to minimize the difference between the actual and anticipated output patterns of a training set, neural networks can be trained to learn a highly nonlinear input/output relationship. The backpropagation method aids this type of guided learning.

The neural network's adaptable structure makes it ideal for HEV energy management applications. The nonlinear correlations between inputs and outputs of a well-defined energy management network can be learned and replicated using neural networks. For varied drivers and driving patterns, Baumann et al. [29] devised a control approach that blends artificial neural networks and fuzzy logic to create a load-leveling technique for increased fuel economy and lower emissions. A dynamic model is utilized [30] to explain the driver-vehicle interaction for a general transient and to simulate the vehicle driveline, internal combustion engine, and electric motor/generator (EM). Vehicle load is assessed in real time using a time delay neural network (TDNN) and used to optimize the supervisory control approach in the absence of traffic preview information.

2.4 Energy regeneration through the braking system

According to Chen et al. [31], the included regenerative braking system (RBS) recovers the vehicle's kinetic energy during deceleration, considerably boosting fuel economy. According to studies, a traditional braking system in urban driving scenarios wastes around a third to half of the power plant's energy in the form of heat to the atmosphere during deceleration. And this squandered energy was originally in the form of kinetic energy, or motion energy. As a result, it is critical to be motivated to recuperate this wasted kinetic energy in order to increase electric power demand and expand driving range. From a practical standpoint, recovery of vehicle kinetic energy by converting it to thermal, mechanical, or electrical energy setup is a viable option.

Hydraulic regenerative braking, which has a high power density and energy conversion efficiency, has been used in heavy vehicles, but control strategies for hydraulic regenerative brakes are difficult to fully utilize the regenerative potential due to the low energy density of the hydraulic accumulator, which forces a tradeoff between performance and cost to solve this new control strategy, which will be used as a blended brake control and energy efficacy. High regeneration efficiency and nice braking sensation can be attained if the regeneration and frictional brakes are well synchronized.

2.4.1 EV energy control with hydraulic brake system (HBS)

Based on the study shown in **Table 1**, Chen et al. [31] observed that electric vehicles with blended brake control with the purpose or objective of discussing the mechanism and evaluation of electric vehicle regenerative energy efficiency

Authors	Purpose	Similarity	Unique feature
Liang et al. [32]	To improve the efficiency of electric vehicles	Energy generation and control	Concerned about HEV with HBS
Chengqun [33]			
Wei et al. [34]			
Chengqun et al. [17]			
Chen et al. [31]			

Table 1.
Electric vehicle energy control with HBS.

improvement. The methodologies followed were vehicle tests carried out on chassis dynamometers under typical driving cycles. Three different control strategies were used, namely, the system design, blended brake control, and energy efficiency evaluation. In addition to this, by using the energy flow analysis, two different evaluation parameters were also used: the contribution ratio to energy efficiency improvement and the contribution ratio to driving range extension. In comparison with non-blended regenerative brake control, the contribution ratios made by regenerative braking to energy efficiency improvement and driving range extension were up to 11.18 and 12.58 percent, respectively, under the new European drive cycle (NEDC). Finally, the report identifies future research needs based on the following gaps:-

- Evaluation method of regenerative braking contribution for other types of electrified vehicle, road tests of the evaluation parameters under different driving cycles should be conducted since the test is only made on chassis dynamo meter.

- From the experiment, different mechanism analysis and practical implementation methods were not discussed adequately to get more accurate and better results.

The similarity of this study with other related comprehensive review is efficiency improvement through control and management of regenerative braking energy. The study made by Qiu and Wang [33] same purpose or objective is followed to improve energy regeneration efficiency but the methodology used for the experiment under this study for mechanical and evaluation methods analyzed by energy flow is:

- Proposals have been made to calculate the contribution of regenerative brakes.

- A new regenerative braking control method, known as “serial-2 control strategy,” is introduced.

- Two control strategies, known as “parallel control strategy” and “serial-1 control strategy,” are proposed as the comparative control strategy and vehicle road testing are conducted.

To do such an experiment, the parameters used to get the desired result are two, namely, the contribution ratio for regenerative braking energy transfer efficiency improvement and the contribution ratio to regenerate driving range. The energy consumption of a vehicle with regenerative braking. Then, EmDrive calculated the efficiency of the axle with the RB energy efficiency of a vehicle, with the RB average efficiency of a battery during charging and the energy consumption of hydraulic braking situations obtained. The serial-2control technique produces a significantly higher regeneration efficiency than the parallel and serial-1 strategies. Regenerative braking contributes up to 41.9 percent to improved energy transfer efficiency and 24.63 percent to an increased regenerative driving range, respectively. Finally, the study identifies areas where more research is needed in order to improve the process of evaluating regenerative braking contributions for different types of powered cars.

The torque optimization control of electric vehicles with four-wheel motors equipped with regenerative braking is addressed by Xu et al. [34].with the objective of having better safety and increasing energy regeneration efficiency. The method followed was model predictive control (MPC) theory, with the issues of multiple objectives and constraints of the regenerative braking system well addressed. Hence, a real-time test is demonstrated through the parameters of four in-wheel motors mounted to each wheel, determining the hydraulic braking torque and motor braking, alternating electric motor AME/sim software to verify the advantages of the proposed model predictive controller, motor model, and vehicle dynamics model is effective in the study. The simulation results show that optimizing braking torque distributions improves energy recovery performance for electric vehicles. The study has its own gaps concerning the MPC and should be tested with another strategy to see and compare for a better result.

Chengun et al. [17] is a second study next to Chengun et al. [33] with the same author and objective but with different methodology. This study focuses on novel control strategies (NCS) of regenerative energy braking systems, and its main objective or purpose is to focus on the control strategy of a regenerative braking system of an electric braking system under safety critical driving conditions to ensure the electric vehicle's stability in various types of tire-road adhesion conditions. The method proposed was to investigate using a serial control strategy to utilize proportional integral derivative control to utilize proportional brake force as an antilock brake system (ABS) operation. Three control strategies were developed in this study:

- "the model following control"
- "Frequency selection by filter"
- "PQ method" strategies

This study considers a regenerative braking system that is electrically controlled according to the techniques of conventional hydraulics. The ABS is studied and a control algorithm harmonizing the ABS control function and braking energy regeneration has been developed. A representative passenger car outfitted with a central electric motor is chosen for the case study. Road tests were carried out under various types of road adhesion conditions, and the results were then compared. The simulation test results on the basis of a quarter vehicle model show that "Regenerative ABS" is useful during the critical braking procedure. To see the effect on the ICE road test, the contribution ratio to stable and dynamical braking energy efficiency is enhanced by up to 58.56 and 69.74 percent, respectively, under the serial control technique. According to the ICE road test results, mean deceleration has improved by 4.41 and 14.7% separately in comparison with the bench mark. The study still has its own gaps to be filled by future research work and further recommends that:

- The regenerative braking system's controls performance in different types of electric automobiles.
- The impact of various battery kinds and their degradation mechanisms on the suggested control strategy's performance.
- The impact of various vehicle dynamics modes on the suggested control strategy's performance.

Last but not least is the use of an electric car in conjunction with hydraulic braking system downshifts to improve the efficiency of regeneration energy in electric vehicles. Cooperative strategies (HB, EM) with a hierarchical control approach were proposed by Li et al. [32] to realize cooperative control of regenerative and hydraulic braking during the downshift process. To achieve the ideal down-shift point, an off-line calculation, and an on-look-up table approach are employed to classify the upper controller. A nonlinear sliding mode observer is built for the medium controller to obtain the actual hydraulic brake torque. Cooperative control of regenerative and hydraulic braking is provided for the lower controller to ensure brake safety during the downshifting process, and a pulse width modulation method similar to pulse width modulation is proposed to regulate the hydraulic brake torque using three degree of freedom (DOF) vehicle model to illustrate the vehicle dynamics.

The results obtained from simulation and hardware in-loop tests show that the proposed algorithm is effective in improving the energy efficiency of electric vehicles. The study is most similar to my topic, but it has its own future work recommendation since it faces gaps. Therefore, future research will focus on the tradeoff between dynamic performance and energy efficiency during the braking process. The energy efficiency is only higher at medium speeds and with medium braking strength, which means not at lower speeds and higher speeds in accordance with braking strength. The purpose, similarity and unique features of the authors are indicated in **Table 1**.

2.4.2 EV with super-capacitor compared with other storage devices

The concept behind super-capacitor under power regeneration system.

Energy regeneration system is classified into three categories:

- Fly-wheel energy storage system
- Hydraulic energy storage system
- Electrochemical energy storage system

Among the three electrochemical energy storage systems, electrochemical energy storage system proved to be promising energy storage for regenerative vehicles [35]. When an electric car is driven at high speeds, the transient current generated by brake feedback in the motor bus can reach 200 A or more, causing significant damage to traditional batteries like lead acid and lithium-ion batteries. Super capacitors, in contrast to typical batteries, have high power densities, making it more acceptable for a substantial quantity of braking energy to be quickly transferred to the super capacitors through proper conversion from kinetic to electrical energy. The super-capacitor can greatly enhance energy savings and consequently extend the driving range. Super-capacitors could output huge current instantaneously and then reduce the power output of the batteries. The accelerating capability of electric vehicles and battery life will also be improved accordingly as such installing a super capacitor as an auxiliary power source. Electric vehicles with super capacitor have become the latest research focus at this time. Faggioli et al. [36] suggested various energy system topologies with super-capacitors for electric vehicles, demonstrating that the use of super-capacitors in electric traction systems can result in significant improvements in terms of electric performance, battery life, and energy economy. As may be shown in **Table 2**,

Energy storage devices	Charging time	Life Cycle	Efficiency (%)	Specific energy (WH/Kg)	Specific power (W/Kg)
Super-capacitor	0.3–30 sec	>500,000	85–98	1–10	6000–9000
Ni-Hydride	6 hr	1000–2000	70	60–80	200–300
Li polymer	6 hr	5000	90	150–200	350
Li ion	1–6 hr	5000	95	80–130	200–300
Lead-acid	6–12 hr	500–1000	80	30–50	150–400

Table 2.
Comparison between various electric energy-storing devices [37].

