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Editors' Perspectives: Synergistic Technologies for Dedicated Hybrid Powertrains

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Abstract

Regulatory and market pressure to reduce greenhouse gas (GHG) emission has directed the path of powertrain development towards expanded use of electrification. Powertrain electrification can substantially reduce vehicle GHG emissions and improve fuel economy. The contributory technologies could be related to reducing the demands on the engine for enhanced durability and efficiency and introducing synergistic technologies such as kinetic energy recovery for more efficient energy management. This work reviews the advancement of energy-efficient hybrid powertrains with application of dual motive powers, engine and battery/motors. The focus is on the industrialization perspective of the dedicated hybrid transmission (DHT) development. Based on the DHT framework, dedicated hybrid engines (DHE) are exemplified through those successful hybrid vehicles in the market. Technology challenges for DHT are discussed. The key enablers of controls and model-based design are reviewed to disclose the progress of hybrid powertrain development by using both endogenous fuel and exogenous electricity if applicable. Overall, DHT case studies for both passenger cars and commercial vehicles are presented.

Keywords: hybrid powertrain, dedicated hybrid engine (DHE), dedicated hybrid transmission (DHT), model based design (MBD), control

1. Background

The history of ground vehicles is, in a sense, largely representative of the modernization of human life. In 1769, a steam engine was used to power the first human transporter "car". The first four-stroke engine was developed in 1861, and that made it possible for automobiles to be powered by internal combustion engines (ICE). With the advent of car manufacturers of such as Mercedes-Benz and the Ford Motor Company in the early twentieth century, automobiles have gradually become an integral part of modern human life. At that time several vehicle powertrains technologies were widely used, including steam, battery-electric, hybrid powertrains, and the familiar ICEs. There was no clear dominant technology. In fact, Ford manufactured more steam and electric cars than gasoline ones. Gasoline engines began to become the dominant motive power source for passenger automobiles in the 1930s, while diesel engines took on the corresponding role for commercial vehicles. Designed to effectively use engine power, powertrains have always been the key enabling technology for the success of the vehicle industry. Typically, a powertrain system includes an engine, clutch, transmission, differential(s), and driveshafts to deliver power to the wheels.

The widespread adoption of the ICE-powered vehicles led to significant environmental and health issues, most notably the Los Angeles smog concern of the 1940s and 1950s (Song, 2019-Q3). In the 1940s and 1950s, millions of people drove millions of cars in the Los Angeles area. There was constantly a heavy smog hanging over the city. It was not until the 1950s that scientific research identified emissions from vehicle engines as being one of the leading causes to production of photochemical smog. Since then, the State of California introduced regulatory control on automobile emissions which began to enforce the adoption of exhaust gas treatment devices, catalytic converters for gasoline engines and, later, aftertreatment systems for diesel engines. This regulatory effort has greatly promoted technological advances in the automotive industry: passenger car corporate average fuel economy (CAFE) from 18 mpg in 1978 to 45 mpg today; commercial vehicle NOx emissions from 10.7 g/bhp-hr in the early 1980s to the current 0.02 g/bhp-hr. As the society has become more conscientious of the environment, regulations have begun to shift to the low-carbon emissions era. As environmental concerns drive regulatory and market pressure, full electric and hybrid powertrains are popular research areas in both academia and industry. Within the next few generations of vehicles the use of internal combustion engines as the sole source of motive power has been widely projected to reduce dramatically. As indicated in (NAS, 2010), research efforts will be focused on innovations and industrialization of both mature engine and powertrain technologies and alternative disruptive technologies from this transformative point onwards.

Electronics have also played an important role in advancing engine technology. By the 1960s, internal combustion engines had entered large-scale industrial application for vehicles. In the 1970s, electronic engine control systems emerged that controlled fuel injection and exhaust gas recirculation to maintain high catalytic converter efficiency. Since the 1980s, with the advancement of microprocessor controllers for industrial applications, internal combustion engines have benefited by greatly enhanced engine efficiency and emissions control. With the invention and application of the heated exhaust gas oxygen (HEGO) sensors in the 1980s the closed-loop air-fuel ratio control was successfully applied to the engine system (Cooky et al., 2008). Entering the 1990s, additional control actuators for internal combustion engines were explored to meet more stringent regulations. Multi-variable control technology facilitated engineering application of exhaust gas recirculation (EGR) and variable valvetrain systems. Other advanced technologies were pursued as well, such as variable direct injection, dual injection, and variable compression ratio systems (Su et al., 2018). Ongoing improvements in electronic controls are continuing to provide internal combustion engines with more precise transient torque management along with improved fuel efficiency and reduced emissions. Further gains are also being realized through further development of internal combustion engines within the framework of integrated powertrain systems. Holistic optimization with regard to operating conditions of the entire vehicle can lead to redefinition of the internal combustion engine boundary conditions. As such, the performance of the vehicle system can be improved profoundly. As computational processing capacity continues to improve, the performance of powertrains and vehicles will be incrementally elevated with the application of advanced intelligent controls. Advanced control and calibration research, incorporating technologies like artificial intelligence, will be a large contributor to re-inventing engines so that they continue to be an integral part of the future powertrains.

Historically, the powertrain is one of the core technologies for vehicle development, and hybridization is one of the highlights in today's vehicle industry (Song, 2011). An engine-only powertrain must satisfy several competing constraints that demand compromises in design. For example, low-speed and high-load operation is the most prone to knock, and therefore is the limiting case for selecting compression ratio. Though the engine does not operate in this region often, the compression ratio for the engine must be reduced, lowering thermodynamic efficiency. Hybridization restricts the operating range of the engine, reducing design compromises, and therefore enabling higher efficiency. Additionally, the combustion process inside an engine generates heat, which is then partially converted into mechanical kinetic energy. In this process, a lot of waste heat is produced. One of the focus areas for engine research is to boost the thermal efficiency beyond 50%. From the perspective of energy usage, about only 30% of fuel energy is currently used for acceleration, deceleration, and overcoming rolling and aerodynamic resistance during operation. In general, because there are many stops and starts within a drive cycle vehicle braking can consume as much as 10%+ of the fuel energy. It is well recognized that the energy efficiency of the whole vehicle can be significantly higher if the vehicle kinetic energy during braking is fully recovered and reused. Thus, recovery of braking energy is being studied widely to maximize energy efficiency during vehicle operation.

In another perspective, since electric motors can exhibit large torque levels at low rotational speeds, a dedicated hybrid engine (DHE) is constitutive for powertrain electrification. In 1997, the world's first mass-production hybrid electric vehicle (HEV), the Toyota Prius, was launched, and Toyota has sold over ten million hybrid vehicles to date. The industrialization of commercial vehicle hybrid systems was launched by Eaton in 2002. Electrified powertrains range from micro-hybrid, light hybrid, and full hybrid to plug-in hybrid to meet market and regulatory requirements in a manner deemed most suitable by the manufacturer. Though a greater degree of hybridization may be beneficial from an engine efficiency perspective, the weight, cost, and durability of these systems must be considered as well.

This paper focuses on the impact that hybridization has on engine design and specific enabling technologies of hybridization. Engine performance and design case studies for electrified powertrains are presented, along with comments from the editors regarding the significant impact the shift in design optimization for hybrid engines. Novel combustion strategies are introduced and new-found applications on hybrid powertrains are discussed in detail. Technology challenges for DHTs are addressed from components, modules to development methodologies. Various DHT architectures are discussed and some of the compromises and challenges related to the engine and mechanical transmission selection are highlighted, also in light of future technology developments.

