The Influence of Engine Downsizing in Hybrid Powertrains on the Energy Flow Indicators under Actual Traffic Conditions

Andrzej Szałek 1 and Ireneusz Pielecha 2,*

1 Toyota Motor Poland, ul. Konstruktorówka 5, 02-673 Warszawa, Poland; andrzej.szalek@toyota.pl
2 Faculty of Civil and Transport Engineering, Poznan University of Technology, Piotrowo 3 Street, 60-965 Poznan, Poland
* Correspondence: ireneusz.pielecha@put.poznan.pl; Tel.: +48-61-224-4502

Abstract: The development of internal combustion engines is currently based around the ideas of downsizing and rightsizing. These trends, however, are not very widespread in vehicles with hybrid drive systems. Nevertheless, the authors analyzed the performance indicators of hybrid drives in downsized vehicles. Two generations of a vehicle model, equipped with hybrid drive systems, were used in the analysis in which not only the design of the internal combustion engine was changed, but also other hybrid drive systems (including the transmission, electric motors and high-voltage batteries). The paper analyzes the energy flow in two hybrid vehicles of different generations during tests in real road driving conditions in accordance with the requirements of the RDE (real driving emissions) tests. The authors have confirmed that newer vehicle designs extend the vehicle range by 38% in the electric mode under the conditions of road traffic (68% in the urban conditions). The application of a combustion engine with better operating indexes did not result in its greater load, but led to limitation of the maximum pressure-volume (PV) diagram. The change of the battery to Li-ion, despite its lower electric and energy capacity, led to an increase in vehicle’s working parameters (power and regenerative braking).

Keywords: hybrid powertrain; energy flow; combustion engine; electric range

1. Introduction

The advancement of hybrid powertrains in the last two decades appears to be very significant. It has been directed at modifications in the mechanical design, as well as the design of electric systems. This particularly pertains to modern solutions in transmissions of hybrid systems but also involves electric machines and energy storage devices.

The idea of downsizing is not commonly used as a solution for vehicles with hybrid drives. It involves making changes not only to the internal combustion engine, but also to other power transmission systems, such as gears (e.g., planetary gears), electric motors, control systems and high-voltage batteries. In this study, the authors analyzed two vehicles equipped with hybrid drives of different generations in the same traffic conditions in accordance with the requirements of an RDE (real driving emissions) test. The operating conditions of internal combustion engines, electric motors, energy recovery parameters and operating conditions of batteries were compared (different types of batteries were used for the two generations of drives—Ni-MH and Li-ion). The conducted analyses made it possible to establish the quantitative benefits of modernizing hybrid drive systems in the presented cases. Conducting tests in real traffic conditions increased the quality of the work carried out and the data obtained, as it enabled comparison of other test results compliant with the RDE requirements.

The introduction of the first hybrid systems (Toyota Prius, 1997) was based on mixed solutions (parallel, serial and parallel–serial hybrids). After many years, this system still dominates in the D (large cars) and E (top class cars) segment vehicles [1,2]. There are also solutions referred to as mild-hybrids (electric motor operating as an auxiliary system), but
they are much less popular [3]. Traditional hybrid systems (parallel–serial) are increasingly offered in plug-in versions; i.e., charged from an external source [4].

The latest hybrid solutions are focused on the technological advancement of the transmission and the flow of energy. In electric machines, the maximum power outputs and motor speeds increase, which allows these features to be used at higher speeds of the vehicles [5]. A different solution of a hybrid system consisting of two electric machines was presented by Han et al. [6]. A system was proposed combining a combustion engine, an electric traction engine and an integrated starter–generator (ISG) motor further combined with a transmission. Additionally, an electronic clutch was applied between the ISG and the engine, and an electronic synchronizer between the ISG motor and the transmission.