Authors	Purpose	Similarity	Unique feature
Pezhman et al. [14]	To improve the performance of EV power efficiency through using battery and SC to store and supply energy as synergy	Better storage of energy and control	Concerned with battery and supper capacitor
Long et al. [38]			
Vivekumar et al. [37]			
Zhongyue et al. [39]			

Table 3.
Electric vehicle with battery and super-capacitor.

super-capacitors outperform other chemical batteries. The purpose, similarity and unique features of the authors are indicated in **Table 3**.

3. Comparison between various energy storing devices

As shown in **Table 2**, Vivek et al. [37] investigated comparisons of various energy storing devices that the lesser charging time required to fully charge is supper capacitor with a higher specific power of 6000–9000 (W/Kg), greater than 500,000life cycle, and 85–98% efficiency among other alternative storage devices. The least other alternative is the lead acid battery which exhibited a maximum charging time of 6–12 hr. and a life cycle of 500–1000 with a specific power 150–400 (W/Kg).

Electric vehicles (EVs) are gaining popularity these days due to their unique characteristics such as high efficiency, quiet operation, and minimal emissions. EVs have improved their efficiency in recent decades, and several researchers have cited them as an interesting issue. However, several elements of these vehicles, like as limited ranges due to limited capacity, may make a single energy storage technology insufficient to meet the requirements of EV applications.

The idea of adopting a semi-active hybrid energy storage system (HESS) is appealing since it allows for the use of each storage technology's operating benefits. Chemical batteries have long been the primary energy storage systems in many industrial applications. Newer batteries (e.g., Li-ion) give improved discharge efficiency at higher energy storage density, but they have a low power density and a number of drawbacks, including:

- Limited cycle life as well as high cost

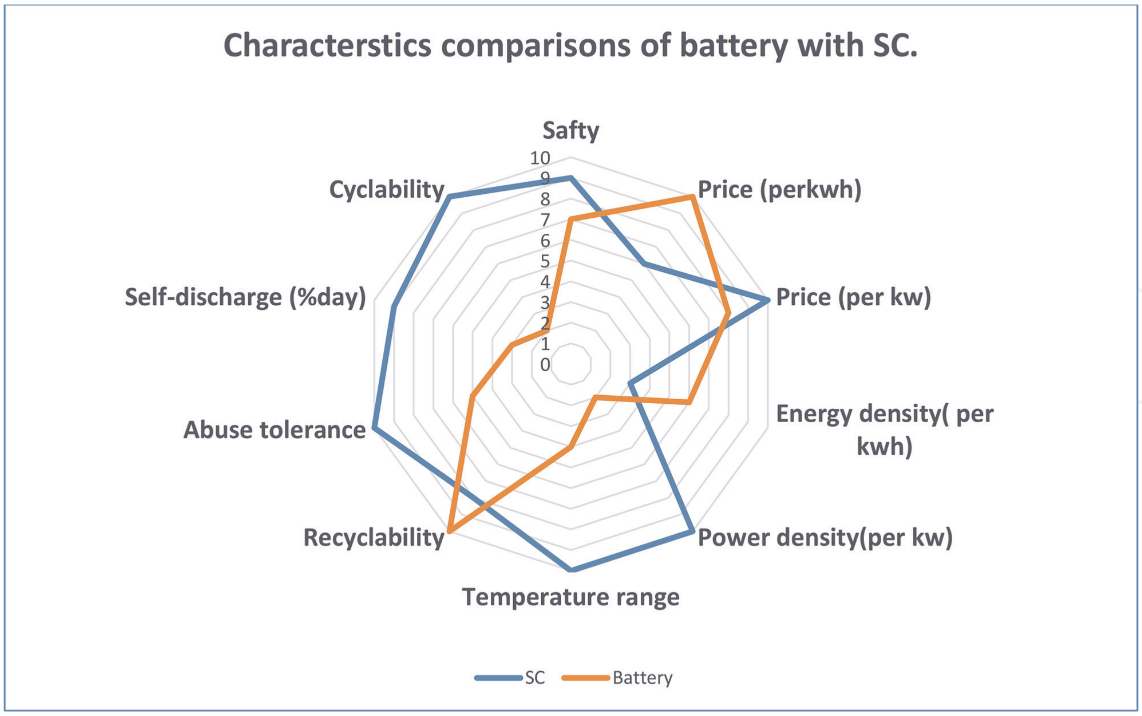


Figure 4.
Characteristics comparison of battery with SC taken from (Pezhman et al. [36]).

- Super capacitor (SCs) are being actively studied and unanimously envisaged as a promising energy storage technology further see **Figure 4**, owing to their desirable merits including:-

- low internal resistance

- High cycle life

- high efficiency

- High power density

- High degree of recyclability

- It works at high temperature range

Based on **Table 3**, electric vehicle, battery, and super-capacitor energy management and control-related reviews for the case of Pezhman et al. [36], a combined storage system is designed to boost or improve the performance of energy supply efficiency, that is, battery and super-capacitor, using a hybrid sliding mode controller (HSMC) with a manufactured model electric vehicle equipped with the proposed controller through a practical test in the case of stochastic EV driving cycle as a parameter. According to the study, the practical and simulation results show that the proposed method can effectively improve the performance of an EV. The study also has a gap and recommends future research work that may concentrate on:

- Investigating control methodologies for three port DC-DC converter with multiple operating modes.

- Exploring advanced and intelligent control methodologies for the DC hybrid power systems.

- Determining how to guarantee system stability and maintain system performance for three port DC-DC convertors with two input sources.

As a disadvantage the model has its own gaps concerning about cost of the additional SC and weight addition on the system which will compromise the efficiency.

The other electric vehicle with super-capacitor for rail used as additional power storage sources as Long et al. [38] studies that its main objective or purpose is to reduce the battery and SC loss or to utilize the recovered regenerated energy without loss through using SC since there are power voltage fluctuations from the main supply system leads to battery power loss. The approach utilized to manage is a rule-based EMS (RB-EMS), which gives the SCs charging priority over the batteries when the car is braking, and this way was finally tested with a conventional SC through simulation and testing findings. The suggested EMS is compared to SOC penalty-based cost function optimization to evaluate losses, and the final result shows that when compared to SOC penalty-based cost function optimization, and it reduces losses by 7.5 percent and prevents SOC from reaching the discharge limitations. Even though the study has acquired this much recovery, more optimization research is needed in the future for a greater energy loss recovery.

When it comes to SC and battery, Vive kumar et al. [37] investigated regenerative braking for an electric vehicle using a hybrid energy storage system, with a focus on the battery and super-capacitor, with the goal of reducing unnecessary energy waste, high power demand, and stresses on the battery by using a super-capacitor to recapture energy from regenerative braking. The method followed an intelligent electronic control strategy for the whole process, using an intelligent electronic buck-boost transformer (IGBT) Buck Boost convertor to control the energy stored in the super-capacitor bank storage with the parameters of the application of the super-capacitor as a power buffer to minimize rapid power fluctuation under acceleration and deceleration. Then finally, the result from the model shows that a large amount of energy can be recovered with minimum losses of energy and stress on the battery pack. Within this area of strategy, regenerative braking energy for super-capacitor vehicles' mechanisms is to improve the efficiency of energy conversion and increase the driving range of electric vehicles.

Zhongyuo et al. [39] conducted an experimental study under various braking conditions and the result verified the higher efficiency of energy regeneration systems using super-capacitors and the effectiveness of the proposed measurement method. A maximum regenerative energy conversion efficiency of 88% was obtained.

3.1 Electric vehicle (EV) power management and control with the state of art

Table 4 shows the state of the art in terms of electric vehicle regenerative braking control and management strategy (battery, super capacitor, motor, and so on), and it can be seen that all of the topics discussed have similar purposes or objectives, such as storing more and efficient energy from regenerative braking to extend (prolong) driving ranges or to maximize the efficiency of electric vehicles using better and improved models and systems. And the methodology [23, 40] employed comparable methodological control strategies, such as a fuzzy logic control strategy, and their end results were similarly tested using Matlab/Simulink. However, the former parameters

Authors	Purpose	Similarity	Unique feature
Siddharth et al. [24]	To store more energy during regenerative braking for extending driving rage	Better energy utilization, storage and control	Concerned on state of the arts (Motor torque) electric energy is generated from waste braking force (kinetic energy)
He et al. [40]			
Jian et al. [23]			
Shiva et al. [41]			
Bo-Chiuan et al. [42]			
Md Shumiur et al. [43]			
Jiejunyi et al. [44]			
Laiqing et al. [45]			
Liang et al. [46]			

Table 4.
Electric vehicle with power management and control with the state of art.

employed are nonlinear factors such as soc., speed, and brake force, while the latter uses a single pedal regenerative braking control strategy (RBCS), COS, GOS, Kg, and relative energy recovery rate (RERR) calculations to make driving more easy and intelligent. The average power stored by the battery is raised by 2.5 times as a result of the result achieved in the case of the former, and the vehicle comes to a halt faster. The later topic has a lot greater energy recovery than the first, with (RERR) of 65.99 percent and 55.40 percent, respectively, which is effective in energy recovery when compared to the first. However, they both share the same principle and concept with this reviewing topic and they both consider electric vehicle side only. Concerning future work and the gap between the two processes, the former is ambiguous and difficult to explain SOC, P, I (since they are constantly changing with time). So far, the latter situation is concerned about future work, and the gap is, to some extent, a waste of motor braking energy characteristics.