2. Dedicated Hybrid Engine Technology

An engine-only powertrain consists of an engine and a mechanical transmission to provide the requested vehicle propulsion over a wide range of conditions. A wide range of operations challenges the optimization of engine performance as several trade-offs are required. Figure 1 presents the challenges to attain the best performance under different working conditions to meet speed and torque requirements. During the high load, delaying the combustion phasing could avoid or mitigate knocking at the cost of fuel efficiency; for the best efficiency operational region, the thermal efficiency is the key indicator of the engine performance; usually under a part load (i.e., low load condition), a combustion engine runs at a very low efficiency because of pumping friction loss. The engine efficiency improvement is always a primary task for the engine research and development. In addition, the environmental effect poses another dimension of technology difficulty to tackle, such as cold start with extreme low emissions. In order to meet emission regulations, gasoline engines require stoichiometric operation to enable a three-way catalyst, and a complex lean-aftertreatment system is a must for diesel engines.

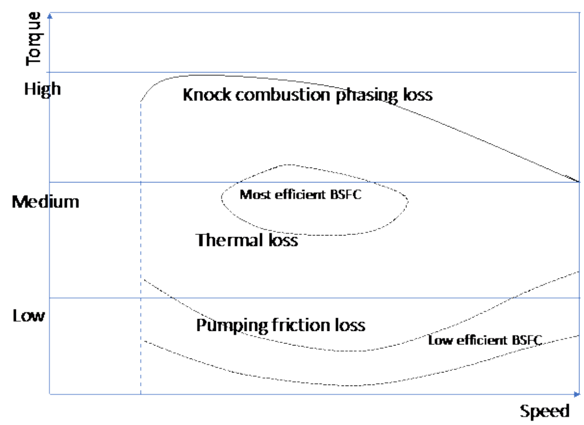


Figure 1. Primary efficiency mapping throughout an engine's typical operation

Powertrain hybridization is the synergy of the dual motive powers of the engine and electric motor to attain lower emissions and improved efficiency. Figure 2 presents the operation of the electric and ICE components of a generic hybrid powertrain. The hybrid operation optimizes the energy consumption of the powertrain. For example, the powertrain controller can prioritize the electric drive for vehicle launch and enable the engine only when the overall fuel economy is improved with engine operation. While the vehicle decelerates, the electric drive can recuperate a portion of the vehicle's kinetic energy through regenerative braking. The control strategy of hybrid powertrains significantly affects fuel economy and still is an on-going research topic. Several publications integrate the hybrid powertrain control with optimal control methodologies, like model predictive control (MPC) [6-8] and dynamic programming (DP) [9-11]. Fuel economy improvements up to 30% have been demonstrated through simulation and experimental validation. These methods require detailed knowledge of the powertrain dynamics. Therefore, the calibration of control system becomes highly coupled with powertrain layout and component design. Engine technologies used for hybrid powertrain must be assessed both in terms of steady-state efficiency gain and transient response. In the following sections, the dedicated hybrid engines from Toyota and Honda are examined as case studies.

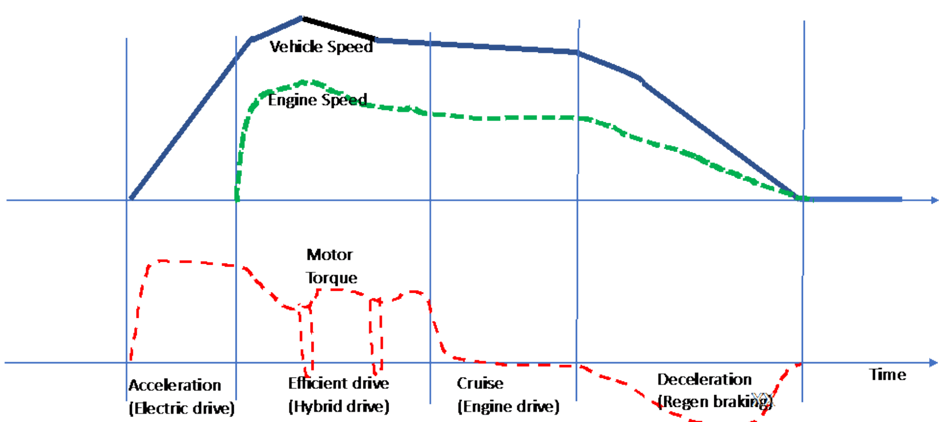


Figure 2. Generic hybrid vehicle operation Characteristics

2.1 Toyota Gasoline DHE

Toyota has produced a hybrid technology platform from the 1990s for the Prius and the hybridized models of Toyota and Lexus. The conventional automatic transmission is replaced by an electronically-controlled continuously variable transmission (e-CVT). The e-CVT applies one single planetary gear with a generator to optimally tout the high efficiency of the engine operations. This e-CVT system sends electrical signals of both the gas pedal and the gearshift lever to a hybrid controller so that such a drive-by-wire system can further translate the driver's intention to better meet the operation requirements but also avoid direct mechanical connection between the engine and the engine controls for high system reliability. The internal combustion engine for the e-CVT hybrid system is different from one used with a conventional automatic transmission. For a conventional car, firstly the engine must be sized to meet both hard acceleration and climbing steep hills; that means the maximum efficiency of the sized engine generally locates at the mid operational regions (i.e., around half of the engine's peak power output), as shown Figure 1; such an engine almost always operates in low efficiency while providing peak power. In contrast, the hybrid system can boost the peak drive power from both engine and electric drive as needed, and therefore allows to use a smaller engine. The smaller engine can operate closer to the most efficient region to meet most power demands encountered in normal driving, which are usually a larger fraction of its peak power.

One significant specification of DHEs is a maximum engine speed of 4500 rpm in the Generation II Prius (2000 - 2003) and 5000 rpm in the Generation III Prius (2003 onwards), respectively. The speed limiting allows lightweight parts to be used, contributory to reducing both inertia and friction losses. With an offset of the crankshaft regarding the cylinder axes, the cylinder forces from the piston to the crankshaft go along a straight connecting rod. Furthermore, the energy loss in operating the valves is minimized because of adopting narrow valve stems and low force springs. Other DHE features are application of low friction roller rockers, improved combustion system, a small diameter spark plug to improve knocking, and reduced weight. The discussed mechanism layout with increased rigidity leads to improved NVH during the combustion cycles. As such, one major characteristic of the hybrid system can be "engine rightsizing" without sacrifice of vehicle performance and efficiency (Kawamoto et al., 2009).

The hybrid system is designed to apply optimum control of the engine, motor, and generator through the e-CVT for different driving conditions. Additionally, the engine uses a high-expansion ratio cycle "Atkinson cycle" rather than the usual Otto cycle. It is particularly effective to reduce pumping loss at low loads. The Atkinson cycle delays the timing of intake valve closing significantly to reduce the effective compression ratio while maintaining a high expansion ratio. For the 1.8L hybrid engine of the third generation of the Toyota hybrid system, the geometric compression ratio reaches 13.0 for improved fuel efficiency. However, the effective compression ratio is lowered to prevent knocking, while the expansion ratio is raised for controlling the thermal efficiency improvement.