Current engineering works are also carried out in relation to the PV diagram of modern engines (Atkinson [7,8] or Miller cycle [9]). Their optimization pertains to the cooperation of the engine with the electric machines in serial [10] or parallel powertrains [11]. The research on modeling and control of the engine start for full hybrid electric vehicles based on the system dynamic characteristics was presented by Liu et al. [12]. The problems of torque compensation in hybrid parallel drives were addressed by Part et al. in [13]. The tests also included an assessment of the amount of change in the estimated engine net torque. Taking this value into account results in the reduction of errors in the estimation of the output torque of the combustion engine. Similar works also discuss the adjustment of the engine speed during gear changes in hybrid drives [14].

A wide variety of research works related to the energy flow in conventional and hybrid powertrains was presented by Dong et al. [15]. This work was primarily related to the conditions of the combustion engine operation and its share in the hybrid system. The energy flow was not analyzed under typical traffic conditions.

Downsizing of hybrid drives should take into account changes in the combustion engine performance indicators and changes in the electric drive operating parameters. There is currently no clear direction for such activities, which points to the need for conducting research and analysis of downsized hybrid vehicles.

The aim of the research works is the assessment of the energy flow in hybrid systems with a simultaneous indication of the changes and technological advancement in two generations of such systems. New generations, even though slightly different, still use the serial–parallel configuration composed of two electric machines. The system has six different operating modes: single-motor driving mode, dual-motor driving mode, serial driving mode, parallel driving mode, engine-only driving mode and regeneration mode.

Current research on the analyses of the energy flow primarily aims at exhaust emissions and electrical energy consumption [16]. The energy flow investigations are tightly related to the method of determination of the battery state of charge. They are based on solutions of varied rate of efficiency [17]. The research proposed by the authors is related to the comparative analyses of different generations of the same vehicle model.

The studies conducted so far that can be found in the scientific literature indicate mainly analyses that were performed in relation to various vehicles equipped with hybrid drives. There are no analyses, however, indicating generational changes in such drive systems. For this reason, the issues that may complement and complete the existing knowledge in the field of hybrid drives operation have been addressed.

2. Materials and Methods
2.1. Research Objects

The assessment of the energy flow was carried out on two generations of Toyota Yaris (Table 1). The authors investigated the older along with the newer hybrid powertrain solution, the latter of which was downsized. This was a unit with a reduced number of cylinders and the same displacement (1.5 dm$^3$). Both engines were naturally aspirated.

Despite the newer emission standard (Euro 6d), the 3-cylinder engine meets the same emission limits as its predecessor (Euro 5). However, the new emission standard additionally requires the confirmation of the exhaust emissions standard limit values during vehicle
operation (ISC-in-service conformity). The change also extends to equipping of the vehicle with fuel consumption monitoring (FCM). The power output of the combustion engine was increased by 20%, also increasing the engine RPM, at which the maximum power was obtained. The engine torque was increased by 10% with a simultaneous increase of the engine RPM, at which maximum torque was obtained.

Table 1. Engine characteristics [18–20].

| Component/Parameter       | Yaris 1.5 dm³; 4-cyl.          | Yaris 1.5 dm³; 3-cyl.          |
|---------------------------|--------------------------------|--------------------------------|
| Engine                    | 1NZ-FXE                        | M15A-FXE                       |
| Valvetrain                | 16-valve DOHC, chain drive     | 12-valve DOHC, chain drive     |
|                          | (with VVT-i)                   | (with VVT-iE and VVT-i)        |
| Fuel system               | Sequential multiport fuel      | Sequential multiport fuel      |
|                          | injection                      | injection                      |
| Displacement              | 1497 cm³                       | 1490 cm³                       |
| Compression ratio         | 13.4:1                         | 14.0:1                         |
| Max. output               | 55 kW @ 4800 rpm               | 68 kW @ 5500 rpm               |
| Max. torque               | 111 Nm @ 3600–4400 rpm         | 120 Nm @ 3600–4800 rpm         |
| Emission regulation       | Euro 5                         | Euro 6d-ISC-FCM                |
| Engine service mass       | 81.9 kg                        | 87.3 kg                        |
| Hybrid system max. output | 74 kW                          | 85 kW                          |

The newer powertrain solution was fitted with the MG2 unit (an electric motor with a higher power output and lower torque). The modifications were compensated by a different hybrid transmission, from which two planetary gears were removed. The full description of the newer solution was presented in [18,19]. Similar designs were applied to midsize sport utility vehicles [5]. The new hybrid system has its maximum supply voltage increased by 10% (from 520 to 580 V) for both electric machines (MG1 and MG2, Table 2). Aside from the water jacket, the transmission also was fitted with a heat exchanger, known from the solutions utilized in the 4th generation of the Toyota Prius [21].