Though it was mentioned that they all have similar objectives or purposes, the methodology used and the results obtained are different, so to see each one from numbers 3 to 9 in **Table 2**, you should be able to easily understand that a feedback hierarchical controller, a methodology for which was proposed as a methodology, and estimated longitudinal velocity and input-to-state stability theory were used as parameters [23]. The results after the simulation test show that the effectiveness of the proposed method in tracking the velocity and improving the energy recovery of vehicles compared to non-regenerative braking. The four-wheel independently actuated motor mounted on each wheel, which adds weight, complexity, and cost to the given model of electric vehicle, is one of the gaps considered.

A novel control strategy for regenerative braking is proposed as a method and for validation as a final test, Matlab/Simulink test is made parameters based on slope information [41]. The front and rear axles are presented in addition to this based on a logic threshold control algorithm with input Z and I (relationship between electrical and mechanical braking). The study's findings suggest that the improved management approach works well on roads with varying slopes. The regenerative braking control strategy is capable of recovering energy and improving brake stability.

The gap obtained is the aerodynamic stability during downshifting, which is one factor influencing the driving range in the case of modified direct torque control and adaptive control theory used a method for this particular study [42]. A modified direct torque control (MDTC) is proposed to generate electrical energy from the kinetic energy and also an adaptive controller is designed to improve tracking error and torque ripple. The parameters used for conventional direct torque control (DTC), MDTC, SOC of the DTC with the modified DTC combined, and model reference adaptive system (MRAS) controller was obtained. The result is that the new switching pattern improves the speed and torque tracking signals the torque ripples. The different feature on the motor is that it uses less direct current (BLDC) for study power converter is not necessary.

The proposed strategy is then proposed as a power management strategy (RE-EV) with DP to evaluate both power management strategies, and the results are extracted from the Matlab/Simulink test. The proposed strategy can approach approximately 70% control performance of DP results compared to the thermostat control strategy (TCS). The computation power of the multi-mode switch strategy increases by 8, 11, and 10%, respectively, when compared to TCS for three untrained driving patterns. To finalize the findings, the results indicate that the proposed strategy can require lower computation efforts in exchange for better control performance of fuel economy and battery protection. This result is obtained by using the parameters of two design criteria; battery energy losses for battery protection and fuel energy losses are for addressing fuel economy and considering driver comfort, battery life, limitations of noise, vibration, harshness, and battery charging currents, which are expressed as the gaps that are not yet solved, but maybe for future work.

The electric vehicle study conducted by a novel coordinated control strategy is proposed in order to facilitate the V2G capability of 3p AC and DC type EV charging stations in an island commercial hybrid AC/DC microgrid [43]. The whole system is designed in Matlab/Simulink with respect to the parameters followed is a three-layered coordinated control to incorporate three-phase (3p) alternating current AC type electric vehicle energy storage system (EV-ESSs) for the improved hybrid AC/DC microgrid operations, bus RMS voltage regulator, respectively. Based on the comparative case studies, improved voltage regulation and power sharing performance have been with the presence of homogeneous single-phase EV charging, and better energy conversion is obtained. This research must integrate market operations and investigate the effects of the distributed control approach to reduce communication dependency in the future.

Jiejunyi et al. shown in [44] a method used a 4-speed transmission system with corresponding control strategies is proposed and investigated in order to achieve power on shifting during regenerative braking. A detailed mathematical model is built on an advanced multi-speed transmission power on shifting strategy is proposed. The parameters adopted for the system are based on the full-size sedan, in which regenerative braking is more significant. Based on the selected vehicle specifications, a systematic choice of suitable gear members is made. The results obtained from this show that with the proposed system, the regenerative braking efficiency can be improved by 45% in a typical NEDC cycle. A similar concept related to this topic is electric vehicle energy regeneration control and management. The difference and its unique feature is energy control in terms of power on shift control. The gaps for future work recommendations are weight, cost, and complexity of the model or system.

Laiqing et al. indicated in [45] the methodologies adopted in this system or model is a hierarchical control architecture that consists of three layers in the proposed strategy, which is a novel energy-saving control strategy for electric vehicles based on the movement of the preceding by forward radar. The parameters according to the relative motion between the Ego-vehicle and the preceding vehicle are designed and simulated under commission for the urban driving cycle (CUDC). From this, the average energy-saving percentage of the 90 groups of simulations under CUDC conditions is about 9.6%. The average energy consumption of the experimental bus under actual urban traffic conditions is reduced by 5.9%. The system uses an intelligent radar system to control the torque output energy and this creates a new and different experiment than the existing revision topic.

3.1.1 HEV regenerative braking energy management and control

When a hybrid electric vehicle (HEV) is combined with a hydraulic brake system (HBS), there is a tradeoff relationship in terms of regenerative braking efficiency. This means that when braking is performed by the motor torque, the vehicle will not come to a complete stop immediately, but will instead be a cause of an accident. On the other hand, when additional braking is applied by the hydraulic brake system by the driver to deter an accident, the regenerative energy efficiency increases. To reconcile these phenomena and to have both safety and regenerated energy efficiency, a program and model should be proposed to gain both. In this classification of **Table 5**, reviewed articles share a common goal or objective, which is to improve regenerative braking efficiency, fuel economy, and environmental concern through various control and management strategies.

Wisdom et al. showed in [11] the controlling models and their effects on various research topics in their modeling and control of HEV regenerative and sustainable energy review. The objective or purpose of the study was to develop a real-time control strategy capable of coordinating the onboard power source to maximize fuel economy and reduce emissions by using sample parameters of off-line and on-line control management strategies. The comprehensive review and discussion of various journals as a method to reach the findings or results of energy optimization on hybrid electric vehicles of different systems and state of the art to obtain energy optimization through using different proposed strategies leads to reduced emissions and fuel costs. But based on the review, tremendous gaps are faced and future work is also recommended. Exploitable research gaps in rule-based control methods, dynamic programming, the equivalent consumption minimization strategy (ECMS), and model predictive control (MPC) strategies have all been discovered as part of this dissertation. These study gaps indicate that present HEV control algorithms are still weak,

Authors	Purpose	Similarity	Unique feature
Wisdom et al. [11]	• To store more energy during regenerative braking for extending driving rage • To maximize fuel economy and reduce emissions. The focus of the strategy is to maximize energy recovery in the battery using the motor as much as possible.	Better energy utilization, storage and fuel consumption control	Concerned with hybrid system power supply from both fuel cell engine and electric motor including regenerative braking
Liang et al. [47]			
Jian et al. [48]			
Sulakshan et al. [49]			
Liang et al. [50]			
Zhang et al. [51]			
Lars-Henrik et al. [52]			
Grandone et al. [13]			

Table 5.
Hybrid electric vehicle energy management and control.

particularly in terms of optimizing brake energy regeneration and charge surviving sub-optimal control using partial and no route preview information. Future studies toward mitigating these research gaps are expected to yield control strategies capable of realizing the ultimate charge-sustaining fuel-saving potential of HEVs in real time.

The energy conservation improvement of down shifting to maximize the regenerative energy stored in the battery is the objective used in the study by Liang et al. [47]. The research platform was an HEV with an automated manual transmission (AMT), and simplified dynamic models of the HEV system were produced as part of the procedure. Based on the research, two innovative down-shifting strategies based on DP algorism are given, and the results are validated using Matlab simulation with single shaft HEV and HBS cars. Varying gear position regenerative braking effects are examined, as are differential initial speed braking severities. The study found that downshifting improves the energy conservation of the regenerative braking mechanism by 10.5–32 percent as compared to not downshifting. The DP-based technique provides global optimal solutions and enhances energy saving by 21–32.4 percent, demonstrating that regenerative braking's potential cannot be realized in practice, but rule-based strategies can. The rule-based technique provides instantaneous optimal solutions and improves energy conservation by 10.5–29.7%, with considerable fluctuations in improvement. The study found the following gaps, which should be addressed in future research:

- Down-shifting control during regenerative braking process is a problem with ABS

- The control strategies are not effective and stable enough to bring adequate energy conservation and efficiency so more effective and efficient control strategies are necessary.

Another similar study was conducted by the same author with the same objective but with different methodologies, parameters, and results. It was conducted by Liang et al. [50] to improve the stability concern raised by the previous study with the objective of recovering braking energy stability during emergency braking. To acquire the optimal distribution of braking torque, the modified nonlinear model predictive control (MNMPC) approach is proposed, with the particle swarm optimization (PSO) algorithm being used. For road conditions with varying road adhesion coefficients, simulation and hardware in-loop-testing (HIL) are also performed (to know the MNMPC accuracy result). As a result of the findings, the proposed technique may assure vehicle safety during emergency braking scenarios while also improving recovery energy by about 17% when compared to a traditional rule-based strategy in a general braking condition. A future research study might be conducted using the MNMPC strategy and the parameters employed in the proposed approach, which, when calibrated properly, could increase algorithm performance.