Table 1. Comparison of dedicated hybrid engine with base from Toyota (edited per Kawamoto etc., 2009)

Engine Type	Displacement (cc)	Cylinder	Bore×Stroke (mm)	Valve Train	Intake Closed Timing (°CA)	Compression Ratio	Maximum Power	Maximum Torque	Emission Regulation	Major Technologies
Dedicated hybrid engine (DHE)	1797	In-line,4-cylinder	φ80.5 × 88.3	Intake VVT-i Roller rocker drive	61~102 ABDC	13:1	73kW/5200rpm	142Nm/4000rpm	AT-PZEV	Atkinson cycle Cooled EGR Electric water pump
Base engine	1497	In-line,4-cylinder	φ75.0 × 84.7	Intake&Exhaust VVT - i Direct drive	30~65 ABDC	10:1	100kW/6000rpm	175Nm/4400rpm	ULEV2	Dual VVT-i

As listed in Table 1, one of the major technologies for this DHE development is the cooled EGR system. Cooled EGR reduces pumping losses at low loads and mitigates knock at high loads. Reduced knock at high loads enables an increased compression ratio, improving efficiency across the entire operating map. EGR cooling can also help lower the exhaust gas temperature. During the low load conditions, increasing the EGR rate can reduce the pumping loss to improve the fuel efficiency. Under the high load conditions, since the ratio of the pumping loss is minimized with a fully open throttle; thus, the choice of advancing the VVT-i angles with cooled EGR is an effective way to increase the effective compression ratio for better fuel consumption. In order to meet the high-speed driving conditions, it is necessary to use the cooled EGR gas to reduce both combustion temperature and maximum compression temperature; the incurred lower (exhaust gas) temperature as well as advance of spark timing allows to produce maximum power output at an improved efficiency while driving with a stoichiometric air-fuel ratio. Overall, combination of EGR cooling and VVT-i helps to achieve an optimum balance between thermal efficiency and output power throughout all engine speeds and loads. The effects of the Atkinson cycle with EGR under typical conditions during urban driving are shown in Figure 3. It can be observed that the dedicated hybrid engine achieves 8.5% higher fuel efficiency compared to the base one. Furthermore, the cooled EGR system boost an extra 1.7% higher fuel efficiency compared to the Atkinson cycle only.

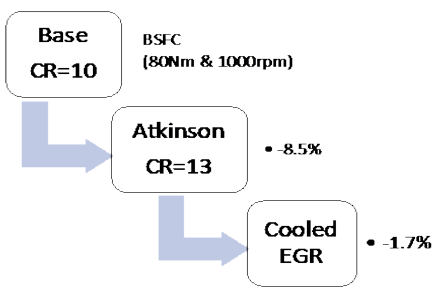


Figure 3. Contribution of Atkinson and Cooled EGR to FE improvement

An integrated electric water pump to the engine system is another critical technology used in the Toyota DHE. The pump design targets at on-demand operations to optimize the pumping rate with reduced flow resistance, and improve the fuel efficiency by controlling flow rates under low and medium engine loads and enhancing anti-knocking functionality for high load conditions. With synergetic design, the pump motor is about 90% smaller in size with 60% less of flow rate to meet similar operational requirements equivalent to mechanical water pump. From the mechanical system perspective, the integration design also eliminates drive belts and mechanical seals to reduce friction while improve reliability. Working together with the heat recirculation system, the electric water pump can further optimize the heater flow for better performance and help out quick engine warm-up by reducing cooled water flow at cold start-up for emission reduction advantage.

The data shows that this new heat management system delivers 19% higher practical fuel economy for winter operations.

Finally, a hybrid engine is optimized to produce lower emission than an engine designed for an engine-only powertrain. It is worth noting that the Toyota hybrids use the electric drive with engine shut-off at cold start to achieve cleaner exhaust emissions. Otherwise, high hydrocarbon (HC) emission concentrations could occur from the cold engine operation due to low exhaust gas temperatures during low load operation. With the aid of power-split e-CVT, quick load changes for rapid acceleration and deceleration can be met by the electric drive power, and the amount of compensation fuel in transient conditions on the engine can be mitigated significantly with stable air-fuel ratio control. Furthermore, a warm-up control strategy and an exhaust heat recirculation system are optimized to activate the catalytic converter as fast as possible. With these optimizations, the Toyota DHE broadens the range of conditions to meet AT-PZEV, the most stringent emission regulation in the United States.

2.2 Honda Gasoline DHE

A 2.0L gasoline engine has been developed to dedicatedly and effectively suit a full hybrid system for medium-size cars. Similar to the Toyota DHE, it is reported that Atkinson cycle, cooled EGR, and enhanced exhaust system with quick warm-up controls are engineered for the Honda DHE. Table 2 presents the technical specifications of both Honda DHE and the base Honda engine. Both engines have about the same size, while DHE includes more fuel-efficient technology. In the following edited description majorly based on (Yonekawa et al., 2019; Ueno et al., 2000), the more focus goes to presentation of operation modes and those corresponding controls to enhance the DHE performance.

Engine Type	Displacement (cc)	Cylinder	Bore× Stroke (mm)	Valve Train	Intake Closed Timing (°CA)	Compression Ratio	Maximum Power	Maximum Torque	Emission Regulation	Major Technologies
Dedicated hybrid engine (DHE)	1997	Inline 4	81X96.7	VTEC & E-VTC (intake) Finger rocker arm/HLA (exhaust)	(N/V)	13:1	105KW	165Nm	SULEV20	Atkinson cycle Cooled EGR Electric water pump
Base engine	1998	Inline 4	81X96.9	VTEC (intake) Rocker arm/rocker shaft (exhaust)	(N/V)	10.6:1	115KW	192Nm	EURO5	VTEC

One key mechanism is Honda's variable valve timing and lift electric control (VTEC) to enable the use of two different cam profiles during operation. The "standard" cam profile has normal duration valve lift for power and engine start, while a fuel economy (FE) cam profile with long lift duration is used to enable Atkinson cycle operation. The optimal use of the two cam profiles is selected based on engine loads, as shown in Figure 4 (modified from Yonekawa etc., 2013). The FE profile use is maximized until it can no longer produce the required output. This engine also includes exhaust side finger rocker arms with Hydraulic Lash Adjuster (HLA) for reduction of weight and friction. According to different load conditions, the DHE can operate in either cam or FE mode to provide the most efficient power to a vehicle. In general, high load needs the engine to work in hybrid mode, while it is necessary to avoid running the engine only under low loads. In-between, the engine can deliver power at the best efficiency to wheels directly in the medium load, especially at high cruise speeds. It is also observed that the peak output with better fuel consumption is produced from output cam. FE cam inherently has higher return flow because of its wide duration, and thus lowers the fuel efficiency at the large torque area. In order to get high torque, FE cam needs to reduce EGR. But in other torque areas, FE cam's wide duration can help to reduce pumping loss by effect of Atkinson cycle. During the engine start, output cam is used to contain feed emission. The combustion with output cam is more stable to allow much retard of ignition timing. In this way, the output cam produces just half of the amount of HC with FE cam.