Table 2. Characteristics of the MG1 generators and MG2 motors in both powertrains [18–20].

| Parameter                  | Yaris 1.5 dm³; 4-cyl.          | Yaris 1.5 dm³; 3-cyl.          |
|----------------------------|--------------------------------|--------------------------------|
| Generator No. 1 (MG1)     |                                |                                |
| Type                       | Permanent magnet motor         |                                |
| Function                   | Generator, engine starter      |                                |
| Max. voltage               | DC 520 V                       | DC 580 V                       |
| Motor–Generator No. 2 (MG2)|                                |                                |
| Type                       | Permanent magnet motor         |                                |
| Function                   | Generator, wheel drive         |                                |
| Max. voltage               | DC 520 V                       | DC 580 V                       |
| Max. output                | 45 kW                          | 59 kW                          |
| Max. torque                | 169 Nm                         | 141 Nm                         |

An increased voltage in electric machines resulted from the voltage of the inverter (Table 3). The voltage of the battery was increased by 19%, which resulted from the substitution of the Ni-MH with the Li-ion battery (Table 4). The Li-ion battery, despite its newer design, had a capacity lower by 33% (4.3 Ah compared to 6.5 Ah). Despite the lower capacity and the increased voltage, the energy capacity of the Li-ion battery was 18% lower than its predecessor.

Table 3. Characteristics of the boost converters [20].

| Parameter                        | Yaris 1.5 dm³; 4-cyl.          | Yaris 1.5 dm³; 3-cyl.          |
|----------------------------------|--------------------------------|--------------------------------|
| Rated voltage (inverter side)    | DC 520 V                       | DC 580 V                       |
| Rated voltage (HV battery side)  | DC 144 V                       | DC 177.6 V                     |
A lower value of the energy capacity does not necessarily have to translate into an increased number of charge/discharge cycles for the battery. This may be due to the greater SOC voltage range of the new batteries compared to the older Ni-MH batteries. This results in an increased durability and lifespan of the new solution.

Table 4. Battery specifications in the analyzed hybrid powertrains [20].

| Item                     | Yaris 1.5 dm³, 4-cyl. | Yaris 1.5 dm³, 3-cyl. |
|--------------------------|-----------------------|-----------------------|
| Type                     | Nickel metal hydride (Ni-MH) battery | Lithium-ion (Li-Ion) battery |
| Cell quantity            | 120 cells (6 cells × 20 modules) | 48 cells (24 cells × 2 stacks) |
| Nominal voltage          | 144 V                 | 177.6 V               |
| Battery capacity         | 6.5 Ah                | 4.3 Ah                |
| Energy                   | 0.936 kWh             | 0.763 kWh             |

2.2. Research Equipment and Methodology of Determination of the Energy Flow

The measurements were performed using a specialized, dedicated diagnostic tester utilizing the OBD (on-board diagnostics) connector. The research used data provided by one of the vehicle systems—the hybrid control. This system operates using selected vehicle data, internal combustion engine data, parameters of the electric motors and the parameters of the high-voltage battery. The vehicle driving conditions were determined based on the measurements of the vehicle speed and the data sampling time. The resolution was 20 Hz. For further works, the authors used filtered data of the frequency f = 1 Hz.

The assessment of the energy flow was carried out based on the measurements of the engine speed and load, the speed and torque of the electric motors/generators, the battery voltage and the current (including the boost voltage).