As illustrated in [51] by Jian et al., to overcome the problem, a hierarchical control technique is recommended (vehicle braking safety). The simulation experiments are used to show how regenerative braking affects battery aging and the effectiveness of the proposed method, while controller-in-the-loop testing is used to check the real-time computation performance. The parameters used to control the upper-level controller (general braking mode) and the lower-level controller (pneumatic braking and EM) are listed below. The proposed control strategy applies to the entire cycle of city busses on straight roads. The result of the proposed method can ensure the vehicle's safety in the braking process and mean while balancing the battery's aging and energy recovery. The study recommends future work for further research due to the still existing gap. It is hoped that the model will be extended with driving modes to investigate the influence of many cycles on battery life and energy recovery. The other one is a large recovery current that can cause damage to the battery and reduce its life.

As Sulabshan et al. pointed out in [52], an effective ABS controller is required to achieve high braking efficiency without sacrificing regenerative efficiency (to avoid trade-off). The intelligent sliding mode scheme (ISMS) uses a supervisory logic-based motor torque limiter and slip controller to achieve this. The plan has undergone extensive testing. The proposed controller is an effective ABS controller system, a slip controller, a magic formula, and a two-wheel model are used. From this effect, high braking efficiency and considerable energy regeneration without overcharging the battery are obtained. But the study still faces a challenge and encountered a research gap, and to recommend for future work, higher order SMC (HOSMC) will be explored with fuzzy logic or ANN to generate an HEV system to improve overall performance.

Zhang et al. pointed out in [51] a "modified control strategy" with "baseline control strategy" as a comparative control strategy and the results obtained by this strategy have been tested with simulation and hardware in-loop-test (HIL) carried out, and bench tests and road tests have been conducted to improve the regeneration efficiency problem in the HEV in combination with HBSs. The test was conducted with a rear-drive electrified minivan equipped with a rear motor as the parameter. The simulation and HIL test results reveal that the updated control approach has much higher regeneration efficiency than the baseline control strategy. The updated control approach had a regeneration efficiency of 47%, which was 15% higher than the baseline control method. The quantity of total recoverable energy is the modest because the target minivan is rear-driven and has little mass, according to the recommended future work for researchers in this field of study. As a result, regeneration efficiency would be limited.

- Because of the modulation of wheel pressure during regenerative braking, brake pedal sensation will be impacted, and it will be difficult to maintain an adequate brake pedal feel.

- Because of its low inertia, the target minivan is sensitive to changes in brake torque, making it difficult to ensure braking.

Lars-Henrik et al. illustrated [52]. The parameters used are GPS-derived speed and altitude data from real-world car-driving to estimate the overall potential for energy regeneration under car driving, and two drive trails are investigated on BEV and MHEV. And methods to solve the issue: the speed profiles of the new European drive cycle (NEDC) and worldwide harmonized light vehicle test procedures (WLTP) test cycles are used for comparison, and the results from real-world driving are compared to the NEDC and WLTP test cycles. The results or findings obtained indicate that regeneration of braking energy under current driving conditions could increase energy efficiency with average energy savings at the wheels of about 15% for a battery EV and up to 10% for a "milled" hybrid. The gap observed is energy savings by engine stop/start ability, which will contribute to its economic viability not considered in this study.

Grandone et al. in [13] studied the development of a regenerative braking control strategy for hybridized solar vehicles with the aim of developing the best braking strategy that allows the trade-off between mechanical and regenerative braking on hybridized vehicles. Methods followed to estimate the vehicle braking torque considering aerodynamics, vehicle friction, and engine passive losses in different gears have been developed and identified over road tests, for a vehicle hybridized with wheel motors on the rear wheels, so far the parameters considered. The model which is useful for real-time battery control has been developed based on this condition. Regenerative braking is installed on the rear brake axle with rear total torque ratio (RTTR) and driveline torque effect integration of state-of-the-art components (PVP, wheel motors, and batteries). The preliminary results show that the model is useful for designing real-time braking strategies, if properly combined with estimation of slipping coefficient and use of ABS system, and it will eliminate the trade-offs. The purpose, similarity, and unique features of the authors are indicated in **Table 5**.

3.1.2 Plugged in hybrid vehicles (PHEV) power generation and management

When energies are fully discharged, it is possible to obtain an external power supply from the power grid by plugging in a power supply cable (socket) into the power supply system while in a stationary position for energy control and management in the case of PHEV. The main goal is to obtain more energy supply during highway driving conditions at acceleration time, which helps with better fuel economy and emission reduction. So, in this regard, according to **Table 6**, some researchers are working hard to improve energy efficiency by employing various control strategies and models. For that reason, as Yu et al. indicated [53]. The suggested PHEV algorithm results are compared with the determinacy rule-based energy strategy for HEV with a similar battery capacity as PHEV. The proposed energy management method is implemented in the advisor on a PHEV model, which is then simulated using Mat Lab and Simulink. The parameters considered are for several numbers of drive cycles and the paper chooses nine words to describe Treq. The fuzzy set of Treq is the input and output (Tm) variables of the fuzzy set and its domain provision (NBB, NB, NM, NS, O, PS, PM, PB, PBB). The SOC is set up into three fuzzy subsets (L, M, and H) and the domain [0, 1]. The simulation results in the cycle of road conditions show that with an appropriate distribution of ICE and motor torque, the suggested energy management approach may successfully minimize exhaust emissions and improve fuel economy. The gap created by this experiment is that the basic fuzzy control model in adviser was built based on theory, and control rules in general have poor practicality.

Shown in YU-Hui et al. [55] the power management of a semi-active hybrid energy storage system (HESS) and an assistance power unit (APU) is proposed, with MPCS regulating output power between battery and ultra-capacitor packs and a rule-based strategy controlling output power between APU and HESS. To optimize the control approach, the dynamic programming algorithm will be used. Three typical cycles verify the following parameters:

- Manhattan Cycle
- CBD cycle
- UDDS HDV cycle (urban dynamometer driving schedule heavy duty vehicle)

In the model predictive control process, a period of the future velocity will be predicted.

Authors	Purpose	Similarity	Unique feature
Yu Zhang et al. [53]	• To maximize fuel economy and reduce emissions and to obtain more power torque in different driving condition • To store more energy during regenerative braking for extending driving rage	Better energy utilization, storage and fuel consumption control	Concerned on power is generated from plug-in- (external electric power) electric supply with hybrid power from both fuel cell engine, electric motor and - including regenerative braking
Shuo et al. [54]			
Zheng et al. [26]			
Yu-Huei et al. [55]			

Table 6.
Plugged in hybrid vehicles (PHEV) energy control and management.

The results show that the proposed control strategy can promote fuel economy compared with the original control strategy, especially in the charge-sustaining mode under the Manhattan driving cycle (21.88% improvement). The future work recommended by the study and considered as a research gap is the durability of the proposed control strategy, which needs a real driving cycle test on the street and then tested through bench testing.

As Zehng et al. [26] determine the engine fuel rate with respect to battery power in this paper, an intelligent algorithm based on the quadratic principle (QP) and simulated annealing (SA) methods is proposed for the energy management of series plug-in HEVs in order to reduce fuel consumption. The problem is solved by using quadratic programming and the simulated annealing method together to find the optimal battery power commands and the engine-on power. The simulations were performed to verify the proposed algorithm. The engine and generator inertia are analyzed to improve calculation precision, and the battery's health is taken into account as a parameter. The result, through simulations, is that the proposed algorithm is proven to be effective in improving the fuel economy regardless of the battery health status. Experimental validations, including the actual vehicle test or hardware-in-loop test, will be the focus of future work. The other work-related to this regard is YU-Hui et al. [55]. To solve the optimization problem of HEV fuel consumption and emission reduction, a robust evolutionary computation method called "Memetic algorism (MA)" to optimize the control parameters in HEV is used. The fitness function is linked with advanced vehicle simulation (Advisor) and its setup according to an electric assist control strategy (EACS) to decrease the vehicle engine's fuel consumption (FC) and emissions. The concerned parametric values are taken into account in order to complete the test with the specified model's driving performance parameter requirements. The new European driving cycle (NEDC), federal test procedure (FTP), European Commission for Europe +extra urban driving cycle (ECE + EUDC), and urban dynamometer driving schedule (UDDS) are the four driving cycles used. The results of the tests reveal that the proposed strategy effectively reduces fuel consumption and pollutants while maintaining vehicle performance. The purpose, similarity and unique features of authors concerned on PHEV were indicated in **Table 6**.

4. Thermal management system for EV/HEV/PHEV

Any batteries used in large power storage (utility-based, electric car) will very certainly require some type of temperature control, whether lithium- or nickel-based.

This is an evident need for high-temperature sodium-beta technologies. Electric-vehicle applications place particularly high demands on the technology required to regulate and control the temperature within the battery due to space and cost constraints. This hardware is commonly known as the thermal management system (TMS). To maintain the technology's high efficiency, the TMS must mitigate heat loss from the battery under normal operating conditions and idle periods while allowing sustained high-power discharge periods without reaching unacceptably high temperatures or creating unfavorable temperature differentials within the battery. The TMS in a sodium/sulfur battery typically consists of the following elements to meet these technical requirements: [17].