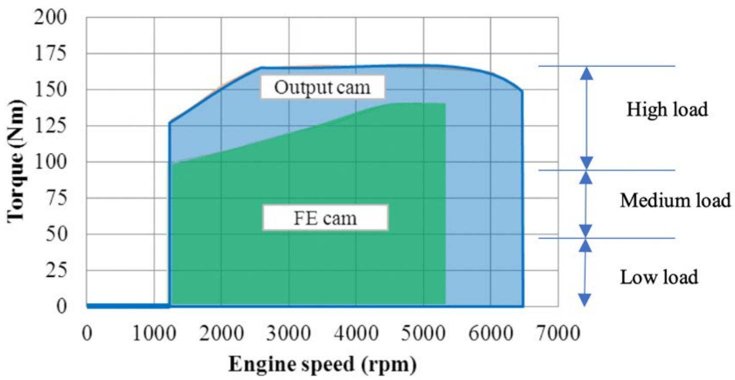


Figure 4. Working loads versus cam modes of DHE from Honda

During the high-load hybrid mode, VTEC and cooled EGR are used together to enhance the fuel economy. A high tumble port increases the tumble ratio from 0.73 (base) to 1.40 (DHE) to offset the slow combustion speeds of cooled EGR. This improves BSFC by as much as 5 g/kWh at medium load, where the hybrid system mostly goes to engine drive mode. Since an optimal reduction of pumping loss can be established via IVC retard and EGR, the control strategy that maximizes fuel consumption can be determined according to changes of the engine load. Therefore, lower fuel consumption can be realized with application of FE cam and VTEC. In another perspective of a high load condition, introducing cooled-EGR gas decreases combustion stability. Thus, the environmental changes such as exterior temperature, atmospheric pressure, and humidity can create significant challenges to warrant best BSFC. The Honda DHE system adopts practical control strategies to adjust the change of exterior environment for better fuel consumption. EGR control refers to the established EGR mass in standard environmental conditions as reference signal, and makes adjustment of the intake air amount according to changes of atmospheric pressure. The EGR flow feedback system uses that adjusted EGR mass to maintain the differential pressure. Operating point control can adapt the operating line according to atmospheric pressure. Two operating lines at normal condition and an ultimate high-altitude condition are set up. An optimal operating line for control is obtained by interpolating those two prepared lines with the measured atmospheric pressure. As such, fuel consumption performance can always be optimized regardless of altitude change. Torque control is to compensate the torque reduction which occurs at high load domain in high temperature condition. In a high compression ratio engine, retard of ignition timing is applied to decrease the torque to avoid knocking. Such torque control serves to secure drivability and fuel efficiency even in severe conditions.

In the medium load, the hybrid system mostly goes to engine drive mode. Since an optimal reduction of pumping loss can be established per IVC retard and EGR introduction, the control strategy of fuel consumption can be determined according to changes of the engine load. Therefore, more efficient fuel consumption can be realized with application of FE cam and VTEC.

Overall, as shown in Figure 5, Honda DHE improves 10% of fuel efficiency compared to the base engine. Atkinson cycle and cooled EGR system combined with the VTEC system help to deliver peak power 105 kW and min BSFC 214 g/kWh.

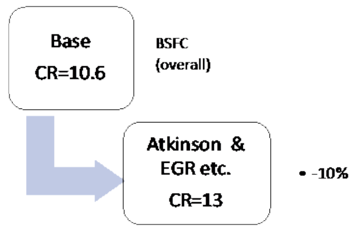


Figure 5. Fuel efficiency improvement of Honda DHE

The Honda DHE is equipped with a dual catalyst system to minimize the emission at engine startup. A close-coupled (CC) catalyst is mounted to the engine body and an under-floor (UF) catalyst is mounted underneath the cabin floor. The control process for the exhaust system is first to use a small amount of feed emission until the close-coupled (CC) catalyst warms up, and then increase the engine load to send high-temperature exhaust gas to warm up the under-floor (UF) catalyst. The new catalyst warm-up control manipulates engine operation using the load of a motor to attain a clean engine startup. Figure 6 shows the PHEV with this DHE can achieve SULEV20.

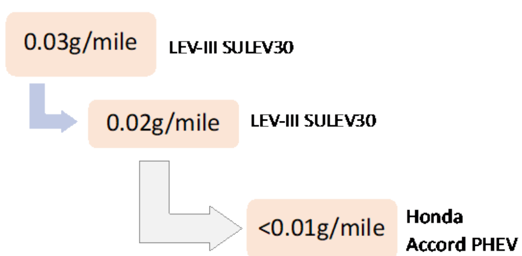


Figure 6. Emission achievement with Honda DHE based PHEV

2.3 Advanced Diesel Engines for Commercial Vehicles

Compression-ignition engines today are the most prevalent power plant type for medium heavy-duty vehicle (MHDV) with high annual vehicle miles traveled because of their high efficiency in comparison to gasoline (spark-ignition) engines. Even though emissions aftertreatment adds the total costs and poses great challenges for technology advancement, new developments in compression-ignition engines (diesel engines) are still progressing forward steadily due to the government-industry partnership. The 21st Century Truck Partnership (21CTP) in USA has demonstrated the technology feasibilities of achieving 50 percent BTE in real-world packaging and on-road conditions in the first phase (NAS, 2019). The new target for the second phase is setting to reach 55% BTE. The technologies deployed potentially might include low-temperature combustion, optimized bowl, injector, and heat transfer, as shown in Figure 7. One effort to improve the combustion process is to shorten the combustion interval so that during expansion the effective work could be improved while reducing the heat loss. The combustion enhancement might boost three percentage points of BTE. Noteworthy is that waste-heat recovery (WHR) can be effective but not practical yet due to packaging and cost today. Any fuel-efficient technology must help to meet emissions regulations while effective for the engine efficiency improvement.

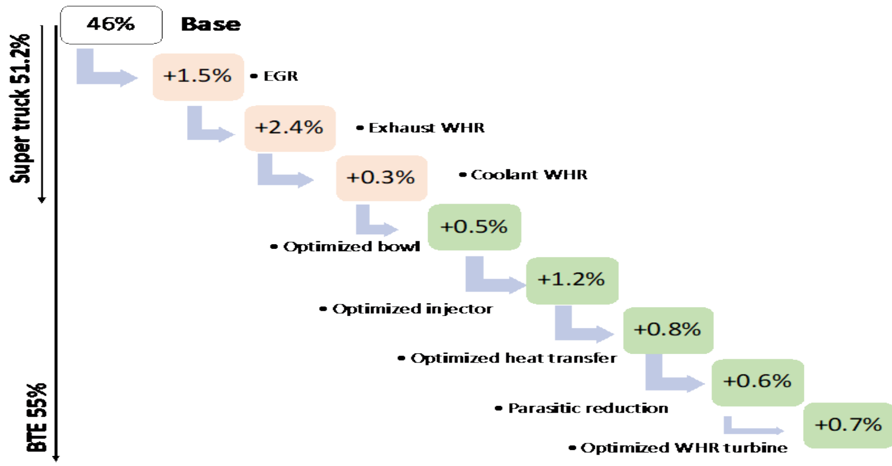


Figure 7. Diesel engine technology from 50% to 55% BTE

EPA has set Phase II regulations, commencing from MY 2021, for light heavy-duty (LHD), medium heavy-duty (MHD, Classes 6 and 7), and heavy heavy-duty (HHD, Class 8). Table 3 presents the target numbers of fuel efficiency and CO2 on HHD. The baseline is 455 g/bhp-hr and 4.4695 gal/100 bhp-hr, respectively. That clearly means that for the MY 2027 engines, a 5.1 percent reduction on average is required beyond the Phase 2 baselines. Correspondingly, the percentage improvement over MY 2021 and MY 2024 are 1.8 percent and 4.2 percent reductions in fuel consumption and CO_2 emissions over Emissions Test cycle (SET), respectively. In this EPA regulation document, it is pointed out that generally the contributing efforts can go to improving the internal combustion process and reducing energy losses in order to meet the Phase II standards. More specifically, the following key means have been identified to improve fuel efficiency (EPA 2016):