Using the above measurement data, the following quantities were determined:

- energy flow:

\[
\Delta E_i = \sum_{t=0}^{t=\text{max}} V_{\text{BAT}} \cdot I_{\text{BAT}} \cdot dt, \tag{1}
\]

instantaneous energy flow values \(\Delta E_i\) were divided in accordance with the following criteria:

- discharging:

\[
\Delta E_{\text{dis}} = \sum_{t=0}^{t=\text{max}} V_{\text{BAT}} \cdot I_{\text{BAT}} \cdot dt \text{ (if } \Delta E_i < 0), \tag{2}
\]

- charging:

\[
\Delta E_{\text{ch}} = \sum_{t=0}^{t=\text{max}} V_{\text{BAT}} \cdot I_{\text{BAT}} \cdot dt \text{ (if } \Delta E_i > 0 \text{ and } T_{\text{reg}} \geq 0), \tag{3}
\]

- regenerative braking:

\[
\Delta E_{\text{reg}} = \sum_{t=0}^{t=\text{max}} V_{\text{BAT}} \cdot I_{\text{BAT}} \cdot dt \text{ (if } \Delta E_i > 0 \text{ and } T_{\text{reg}} < 0), \tag{4}
\]

where: \(V_{\text{BAT}}\)—voltage (V), \(I_{\text{BAT}}\)—current (A), \(dt\)—time (h), \(T_{\text{reg}}\)—braking torque (Nm);

- boost value

\[
\text{boost} = \frac{V_{\text{HV}}}{V_{\text{LV}}} \tag{5}
\]

where: \(V_{\text{LV}}\)—low voltage side (V), \(V_{\text{HV}}\)—high voltage side (V).
3. Results

3.1. Analysis of the Test Routes

All tests were performed on the same test route covering the urban, rural and motorway cycles in the city of Poznan and its surrounding areas (city population in excess of 500,000). The test drives were compliant with the RDE test requirements. These requirements were set forth in relation to the distances of individual routes and the shares of stops and accelerations in individual portions of each test route. The distance of the test route was over 90 km (60–120 km required) and the duration was 95 min (90–120 min required). Each portion of the test should constitute a share of 33%. Detailed requirements were specified in [22,23].

The test drives are shown in Figure 1. The first portion was the urban cycle (up to 60 km/h), the next portion was rural (up to 90 km/h) and the last one was motorway. All possible traffic congestions were considered. The first drive was performed using the newer powertrain (3-cylinder engine with the P910 transmission). The second drive was performed using the older generation vehicle (4-cylinder engine with the P510 transmission). Both images also indicate the hybrid mode, the electric mode and the vehicle stops. The preliminary assessment led to a conclusion that the newer solution increased the potential of the electric mode of the powertrain. This particularly resulted from the application of the Li-ion battery (Table 4) despite the fact that the battery energy was 20% lower (at its maximum state of charge). The initial charging level of the Ni-MH battery was SOC Ni-MH = 48.2% and the Li-ion battery-SOC Li-Ion = 42.7%. While using the Li-ion battery, the electric mode could achieve higher speeds (in case of the Ni-MH battery, conditions occurred sporadically).

![Figure 1](image-url)

Figure 1. Test route with the powertrain operating conditions: (a) newer solution with the 3-cylinder engine; (b) older solution with the 4-cylinder engine.

3.2. Energy Flow Analysis

The energy flow conditions corresponded to the applied batteries. The use of the Li-ion battery allowed its more frequent charge/discharge compared to the Ni-MH one. For this reason (despite its lower energy) the discharge value was approximately 45% higher than it was for Ni-MH (Figure 2). The amount of regenerated energy was also slightly higher (1.83 compared to 1.51 kWh, which constituted a difference of 20% in favor of the Li-ion battery). This also resulted from the fact that the value of the voltage boost in the newer solution was 580 V (580.5 V recorded) compared to the older solution, for which this value was 520 V (538 V recorded, Table 3). The newer solution had a maximum voltage boost of 3.45 (battery voltage: 177.6 V) and the older one 3.88 (battery voltage: 144 V).
3.3. Voltage Boost Evaluation