- A thermally insulated battery enclosure
- An active or passive cooling system
- A method of distributing heat within the battery enclosure
- Heaters to warm the battery to operating temperature and to maintain it at operating temperature during long idle periods, if necessary

The extent and kind of thermal insulation employed in the thermal shell (e.g., conventional, evacuated, or variable conductance) are determined by the intended application. The physical dimensions of the battery, the power-to-energy ratio, the duty cycle, and the duration of any "idle" intervals are all important application needs to consider. Utility-energy-storage applications, for example, are not as limited in terms of weight and volume as those associated with electric vehicles. As a result, utility batteries can use traditional composite material.

Batteries developed. To reduce thickness and weight, batteries designed for electric vehicles used evacuated insulation. Both ABB (ABB Ltd.) and ABB (ABB Ltd. is a Swedish-Swiss multinational enterprise headquartered in Zürich, Switzerland. In 1988, Sweden's Allmänna Svenska …) and SPL (Swiss Propulsion Laboratory) employed double-walled, evacuated thermal enclosures with either fiber board or microporous insulation to develop the firm. To maintain the required amounts of vacuum, chemical gettering agents were introduced within the cage. This was the only design that properly minimized heat loss while delivering the required load-bearing capability [55].

The need for a cooling system is determined by:

- The quantity of heat generated during sustained high-rate discharge,
- The thermal capacitance of the battery, and
- The upper temperature limit of the battery.

Direct and indirect heat exchange with the air, indirect liquid-based heat exchange, heat pipes, thermal shunts, latent heat storage, evaporative cooling, and variable conductance insulation systems are among the ways that have been utilized or are being considered. ABB used an active cooling technology in their EV battery series. The cells were placed on a flat-plate liquid heat exchanger, which transmitted surplus heat to a heat sink made of oil/air or oil/water. The thermal capacitance of the battery could accommodate the temperature rise suffered by the battery if the electrical resistance of the cells and their interconnections is suitably low. Although active cooling was included in later versions, this was the planned approach for SPL.

Battery safety. To ensure that the cell and battery designs were safe under both normal and accident settings, the strategy concentrated on preventing electrical short-circuiting and minimizing exposure to and interaction with any reactive materials. In the case of incidents involving mobile applications, the vehicle industry and different governing organizations have required a strict requirement: the existence of the battery cannot enhance the hazard (contribute to the severity or consequence). The following specific safety considerations were addressed in various sodium/sulfur cell and battery designs:

- Selecting proper construction materials (such as low reactivity and high melting point)

- Limiting the availability and flow of sodium to an electrolyte or seal failure site, thus reducing the potential for large thermal excursions (>100°C) in cells, which can cause damaging cell breaches

- Using components that minimize the effect of cell failure on adjacent cells (e.g., porous or sand filler between cells in stationary batteries)

- Including thermal and electrical fuses to eliminate the potential for catastrophic short circuiting

- Providing protection against the environmental hazards associated with each application; in the case of the sodium/sulfur technology, the thermal enclosure is effective against many of these factors

- Including functional redundancy to ensure that improbable or overlooked phenomena do not result in an unwanted consequence

Reclamation. All batteries, even sodium/sulfur, will eventually approach their end of life and must be recovered or disposed of in some way. Because of its corrosivity, sodium polysulfide, like sodium and sulfur, is classed as a hazardous material. Chromium or chromium compounds are still employed as confinement corrosion protection coatings. As a result, all sodium/sulfur batteries used in terrestrial applications must be sent to a processing facility for recycling, reclamation, or disposal.

Thermal Control Increasing the energy density of EV batteries or improving the energy consumption of the electric powertrain as well as the vehicle’s auxiliary components has received a lot of attention in recent years. Heating and cooling the cabin of BEVs is a problem that many people have been working on for years.

Thermal management has the ability to significantly improve fuel economy and reduce emissions in HEVs and BEVs. Hence, battery heat control is critical for optimal functioning in all climates. Optimization of vehicle thermal management has become a significant commercial segment in recent years.

Thermal Management effects (compare **Figure 5**):

- fuel/energy consumption (e.g., friction losses, combustion process, recovery of energy losses, efficiency),

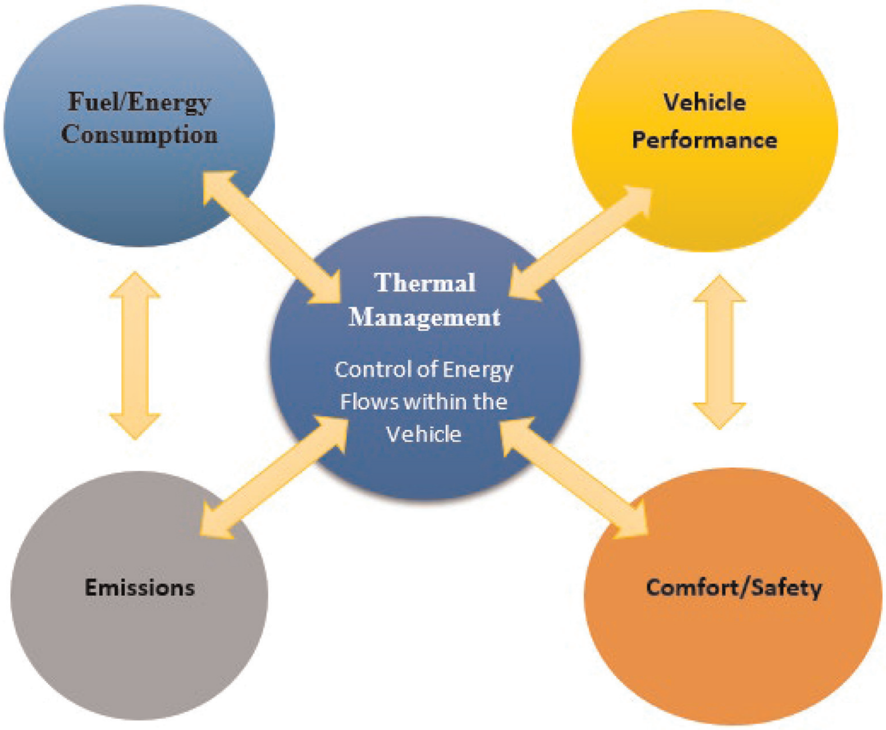


Figure 5.
Thermal management and its impact [56].

- emissions (e.g., cat-light-off, EGR/SCR strategies) (catalytic convertor off) (silicon controlled rectifier)
- engine performance (e.g., effective cooling, engine efficiency, reduction of friction losses),
- comfort and safety (e.g., cabin conditioning, windscreen defrosting)

In comparison with a traditional vehicle, an HEV has additional heat sources such as e-motors, power electronics, batteries, and so on that must be kept within a specified temperature range in order to create high efficiency and protect components from overheating. A complete simulation model is required for hybrid systems due to the interplay between several subsystems such as the combustion engine, e-motor/generator, energy storage, and drive train.

Figure 6 depicts several drive train arrangements, such as ICE, micro HEV, mild HEV, full HEV, and PHEV/BEV, and their requirements in terms of new vehicle constraints, new thermal needs, and new systems and components. This illustration highlights the necessity for additional heat monitoring systems.

Many companies and R&D institutions have recognized the need for thermal management solutions in recent years. As a result, two Task 17 workshops concentrating on Thermal Management Systems (TMS) and HEV concepts were organized in Chicago (2013) and Vienna (2014).

Organizations and research institutes such as ANL, AIT, Delphi, Fraunhofer, qpunkt, and Valeo presented their findings and thoughts. This section includes a list of the most commonly imported ones.

An overview of the impact of ambient temperature and driving behavior on energy usage in HEVs, PHEVs, and BEVs.