- Combustion optimization
- Turbocharger design and optimization
- Engine friction and other parasitic loss reduction
- Exhaust after-treatment pressure drop reduction
- Intake air and exhaust system pressure drop reduction (including EGR system)
- Engine down-sizing to improve core engine efficiency
- Engine down-speeding over the SET, and in-use, by lug curve shape optimization
- Waste heat recovery system installation and optimization
- Physics model based electronic controls for transient performance optimization

EPA makes an assessment on the application rates of the above listed technologies and recognizes that adoption of such as waste heat recovery and engine downsizing will be at lower application rates in the Phase II time frame. Beyond the engine efficiency, EPA directs the application of mild hybrids as "*Pre-transmission hybrid*" to improve the engine performance as well. Basically, either integrated or non-integrated mild hybrid systems offer idle-stop functionality and a limited level of regenerative braking and power assist. These systems replace the conventional alternator with a belt or crank driven starter/alternator, and may add high voltage electrical accessories (which may include electric power steering and an auxiliary automatic transmission pump). The adoption rate of all mild hybrids is predicted to be about 12% in MY 2027. As such, it is understandable that there is no significant development of diesel DHE yet.

Model year	Standard	Heavy heavy-duty	Medium heavy-duty
2021–2023	CO_2 (g/bhp-hr)	447	473
	Fuel Consumption (gallon/100 bhp-hr)	4.3910	4.6464
2024–2026	CO_2 (g/bhp-hr)	436	461
	Fuel Consumption (gallon/100 bhp-hr)	4.2829	4.5285
2027 and Later	CO_2 (g/bhp-hr)	432	457
	Fuel Consumption (gallon/100 bhp-hr)	4.2436	4.4892

This section highlights a brief overview of the technology paths of both diesel and gasoline engines for higher fuel efficiency. The progress of the gasoline DHEs has changed the landscape of electrifying the powertrains for competitiveness. At the same time, the diesel engines are challenged to meet stricter regulation standards of fuel efficiency, emissions, and CO2. The success story of gasoline DHEs can be a foreseeable technology roadmap for higher performance diesel DHEs.

3. Dedicated Hybrid Transmission of Passenger Cars

Conventional transmission is the core piece within the powertrains to convert the power from internal combustion engines to driving forces on the wheels. The inherent challenges with the conventional powertrains are to raise the fuel efficiency and reduce the harmful emissions to meet the upcoming stricter engine regulations. For example, during the cold start or low-power mode, the engine emissions could be much higher than at normal drive. To tackle this kind of emission issues, earlier development of drivetrain hybridization for passenger cars used to adopt conventional drivetrain configurations by integrating an electric machine (maybe more than one) along the power path beyond advancement of combustion improvement. The hybrid technology enriches the solution portfolio to address the performance enhancement from such as start/stop technology, braking energy recuperation, and zero-emission electric driving in low-power mode. This add-on hybrid configuration increases the cost sharply.

Up to date, it is evident that pure ICE drives cannot and will not be able to meet the upcoming and future legislative regulations of emissions and CO2. Since in the foreseeable future full electric vehicles cannot satisfy the requirements on the range and speed of recharging for daily drives, ICEs will continue to be the principal motive power for years to come. One of the proved solutions to improve engine usage is hybridization. The pioneering volume production of hybrid vehicle systems from the technology-leading Toyota and Honda leads to evolutionary landscape change of powertrain electrification. Electric propulsion systems become an integral part of the vehicle-driving system. The industry has shown that add-on electrification could not be a sustainable solution over a life cycle for volume vehicle applications. It is imperative to innovatively combine electric propulsion and ICE into an integrated cost-effective solution in terms of packaging, weight and TLC (total life cost). This leads to development of dedicated hybrid transmissions. By definition, DHTs are assumed to embrace dual motive powers to offer different operational modes such as electric drive, engine drive, and hybrid drive (parallel and serial). Both electric propulsion and ICE complement each other in terms of functionality and efficiency. In the following section, two DHTs with a great success in today's automotive market will be briefly described.

3.1 Planetary-based Toyota DHT

The Toyota eCVT is basically an integration of a motor-generator to a DHE (elaborated in Section 2) through a set of epicyclic gearset, while another traction motor on the driveshaft is responsible for electric drive. The motor-generator replaces both alternator and starter motor. Both motors can convert electricity to motion (mechanical power) or vice-versa. The planetary gear based DHT allows the engine to run at the optimal efficiency speeds but independent of wheel speeds because of the eCVT functionality. Since 1997, Toyota has developed five DHT generations as shown in Figure 8. It can be observed that all five systems adopt the same configuration to apply a planetary gear to integrate MG1 to the engine (DHE). With the ring gear to output the combined power to the driveshaft, the engine is connected to the carrier while MG1 to the sun gears. The governing equation of the planetary gear based eCVT in physics follows

$$(Z_R + Z_S)\omega_C = Z_S\omega_S + Z_R\omega_R \tag{1}$$

where Z_R and Z_S are the number of ring and sun gears, respectively.

Theoretically, even though the vehicle speed operates in a wide range from zero to high speeds, the engine speed (on the carrier) can be constant by properly tuning the MG1 speed. As such, the integrated MG1 and engine complement each other on the driving power supply to form an electronically-controlled continuously variable transmission. This eCVT based hybrid allows to provide extra torque under the constant vehicle speed through MG2 or change the vehicle speed at a constant torque with MG1.That means the engine can float away from vehicle-speed variations. Since the electric drive can meet instantaneous power demands to even out the load variations on the engines, engines can be set to meet the average driving power rather than peak powers. Therefore, downsize becomes feasible without potentially reducing the driving performance. On braking side, regenerative braking mitigates the wear of mechanical brakes for less maintenance and longer service. As a matter of fact, this eCVT architecture not only can accomplish fuel-saving but also reduce the wear-and-tear on the ICE with more steady speed operation.

The first generation is only used for Prius cars for significantly higher efficiency than the conventional cars in the late 1990s, but the accelerating performance is marginal because MG2 has 1:1 ratio without torque multiplication to the driveshaft. The second generation utilizes another planetary gear with a fixed carrier to offer 2.5:1 reduction ratio for MG2. The objective is to offer torque multiplication for vehicle launch while increase the power density of the motor MG2 (i.e., downsize) for more cost-effective design. The 2nd generation of hybrid systems are applied to other Toyota models and brands like Lexus as well. The 3rd generation uses two clutches (or brakes) on two planetary gearsets to form two speed gear ratios of 3.9 and 1.9 for MG2. The engine has a different transmission path from MG2. This configuration provides more room to optimize low- and high-speed driving regimes, respectively. It is reported that this 2-speed design helps to further reduce both the size and cost. Another benefit is to avoid overspeed operation of MG1 and maintain the engine speeds in the relatively narrow region for higher efficiency.