A detailed analysis of the battery voltage boost in relation to the instantaneous route profile is presented in Figure 3. The urban driving conditions in both cases were based on the standard voltage values, as well as the voltage boost, to approximately 30–40% above the nominal value of the low-voltage side. Higher vehicle speeds (particularly in the rural portion) resulted in an increased voltage supplied to the MG2 motor. Still, the values in the range of 40–60% of the voltage boost occurred very rarely. A sudden increase in the vehicle speed in the range above 90 km/h (motorway portion) resulted in the maximum boost for the older powertrain solution. The newer solution used the boost at the level of 60–80%.

The qualitative analysis of the voltage boost ranges indicated that the newer powertrain solution utilized the midrange more frequently (20–60%), while the older solution more frequently applied the maximum boosts.

Figure 3. Analysis of the voltage boost depending on the instantaneous route profile: (a) conditions for boost in both powertrain generations; (b) analysis of changes of the boost usage.

The analysis of the operation of the MG2 electric motor indicated a much wider ranges of operation of the newer solution and much lower values of the maximum torque—Figure 4. These data are compliant with the manufacturer’s specifications [24]. Despite the fact that the manufacturer data indicate a much higher value of the maximum torque (Table 2), in both cases these values oscillated around 100 Nm. The comparative analysis of both motors indicated a slightly higher value in the case of the older solution. At the same time, it generated much lower maximum speeds (approximately 10,000 rpm
compared to 12,500 rpm in the case of the newer solution). During regenerative braking, the increased voltage occurred mainly in the newer powertrain solution. In this case, even when braking at a lower braking moment, the voltage boost was used (this boosted the electric power supplied to the battery). This system, compared to the older powertrain solution, utilized lower $T_{\text{reg}}$ values (the envelope of the braking moment is impossible to identify in Figure 4a). This means that during typical driving (braking) conditions, the system did not regenerate the maximum values of power.

The maximum values of $T_{\text{reg}}$ occurred in the older powertrain. Therein, the maximum values of the braking moment were used at different MG2 motor speeds, which made it possible to obtain the envelope on the MG2 motor characteristics (Figure 4b).

![Figure 4. MG2 motor operating conditions: (a) the newer solution with the 3-cylinder engine; (b) the older solution with the 4-cylinder engine.](image)

3.4. High-Voltage Battery Operating Conditions

The application of the Li-ion battery in the newer powertrain solution indicated an increased possibility of driving in the electric mode. In the system, batteries’ use of the maximum accumulated energy was 18% lower compared to the Ni-MH. Additionally, their capacity was lower by 33% (4.3 Ah and 6.5 Ah, respectively).

The analysis of the operation of these systems under actual traffic conditions indicated a greater (25%) range of charging/discharging of the Li-ion battery ($\text{SOC}_{\text{max}}$: 74.1% and $\text{SOC}_{\text{min}}$: 35.3%) compared to the Ni-MH battery ($\text{SOC}_{\text{max}}$: 68.6% and $\text{SOC}_{\text{min}}$: 39.6%), as shown in Figure 5. The approximately 5% greater SOC range for each of the boundary
values did not translate into a greater electrical capacity, and amounted to 1.67 Ah and 1.89 Ah, respectively.

The comparative results shown in Figure 2 confirmed better properties of the Li-ion battery, which allowed more than 40% higher discharging energy and approximately 20% higher charging energy during regenerative braking. Additionally, much greater values of the energy balance occurred throughout all the modes of battery use (regen, discharge, charge). The energy balance of the powertrain fitted with the Ni-MH battery was 0.11 kWh, and with the Li-ion battery was 0.48 kWh (over 40% more advantageous). It is noteworthy, however, that this value always depended on the battery’s initial SOC and the traffic conditions. The fulfillment of the real driving conditions (RDC) requirements did not always result in identical final energy balance results.

Figure 5. SOC variation ranges of the analyzed batteries.