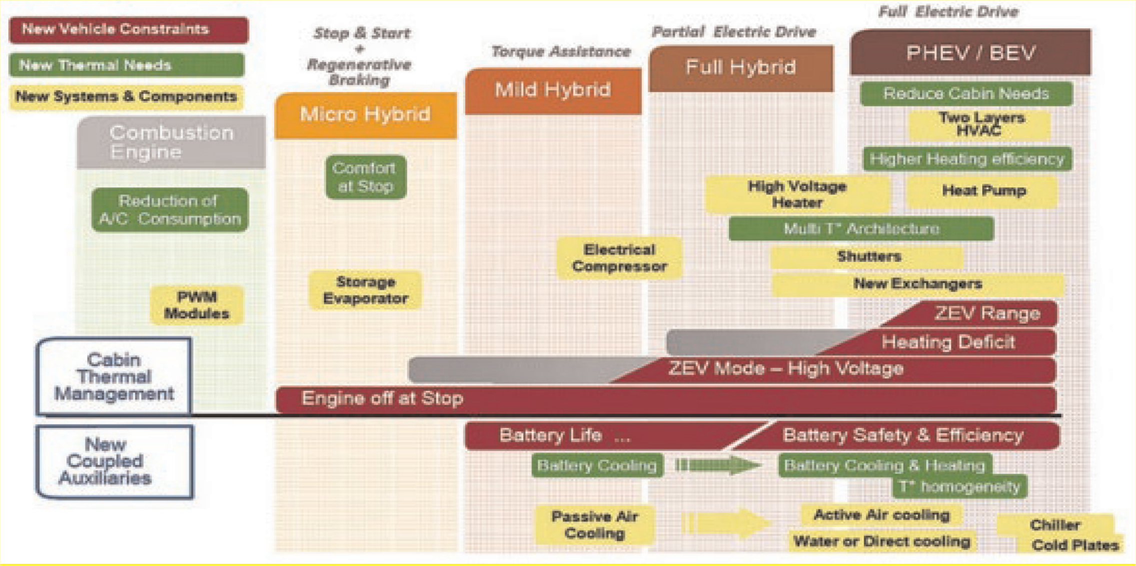
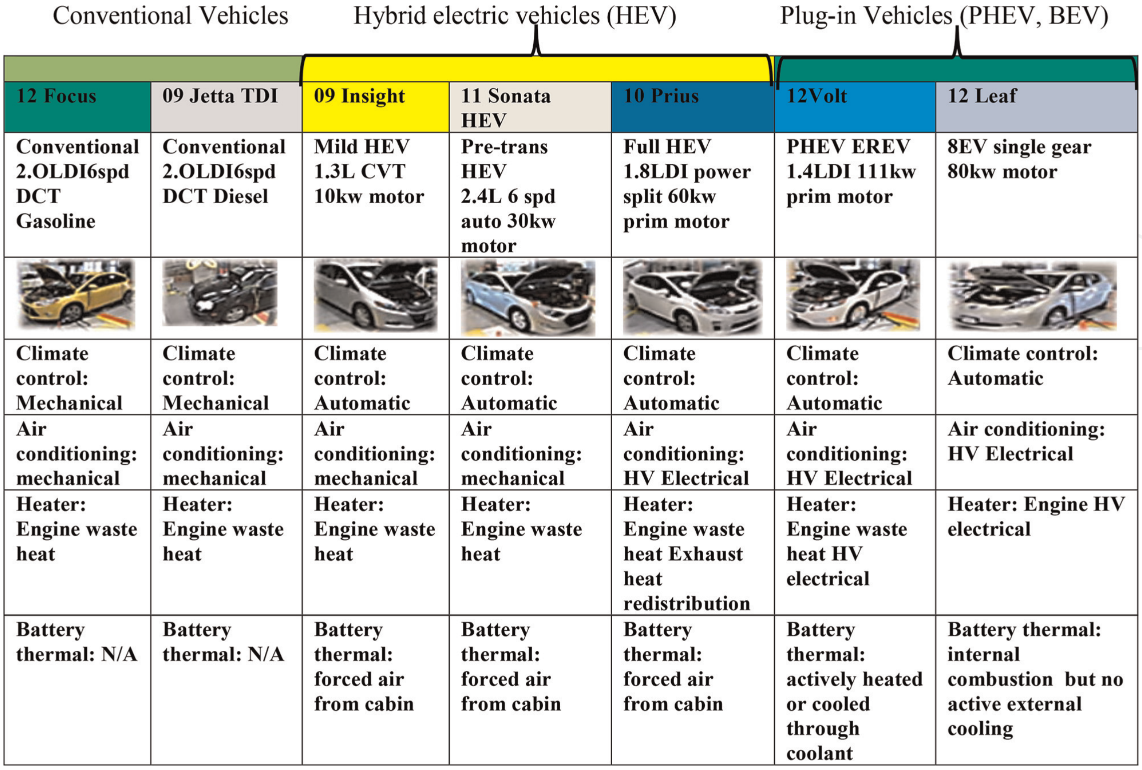


Figure 6.
HEV/EV thermal management activities [56].

The ANL emphasized the impact of ambient temperature and driving patterns on energy usage. As a result, they compared a BEV (Nissan Leaf 2012), a HEV (Toyota Prius 2010), and a traditional vehicle (Ford Focus 2012).

A comprehensive thermal study was conducted, with seven vehicles ranging from conventional vehicles (CV) (gas and diesel), HEVs (mild to full), a PHEV, and a BEV tested on cold start UDDS, hot start UDDS, HWFET, and US06 at ambient temperatures of 7°C (20°F), 22°C (72°F), and 35°C (95°F) with 850 W/m 2 of sun emulation (compare **Figure** 7). The findings of this investigation show the following facts:



Conventional Vehicles		Hybrid electric vehicles (HEV)			Plug-in Vehicles (PHEV, BEV)	
12 Focus	09 Jetta TDI	09 Insight	11 Sonata HEV	10 Prius	12Volt	12 Leaf
Conventional 2.OLDI6spd DCT Gasoline	**Conventional 2.OLDI6spd DCT Diesel**	**Mild HEV 1.3L CVT 10kw motor**	**Pre-trans HEV 2.4L 6 spd auto 30kw motor**	**Full HEV 1.8LDI power split 60kw prim motor**	**PHEV EREV 1.4LDI 111kw prim motor**	**8EV single gear 80kw motor**
Climate control: Mechanical	**Climate control: Mechanical**	**Climate control: Automatic**	**Climate control: Automatic**	**Climate control: Automatic**	**Climate control: Automatic**	**Climate control: Automatic**
Air conditioning: mechanical	**Air conditioning: mechanical**	**Air conditioning: mechanical**	**Air conditioning: mechanical**	**Air conditioning: HV Electrical**	**Air conditioning: HV Electrical**	**Air conditioning: HV Electrical**
Heater: Engine waste heat	**Heater: Engine waste heat**	**Heater: Engine waste heat**	**Heater: Engine waste heat**	**Heater: Engine waste heat Exhaust heat redistribution**	**Heater: Engine waste heat HV electrical**	**Heater: Engine HV electrical**
Battery thermal: N/A	**Battery thermal: N/A**	**Battery thermal: forced air from cabin**	**Battery thermal: forced air from cabin**	**Battery thermal: forced air from cabin**	**Battery thermal: actively heated or cooled through coolant**	**Battery thermal: internal combustion but no active external cooling**

Figure 7.
Wide technology spectrum of research vehicle [56].

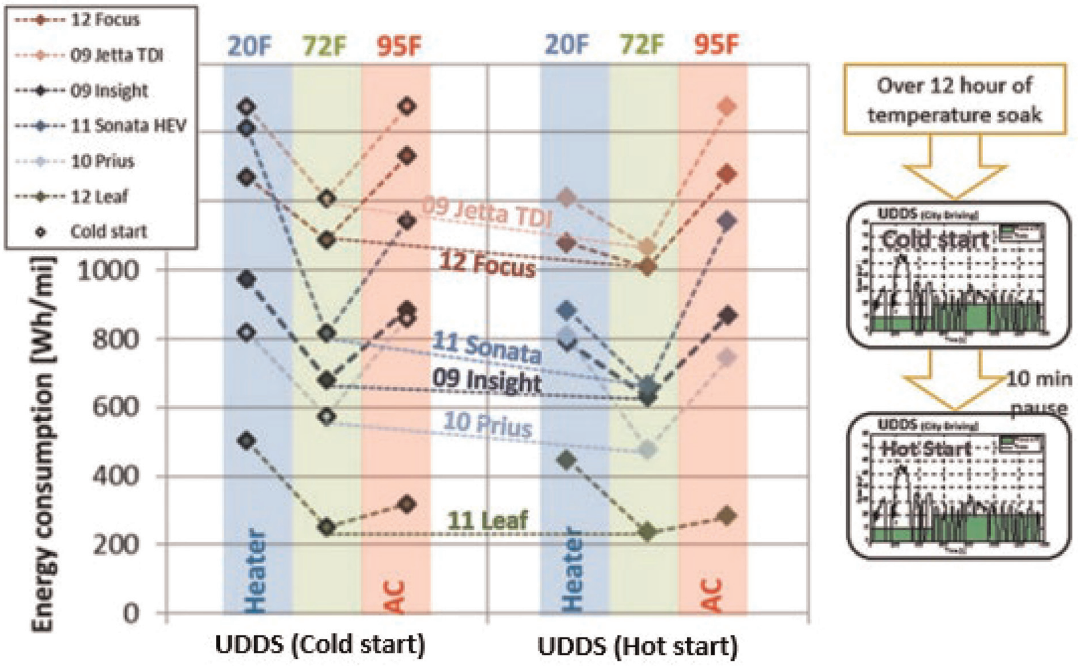


Figure 8.
UDDS energy consumption for cold and hot start [56].

- −7°C (20°F) cold start has the largest cold start penalty due to high powertrain losses and frictions. Once a powertrain reached operating temperatures, the energy consumption is close to the 22°C (72°F) results again (see **Figure 8**),

- 35°C (95°F) environment requires a constant A/C compressor load which impacts the energy consumption across all vehicle types on hot and cold starts,

- worst-case scenarios for the different vehicle types:

- CV: 35°C (95°F) environment due to 4–5 kW of extra air conditioning load,

- HEV: both −7°C (20°F) and 35°C (95°F) have a large range of increase due to a change in hybrid operation (fuel and electricity trade off),

- PHEV:−7°C (20°F) where the PHEV uses both the engine and the electric heater to warm up the powertrain and the cabin,

- BEV: −7°C (20°F) due to 4 kW of heater which can double the energy consumption on a UDDS,

- Battery system resistance doubles from 35°C (95°F) to −7°C (20°F) for all battery chemistries in the study

Looking more closely at the findings, as shown in **Figure 9**, utilizing the heater in an electric car can quadruple the energy use in city driving. **Figure 10** depicts how driving at faster speeds and more aggressively increases the energy consumption of an electric vehicle.