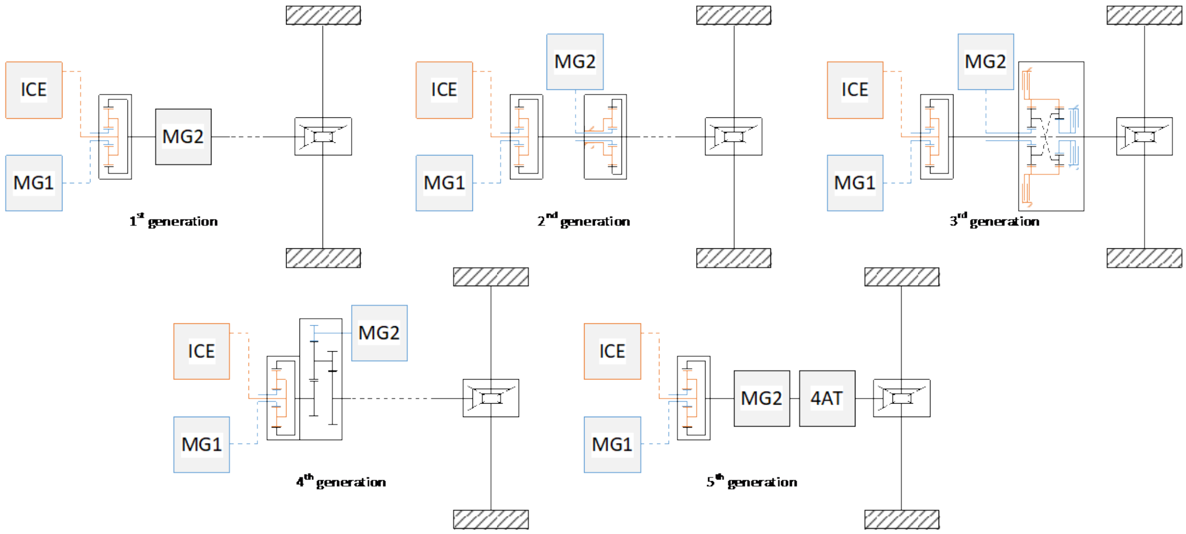


Figure 8. Five generations of Toyota DHT architectures
(Note: MG1=motor generator 1, MG2 = traction motor, 4AT = 4 speed automatic transmission)

Fourth generation connects the traction motor through parallel gears to replace the planetary gearset in the previous models. Notably per the report from Green Car Congress, the motor weight reduced 20% with a better power-to-weight ratio, and the system achieves approximate 20% reduction in mechanical friction losses. Furthermore, helical gears are used in this generation of hybrid transaxles. The benefit is that the system can accommodate higher mechanical loads and is smoother and quieter compared to the earlier transaxles using spur gears.

The significance of the fifth generation as Multi-Stage system is the involvement of four-speed automatic transmission attached to the eCVT output ring. In the 3rd generation, only MG2 gets a two-speed reduction. Since both MG2 and engine run through an automatic four-stage shift system, this keeps MG1 from hitting its redline, the cutoff for electric-only driving, and allows for EV driving as fast as 87 mph (up from 40 mph in previous hybrid models) ("Lexus Tech"). In the SAE paper by (Kato et al., 2017), the system layout is elaborated with architectural configuration, system specification, and comparative study with regard to the 3rd generation. Fifth generation offers higher efficiency in either low speed or highway drive. Notably, a control replicating the feel of a ten-speed gearbox is developed to enhance dynamic drivability in line with the intentions of the driver when accelerating. A model-based shift control for the power split device is based on the optimal control theory to operate the multiple-input and multiple-output hybrid system. Eliminating the rubber band effect during the shifting process significantly improves driver feel and control.

Based on the materials reviewed, Toyota DHT systems employ the high voltage battery from 0.9 to 2kWh and gradually migrate from NiMH to Li-Ion. Usually the battery is recommended to run around 50% SOC for longevity and performance. Active air-cooling system is used for the battery thermal management. The power density of the battery packs increases significantly through generation iteration. The DC voltage systems usually provides max 650Volt DC, and nominal 288, 24 and 12 Volt DC. The converter can boost the hybrid battery's power from 288 volts up to 650 volts as needed for maximum power.

The technology progress of Toyota DHTs shows that the transmission architecture is the key to establish the optimal utilization of both electric drive and engine. The eCVT system leads the way to develop DHE for higher operation efficiency within the DHT framework. Traction motors need reduction gears to downsize for higher power density. The gear reduction device made of parallel gears has lower frictional loss than planetary gearset ones. Electronic controls including inverters also need to reduce power losses for better efficiency. Finally, it seems that multi-speed transmission could be an integral part of the hybrid systems with application of a power split system to enhance the vehicle drive performance.

3.2 Gearbox-less Honda DHT

Hybrid system architectures can be drastically different from each other in order to improve the vehicle operation efficiency. Honda has developed a two-motor hybrid system without using step-geared transmission at all. To further boost the vehicle efficiency, the brake booster, air conditioner, and cabin heater are all electrically powered (Ohkubo et al., 2013). So far, all three generations of Honda DHT have the same system architecture "series-parallel hybrid" as shown in Figure 9. Generation iteration emphasizes majorly on the efficiency improvement, packaging size, electrical system upgrade, and cost-performance enhancement. Clearly this direct-drive DHT system has no transmission in the conventional sense, and there are only four parallel gearsets with fixed ratios along the drivetrain path. Honda reports 46-80% reduction of friction compared to a conventional automatic transmission. By controlling the clutch, this DHT has three propulsion modes: electric drive mode, engine drive mode, and hybrid mode without involvement of any gear shifting. Notably, unlike the Toyota eCVT based DHT, there is no rubber band effect while accelerating the vehicle with the engine droning at high speeds. According to the research reports (Higuchi, Sunaga, etc., 2013), this hybrid system is claimed to consume 70% less fuel than a conventional gasoline powertrain.

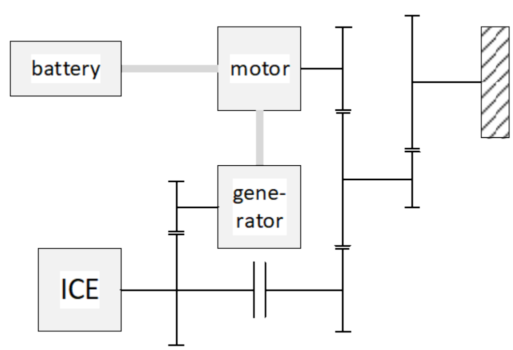


Figure 9. Configuration of Honda DHT System

The DHT system uses a DHE which adopts Atkinson cycle, two-mode variable intake-valve-timing and -lift system, and Recycling cooled exhaust gas (EGR) as discussed in Section 2. Within the hybrid system, there are two electric machines, one motor and one generator. The AC motor can run at a max speed of 12,000rpm with a full torque from 0 to 4000rpm. The motor provides propulsion during electric and hybrid drive mode. During decelerating and braking, this drive motor can act as a generator to recuperate the kinetic energy to the high-voltage battery. The AC generator does not drive the wheel directly but can provide the drive motor with electric current to augment or replace juice from the battery during cruising. The other major function of this AC generator is to start the engine. Above 43 mph, this generator works as a motor to spin the engine up to speed. Then the clutch locks up to let engine drive the wheels directly with the engine speed proportional to the vehicle speed. Beyond this speed, the engine runs in its most efficient operating zone by adjusting both motor and generator accordingly through an intelligent electronic controller.