Figure 6 presents the characteristics of operation of both batteries applied in the tested vehicles. The Li-ion battery had a wider range of the values of current (almost 40%, particularly when charging; see Figure 6a). During the discharge, the values were greater by approximately 30%. The values of the maximum voltage for both batteries were similar (despite the fact that the voltage nominal values differed by approximately 30 V; see Table 3).

The nominal values of voltage were close to the ones declared by the manufacturer, but the changes in voltage occurred in the case of the Ni-MH battery. This was reflected in the values of electric power flowing through the battery. The values of power for the Li-ion battery were 60% higher during its discharge and 30% higher during its charging. Such calculations indicated a greater share of the electric mode during vehicle operation in the newer version of the powertrain (Figure 6b).
3.5. Analysis of the Operating Conditions of the Combustion Engines

Downsizing of combustion engines led to the reduction of the number of cylinders in the newer solution. Despite the same displacement and the applied Atkinson cycle, the compression ratio was increased from 13.4 to 14, and a system of electric variable intake valve timing (VVT-iE) was introduced. The maximum power output was increased by 13 kW and, at the same time, the maximum engine speed was changed to 5500 rpm. The maximum value of torque was increased by 8 Nm for the same engine speed. The newer combustion engine meets the Euro 6 standard (the older met Euro 5). The weight of the engine increased by 5 kg.

The analysis of the engine operating conditions is shown in Figure 7. The newer version, in typical traffic conditions, operated mainly on medium loads (Figure 7a). The maximum values of torque and engine speed were not reached. Referring to the older version, one can observe a high engine load under the conditions of hybrid operating mode. This means that the engine was heavily loaded in this configuration, which resulted from the lower value of the engine torque and power at the medium engine speed. This was additionally influenced by the lower power of the MG2 electric motor. It was more than 30% lower compared to the motor fitted in the newer solution. The higher value of torque by more than 15% did not translate into its better use. This is shown in Figure 4.

![Figure 7](image)

Figure 7. Operating conditions of the combustion engine: (a) density characteristics of both generations of combustion engines; (b) PV diagram of the combustion engines and their use.

Higher indexes of the 3-cylinder engine did not translate into its more efficient use during operation. As shown in Figure 7b, the T-n diagram of the combustion engine fell below the absolute values of torque of the older solution. It was confirmed that these values were approximately 30–40% lower compared to the older engine version. This meant that the newer version of the entire hybrid powertrain did not require a heavy load of the combustion engine when in operation. This should result in a greater operating share of the electric mode.

3.6. Analysis of the Share of the Electric Mode

The final evaluation of the powertrain mainly related to the vehicle range in the electric mode. Two aspects were considered: the share of the electric mode in relation to the covered distance and the same share in relation to the driving time. The results of the research and analyses are shown in Figures 8 and 9. In Figure 8, the authors analyzed the
newer solution (3-cylinder engine). From the analysis, we know that when we considered the vehicle stops, this part of the vehicle test was mainly realized in the EV mode (only in a few cases was the combustion engine operative; see Figure 8a). The greatest share of the EV mode occurred in the urban conditions—over 55% of the entire test drive duration. The vehicle stops were not included in this value. In the rural portion, this share dropped, but was still significant (over 30%). In the motorway portion, the share of the EV mode is the smallest (5%). This value resulted from the driving conditions—the EV mode activated mainly when braking, but at speeds above 90 km/h (motorway conditions requirements). If we considered the vehicle stops in the drive time in the urban conditions, this share increased to 79% (Figure 8b). The average share of the electric mode in actual traffic was 38%. These values were slightly lower in relation to the covered distance (Figure 8b). However, even in relation to the covered distance, the share of the EV mode in the urban conditions was 67%.

The older solution of the hybrid powertrain did not have so many benefits from driving in the EV mode compared to the newer solution. Despite the fact that the vehicle stops were also realized in the EV mode, the drive in this mode in the urban conditions was only 40%, which rendered this share almost 30% lower. In the rural conditions, this share was very small, and in the motorway portion was practically nonexistent (Figure 9a). Still, the average share of the EV mode in the urban conditions (vehicle stops included) was 68% and then dropped suddenly in the outstanding portions of the test. The average share of the EV mode in the entire test route was only 23% (Figure 9b). In relation to the covered distance, these shares were even lower.