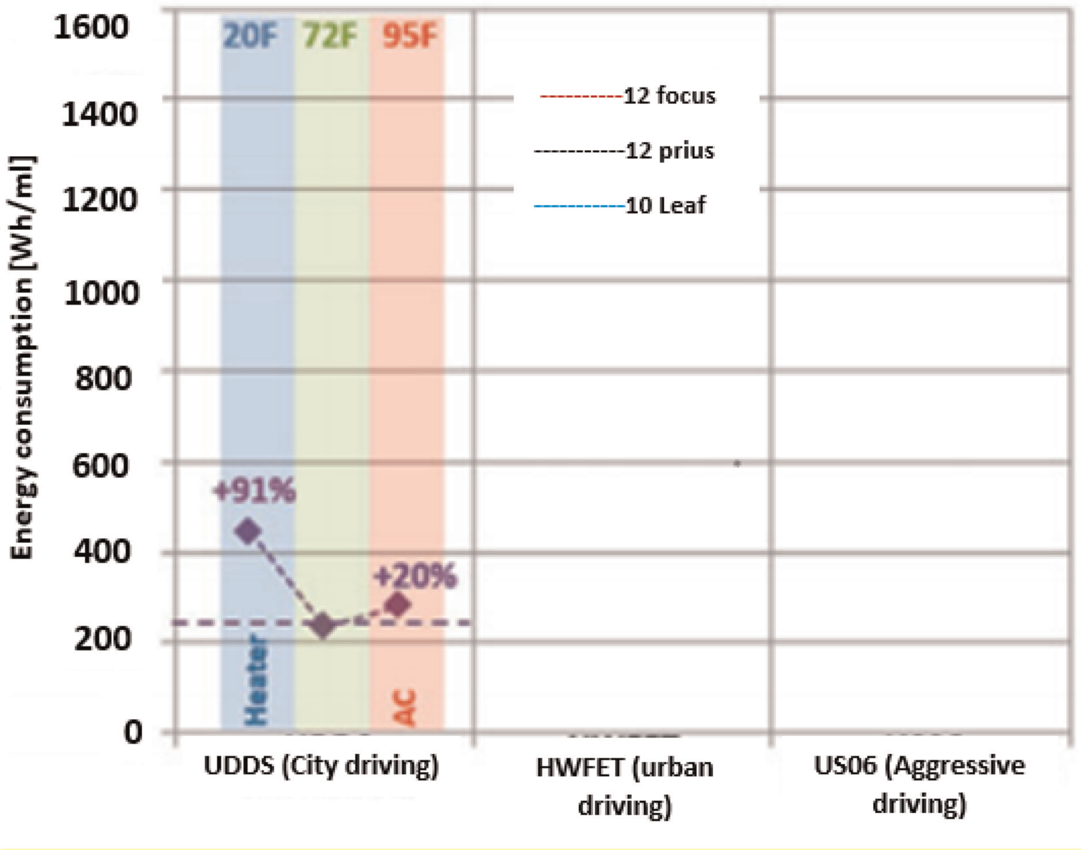


Figure 9.
Using the heater in an electric car may double the energy consumption in city type driving [56].

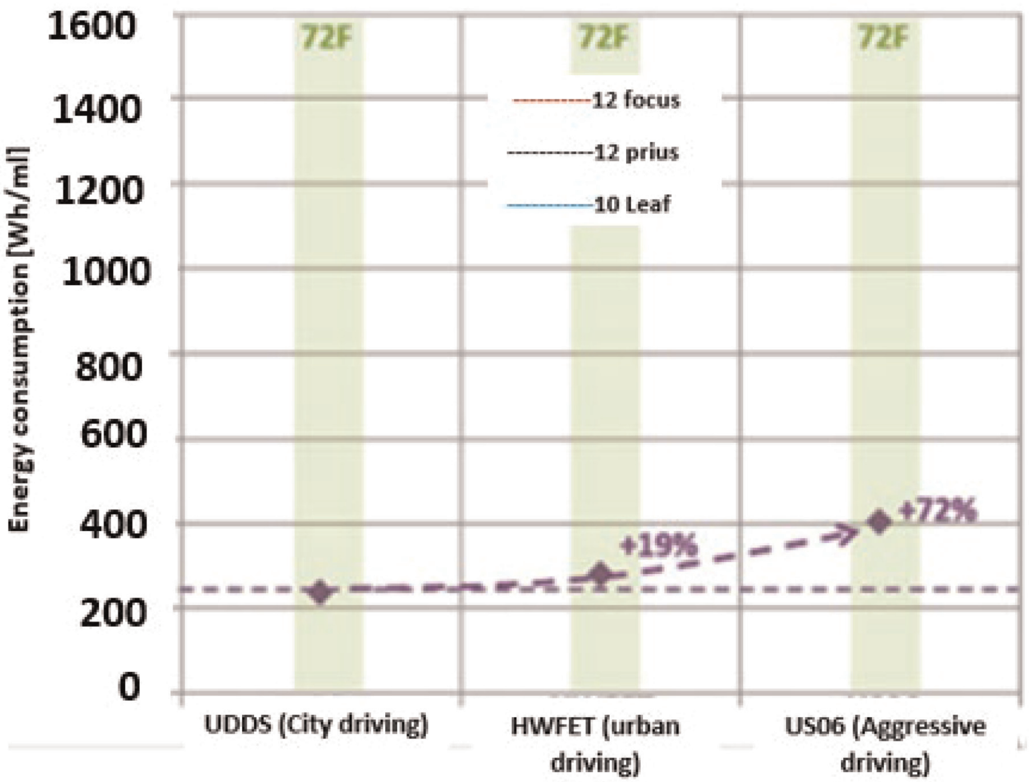


Figure 10.
Driving at higher speeds and aggressively will increase the energy consumption in an electric car [56].

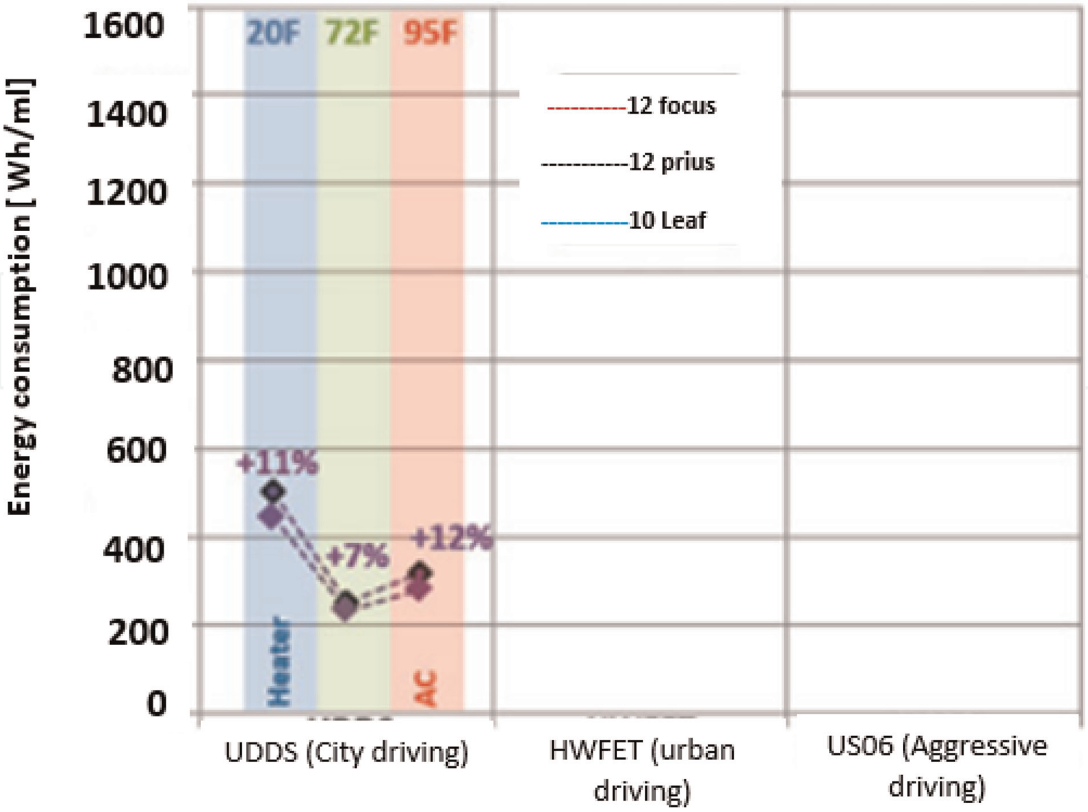
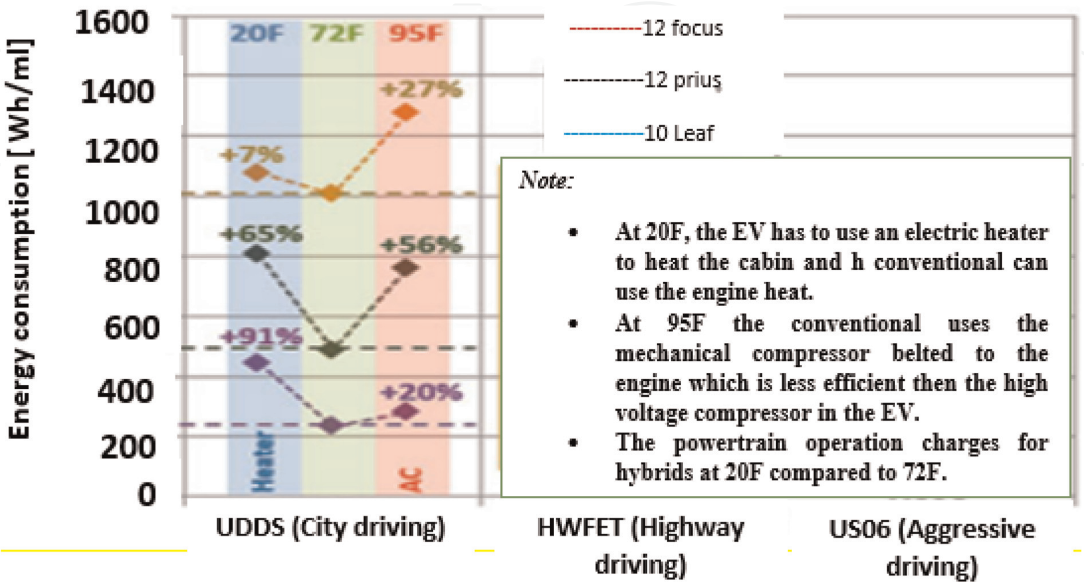