As elaborated in the paper of (Higuchi and Shimada, 2013), the IPU (Intelligent Power Unit) uses the passive air cooling located in the trunk room, while the PCU (Power Control Unit) upon eCVT and the engine have separated water cooling circuits. The PCU module includes inverters, a VCU (Voltage Control Unit), ECUs (Electric Control Units), various sensors and condensers. ECUs control a motor and a generator. The VCU amplifies the battery voltage for inverters. The speed-torque curves of a motor are changed by adjusting the battery voltage, i.e. the motor operating voltage. Figure 10 presents the transition of the motor efficiency maps and the maximum outputs per the motor operating voltage of high voltage (HV) and low voltage (LV). That means a high-torque and power motor is realized without expansion of motor size but by raising the inverter voltage. In fact, adjusting the motor operating voltage can align the motor efficiency maps to agree with actual duty cycles for best system efficiency. For example, lowering the motor operating voltage can achieve higher system efficiency in low load conditions of such as city drives. This relationship is an integral part of the DHT control strategy.

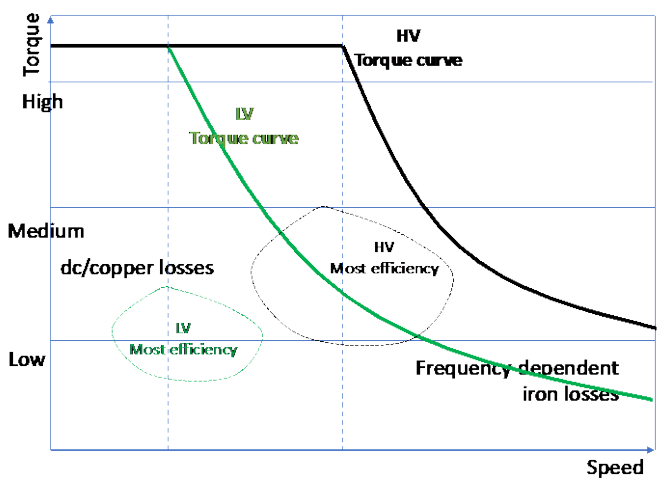


Figure 10. Motor efficiency mapping with voltage controls

With three propulsion modes, engine, motor and generator are holistically optimized to provide the best fuel efficiency according to the efficiency selection strategy, as shown in Figure 11. With a base reference of the flat-road load, drive mode efficiency map is prespecified as a 2D map. This efficiency map is applied to the mode switching control strategy (IDE, 2013). For each drive mode, “Engine drive”, “Hybrid Drive”, “Motor Drive” can be selected. It is worthy of noting that driving situations of such as cruise and slight acceleration should be an essential part of the mode shifting control strategy.

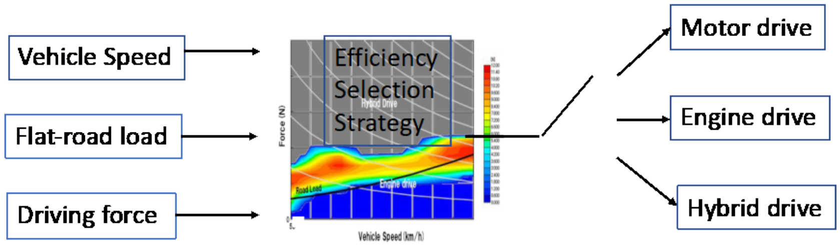


Figure 11. Holistic optimization of propulsion efficiency for Honda DHT

3.3 Series Hybrids

Another hybrid technology which should be reviewed is the series hybrid. The propulsion system is a full electric motor drive, as shown in Figure 12. The engine is mechanically decoupled with the driveshaft. MG1 works as generator only to produce electricity so that the engine could be connected electrically to the traction motor MG2. This allows the engine to stay at most efficient point and with a simpler emission control. The motor MG2 is designed as sufficiently powerful motor to provide full vehicle performance, and so is good to maximize the amount of regenerative braking, which is especially beneficial to the city drive with frequent stop and goes.

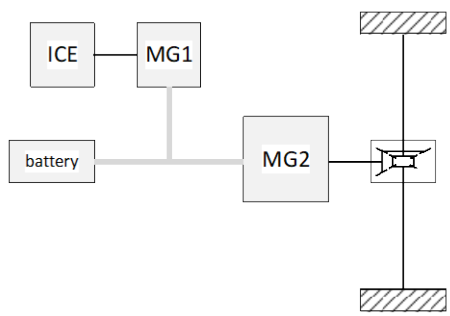


Figure 12. Series Hybrid (Range Extended) hybrids

The exemplary product for successful vehicle application is e-Power from Nissan. Since a1.2-litre three-cylinder engine generates electricity to either directly drive the electric motor or charge the 1.5 kWh lithium-ion battery, the cost is minimized in comparison to an electric vehicle due to a sufficiently large battery for a desired range. In addition, there is no need of an on-board charger for PHEV or EV.

The control strategy for series hybrids is relatively simple because there is only electric drive mode. The battery SOC is used to manage the operation of the engine/generator functions. The electricity in the system should be reserved to be able to provide the necessary acceleration as needed for powerful vehicle drive. The battery overcharge should be avoided during such as a long downhill drive. Similar to other hybrids, antilock braking needs to coordinate service brakes and motor regen braking. However, one of the critical technologies is to develop a highly efficient engine for the series hybrid. The engine technology under active development includes such as free-piston engine, 2-cylinder/in-line/4-stroke engine, catalytic generator, Wankel engine, wave disk engine, RCCI engine, and microturbine engine, to name a few.

4. Electric Hybrids for Commercial Vehicles

According to the statistical data published at https://afdc.energy.gov/data/, the commercial vehicles including trucks and buses are the major consumer of the fossil fuels as shown in Figure 13. While light-duty vehicles refer to wagons, vans, SUVs, and pickups, vehicles with short wheelbases (<121 in.) are generalized as cars. Except cars and light-duty vehicles, the rest of the listed vehicles in the figure comprises the commercial vehicle. Since the large amount of the annual fuel is used by refuse truck, Class 8 long haul truck and transit bus, fuel saving can be very meaningful for reducing the operation cost. Furthermore, Figure 14 presents fuel economy per gasoline-gallon equivalent (GGE) for the corresponding vehicles as shown in Figure 13. All the commercial vehicles have a single digit of GGE fuel economy. Considering their significantly larger fuel used annually and lower baseline fuel economy, hybridization of propulsion systems for commercial vehicles can dig out more potential for fuel savings than for cars and light-duty vehicles. Other benefits of hybrid vehicles can be emission reduction, lower level of GHG, quieter operation, and improved driving performance.