The above-presented changes in the structure of hybrid powertrains (referred to as electrified powertrains) indicate their significant position in the sales market. Compared to standard electric powertrains, they ensure a safe range that is currently a very important factor when selecting the means of transport.

Commercial designs of hybrid powertrains have been present in the market since 1997, are still rapidly advancing technologically and are still subject to intense research, which contributes to their optimization.
4. Conclusions

1. Two different passenger vehicle hybrid powertrain designs were the subjects of the investigations. Their performance in the investigations under the same road conditions allowed for a comparison of the two systems.
2. The advancement of hybrid powertrains has led to their optimization, which significantly improves their share of operation in the electric mode despite lower values of the maximum torque of the electric motor. Such driving parameters are also influenced by the use of the Li-ion battery. The share of the electric mode in the actual traffic conditions was 38%, which translates into a value of 68% in the urban conditions.
3. The application of a combustion engine with higher operating indexes did not eventually improve the operation of the hybrid powertrain: typical operating conditions of the engine were medium speeds and medium loads; such operating conditions will not cause higher fuel consumption in real traffic.
4. The optimization of the powertrain has led to a change of the type of battery: despite the lower electric and energy capacity, its use results in an increased share of the electric mode during vehicle operation.

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Figure 9. Operating conditions of the hybrid and electric powertrains in the old generation (4-cylinder engine): (a) the share of operation of the EV and the HV modes in individual portions of the test (vehicle stops included); (b) the share of the EV mode in relation to time and distance.
References

1. Tran, D.-D.; Vafaeipour, M.; El Baghdadi, M.; Barrero, R.; Van Mierlo, J.; Hegazy, O. Thorough state-of-the-art analysis of electric and hybrid vehicle powertrains: Topologies and integrated energy management strategies. *Renew. Sust. Energ. Rev.* 2020, 119, 109596. [CrossRef]

2. Huang, Y.; Wang, H.; Khajepour, A.; Li, B.; Ji, J.; Zhao, K.; Hu, C. A review of power management strategies and component sizing methods for hybrid vehicles. *Renew. Sust. Energ. Rev.* 2018, 96, 132–144. [CrossRef]

3. Zhou, X.; Qin, D.; Yao, M.; Xie, Z. Representation, generation, and optimization methodology of hybrid electric vehicle powertrain architectures. *J. Clean. Prod.* 2020, 256, 120711. [CrossRef]

4. Zhang, F.; Hu, X.; Langari, R.; Cao, D. Energy management strategies of connected HEVs and PHEVs: Recent progress and outlook. *Prog. Energ. Combust.* 2019, 73, 235–256. [CrossRef]

5. Nobuyasu, S.; Iwata, S.; Nishigaya, M.; Hagino, Y.; Ito, M.; Aihara, H. Development of new hybrid transaxle for mid-size sports utility vehicles. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2020. [CrossRef]

6. Han, Z.; Wu, Z.; Gao, X.; Sun, Y.; Ni, R.; Feng, J.; Zhong, J.; Chen, X.; Zhao, Z.; Yu, Z. Development and demonstration of a new range hybrid powertrain concept. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2020. [CrossRef]

7. Cinar, C.; Ozdemir, A.O.; Gulcan, H.E.; Topgül, T. Theoretical and experimental investigation of the performance of an Atkinson cycle engine. *Arab. J. Sci. Eng.* 2021. [CrossRef]

8. Li, Y.; Wang, S.; Duan, X.; Liu, S.; Liu, J.; Hu, S. Multi-objective energy management for Atkinson cycle engine and series hybrid electric vehicle based on evolutionary NSGA-II algorithm using digital twins. *Energ. Convers. Manag.* 2021, 230, 113788. [CrossRef]

9. Zhao, J. Research and application of over-expansion cycle (Atkinson and Miller) engines—A review. *Appl. Energ.* 2017, 185, 300–319. [CrossRef]