Figure 11.
Cold start energy consumption is larger than the hot start energy consumption [56].

When the cold start energy function and the hot start energy consumption are compared, it is clear that the cold start energy consumption is more than the hot start one (see **Figure 11**).

Figures 12 and **13** illustrate the highest increases in energy consumption for a BEV and a conventional vehicle. Hence, the highest increase in energy usage for an EV



Note:

- At 20F, the EV has to use an electric heater to heat the cabin and h conventional can use the engine heat.
- At 95F the conventional uses the mechanical compressor belted to the engine which is less efficient then the high voltage compressor in the EV.
- The powertrain operation charges for hybrids at 20F compared to 72F.

Figure 12.
Larger energy consumption increase for an EV occurs at -7°C (20°F) and for a CV at 35°C (95°F) [56].

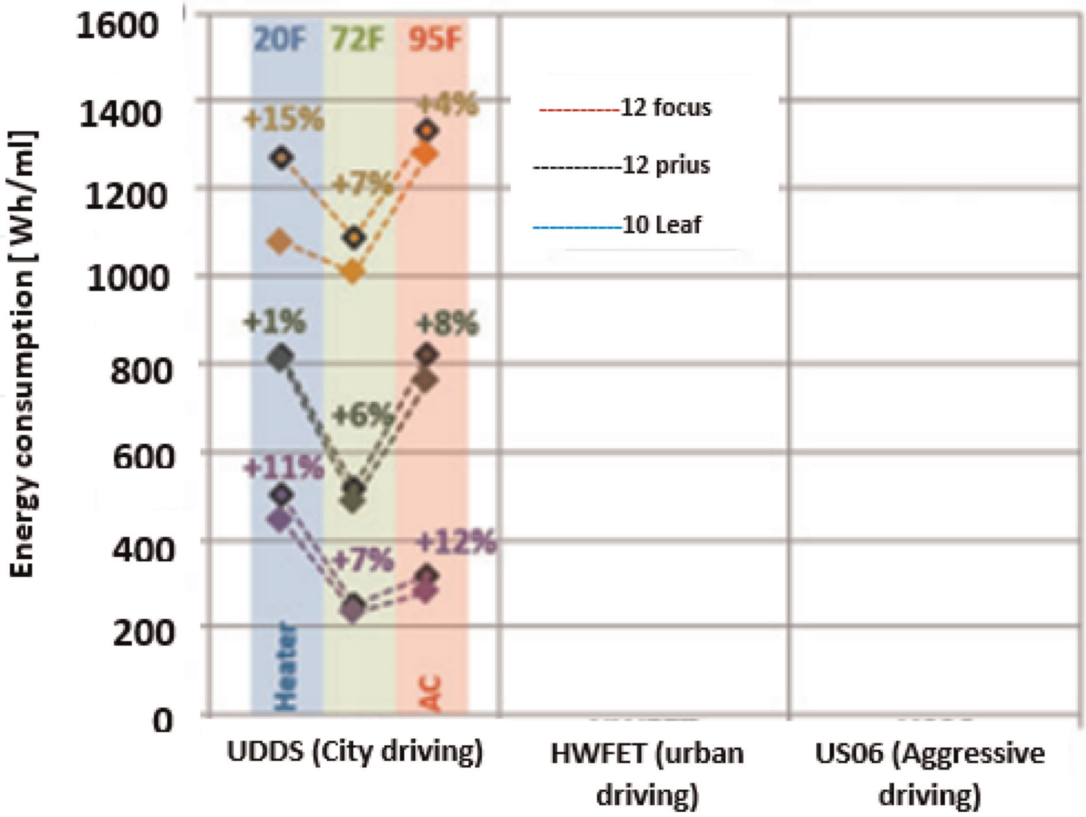


Figure 13.
A conventional vehicle has the largest absolute energy consumption penalty on a cold start [56].

happens at 7°C (20°F) and for a conventional vehicle has the largest absolute energy consumption penalty on a cold start at 35°C (95°F), respectively.

Figure 14 shows that, in general, higher speeds and accelerations result in higher energy consumption, with the exception of the conventional due to low efficiency in the city. Journal of Automotive Engineering has more information on this subject.

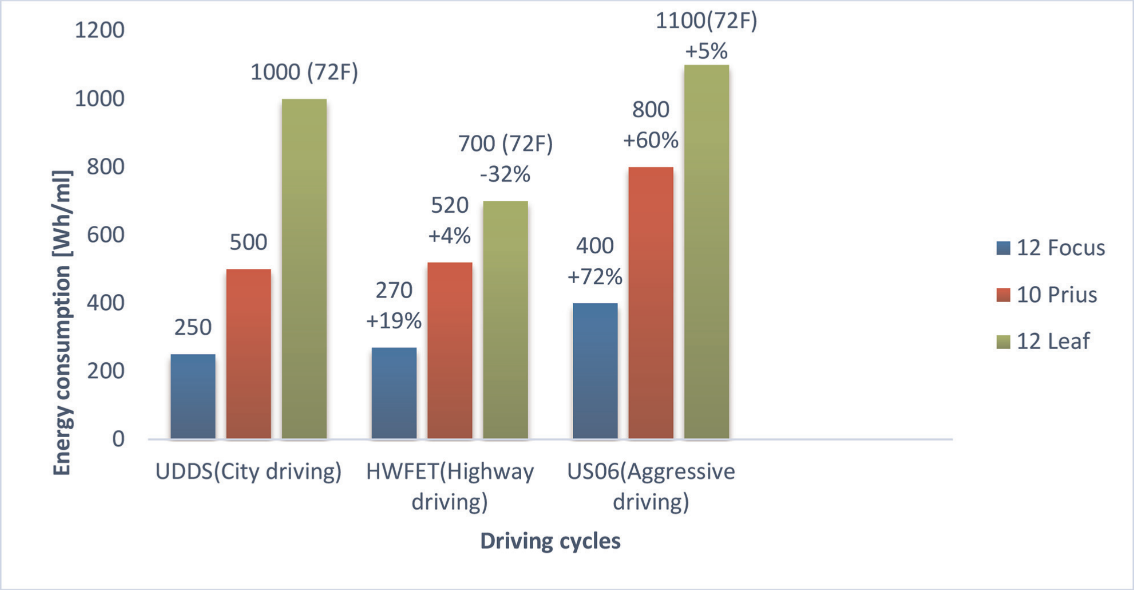


Figure 14.
Generally increased speeds and accelerations translate to higher energy consumption except for the CV due to low efficiency in the city [56].

Driving at higher speeds and more aggressively will increase an EV's energy usage. Cold start energy consumption exceeds hot start energy consumption. The greatest increase in energy usage happens for an EV at 7°C (20°F) and for a conventional at 35° C (95°F). For a cold start, a CV has the highest absolute energy usage penalty. Except for the typical because to low efficiency in the city, increased speeds and accelerations often translate to higher energy consumption.

5. Conclusion

HEVs are becoming more affordable and accessible than ever because of the likelihood of improved fuel economy, vehicle performances, and toward alleviating environmental concern.

To meet the energy demands of different HEV configurations, several power management strategies have been proposed in literature. This chapter presents a comprehensive review of relevant literatures pertaining to modeling and control of parallel hybrid electric vehicles. HEV control strategies were reviewed at depth on two main tiers: HEV offline and online control strategies. This in-depth analysis focuses on the control structure of the techniques under consideration, as well as their novelty and contributions to the achievement of a variety of optimization goals, such as reduced fuel consumption and emissions, charge sustenance, braking energy regeneration optimization, and improved vehicle drivability. Exploitable research gaps in rule-based control methods, dynamic programming, the equivalent consumption minimization strategy (ECMS), and model predictive control (MPC) strategies have all been discovered as part of this study.

For the case of HEV energy management and control, this complete evaluation is vital and necessary for researchers to quickly identify research needs for future research work.

HEV energy output can be managed and controlled by taking into account a variety of factors. Different control systems result in varying levels of efficiency, production, and emission control, but choosing the best and most dependable one is critical.

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