10. Junger, M.; Goerke, D.; Langwieser, M.; Schmiedler, S.; Geringer, B. Analytical methodology to derive a rule-based energy management system enabling fuel-optimal operation for a series hybrid. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2020. [CrossRef]

11. Goerke, D.; Bargende, M.; Keller, U.; Ruzicka, N.; Schmiedler, S. Optimal control based calibration of rule-based energy management for parallel hybrid electric vehicles. *SAE Int. J. Alt. Power.* 2015, 4, 178–189. [CrossRef]

12. Liu, Y.; Chen, D.; Lei, Z.; Qin, D.; Zhang, Y.; Wu, R.; Luo, Y. Modeling and control of engine starting for a full hybrid electric vehicle based on system dynamic characteristics. *Int. J. Automot. Technol.* 2017, 18, 911–922. [CrossRef]

13. Park, J.; Choi, S.; Oh, J.; Eo, J. Engine net torque compensation through driveline torque estimation in a parallel hybrid vehicle. *Int. J. Automot. Technol.* 2019, 20, 619–627. [CrossRef]

14. Hong, J.; Lu, L.; Gao, B.; Zhang, L.; Chen, H. Engine speed regulation during gear shift process of torque decoupled HEV using triple-step nonlinear method. *Int. J. Automot. Technol.* 2021, 22, 415–428. [CrossRef]

15. Dong, H.; Fu, J.; Zhao, A.; Liu, Q.; Li, Y.; Liu, J. A comparative study on the energy flow of a conventional gasoline-powered vehicle and a new dual clutch parallel-series plug-in hybrid electric vehicle under NEDC. *Energ. Convers. Manag.* 2020, 218, 113019. [CrossRef]

16. Pielecha, I.; Cieslik, W.; Szalek, A. Energy recovery potential through regenerative braking for a hybrid electric vehicle in a urban conditions. *IOP Conf. Ser. Earth Environ. Sci.* 2019, 214, 012013. [CrossRef]

17. Kawahara, Y.; Sakabe, K.; Nakao, R.; Tsuru, K.; Okawa, K.; Aoshima, Y.; Kudo, A.; Emori, A. Development of status detection method of lithium-ion rechargeable battery for hybrid electric vehicles. *J. Power Sour.* 2021, 481, 228760. [CrossRef]

18. Taniguchi, M.; Yashiro, T.; Takizawa, K.; Baba, S.; Tsuchida, M.; Mizutani, T.; Endo, H.; Kimura, H. Development of new hybrid transaxle for compact-class vehicles. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2016. [CrossRef]

19. Suzuki, Y.; Nishimine, A.; Baba, S.; Miyasaka, K.; Tsuchida, M.; Endo, H.; Yamamura, N.; Miyazaki, T. Development of new plug-in hybrid transaxle for compact-class vehicles. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2017. [CrossRef]

20. Ikeyama, T.; Ishikawa, K.; Nozawa, N. Development of power control unit for compact-class vehicle. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2020. [CrossRef]

21. Matsumoto, T.; Kato, H.; Takizawa, K.; Yashiro, T.; Okazaki, S.; Tabuchi, K. Development of motor cooling technology in hybrid vehicles. *SAE Int. J. Adv. Curr. Pract. Mobil.* 2020, 2, 454–458. [CrossRef]

22. Merkisz, J.; Pielecha, J.; Radzimirski, S. *New Trends in Emission Control in the European Union*; Springer Tracts on Transportation and Traffic: Cham, Switzerland, 2014; Volume 4, p. 170. [CrossRef]

23. Pielecha, I.; Cieslik, W.; Szalek, A. Impact of combustion engine operating conditions on energy flow in hybrid drives in RDC tests. In *SAE Technical*; SAE International: Warrendale, PA, USA, 2020. [CrossRef]

24. Fushiki, S. The new generation front wheel drive hybrid system. *SAE Int. J. Alt. Power* 2016, 5, 109–114. [CrossRef]