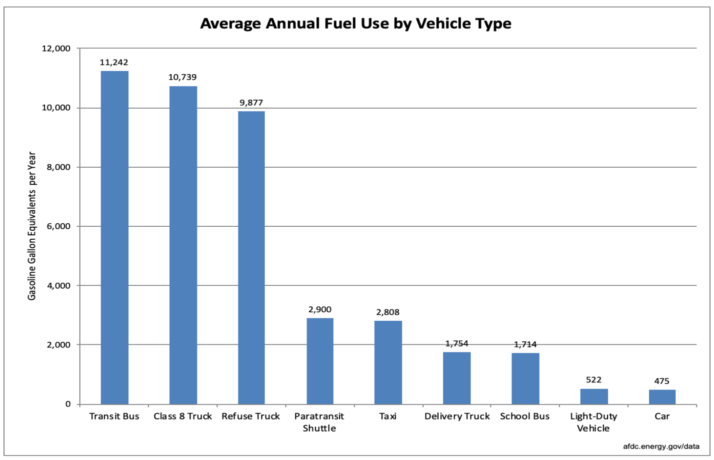


Figure 13. Average annual fuel consumption of various vehicles in USA

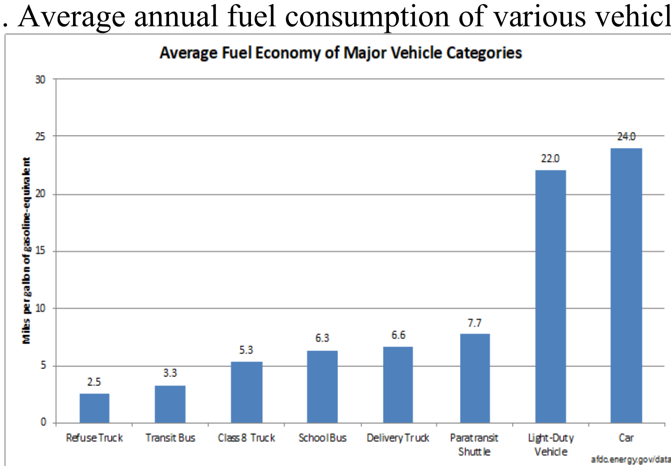


Figure 14. Average fuel economy of various vehicles in USA

It is worth noting that since the medium- and heavy-duty trucks possess a large curb vehicle weight and carry a heavy payload the kinetic energy is significant even at a low speed. Furthermore, the variation of vehicular kinetic energy can become more significantly sensitive to the road slope change compared to passenger cars. As such, a hybrid system for a large commercial vehicle requires a large capacity of electrification modules and components. Such electrical system can be frequently demanded to experience large currents to meet the varying road loads. Electrical components and wiring harness with higher electric power specification are much costlier. From the production perspective, there is a relatively low annual volume for every category of the commercial vehicles. Low production volume cannot help to effectively reduce the cost either. Consequently, the suppliers of electrified steering, braking and heating/cooling are not commercially available for enhancing the vehicle electrification competitiveness. All these combined factors lead to an unfavorable introduction of hybrid technologies to many trucks because of cost. Even though hybridization of MD and HD truck powertrains for industrialization has lagged behind car hybrids, there are some successful developments for niche applications of such as bus and delivery trucks. In this section, the corresponding dual mode and parallel hybrids are explained in the following.

4.1 Dual-mode Hybrids for Bus Applications

The most successful hybrid system for transit and city buses is the dual mode from Allison. Up to date, there are more than 8000 units on buses operated worldwide. The system uses two concentric three-phase AC induction motors and 3 planetary gear sets with one rotating clutch and one stationary clutch, as shown in Figure 15. The schematic diagram can be found out in (Grewe et al., 2007). An input damper is used between engine and the drive unit to transmit engine power to the transmission. The damper can absorb torsional vibrations inherent with engine operation. Hydraulic actuators are applied to engage/disengage both rotating and stationary components.

This hybrid drive unit can offer two modes of either parallel or series. Series mode: through opening the rotating clutch, Motor A is spun by the engine to produce electricity as range extender or stays without rotation while Motor B can drive the vehicle electrically, for example, to launch the vehicle in most cases; Parallel mode: all the three driving modules of engine, Motor A, and Motor B are connected to the driveshaft mechanically to maximize the energy management to the best efficiency. Both motors can work as generator for regenerative braking. In general, generating occurs when mechanical rotation frequency is greater than stator field frequency, while motoring occurs when stator field frequency is greater than mechanical rotation frequency (from the SEPTA report). Actually, since the parallel mode allows three driving devices (engine and two motors) work together independently and simultaneously, one motor at least can work as generator if necessary. Then the electric path can include generating and motoring concomitantly. Thus, such working mechanism is a combination of series and parallel, which might be called as Series-Parallel mode.

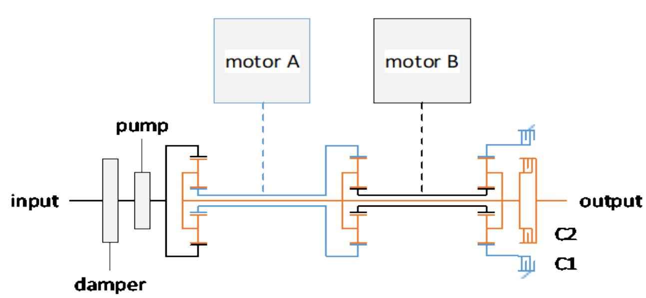


Figure 15. Mechanical layout of Allison dual mode hybrid system (courtesy of SEPTA)

According to the system specification from the Allison hybrid website, other hybridizations include DC to DC converters with electrical efficiencies of 91-95% to replace large belt-driven alternators on the engine. The converter powers not only traditional 12/24-volt busloads, but also accommodates the electric radiator, charge-air-cooling and hybrid drive electric fans (by eliminating hydraulic fan drives). The high efficiency converter can offer 250 and 300 Ampere-at-Idle, which are equivalent to some 400 up to 500 amperes belt driven alternators, respectively. With average 750 start-stop cycles per day the bus hybrid system can effectively reuse the recovered kinetic energy electrically. All these applied hybridizations help to accomplish more than 25% fuel savings dependent on the bus duty cycles. Beyond that, this hybrid system can be applied to medium-duty trucks for distribution, refuse, utility and shuttle bus applications as well. Not only does the hybrid system embrace full regenerative braking, higher performance and reduced emissions, but also provides a quiet, smooth and efficient ride.

4.2 Parallel Hybrids for Delivery Truck Applications

The research on parallel hybrids for commercial trucks has been active worldwide. The leading performer among the global industry is Eaton. The production parallel hybrid has been adopted at a noticeable volume for buses, MD and HD trucks globally. The technology development of parallel hybrids for delivery truck application is exemplified in the following. Figure 16 presents the basic layout of the Eaton parallel hybrid on a delivery truck. This pre-transmission parallel hybrid uses one single electric motor/generator (MG) installed between the engine/clutch and the automated manual transmission (AMT). The auto clutch can separate the engine operation and motor drive mechanically. Here are some significant operations with this hybrid system architecture:

- Open clutch: the vehicle can go to a pure electric drive mode. As such, the hybrid vehicle uses the motor to launch the vehicle as normal drive function. The engine would not be involved so that emissions can be avoided. Only if the electric drive system cannot work properly, the vehicle goes to the limp mode and use the engine power for vehicle launching.
- Close clutch with a neutral gearbox: the engine and motor/generator can produce electricity for battery charging or electric PTO, while the vehicle is stationary. This function is especially useful for utility trucks.
- Close clutch and geared transmission: the hybrid operation can optimize both the electric motor and the combustion engine to work in tandem through the transmission to the best propulsion efficiency.

In general, parallel hybrid systems for trucks are developed by integrating a motor/generator with an existing AMT. This kind of hybrid development can avoid procuring a new transmission to save the cost. The motor and engine torque can be multiplied through the transmission gearbox to improve the driving performance. The electric drive can take advantage of kinetic energy management to save the fuel consumption on vehicle drives. The major compositions of the Eaton parallel hybrid system are

- 6-speed automated manual transmission and 44 kW traction motor/generator
- An auto clutch with an electrical actuator
- 1.9 kWh lithium-ion battery pack (or scalable capacity as needed)
- A separate hybrid control module with J1939 CAN

- Cummins 6.7L ISB in-line 6-cylinder diesel (commonly used) as well as other options
- Auxiliary Power Generator (APG) Inverter for on-board equipment and 120V auxiliary power

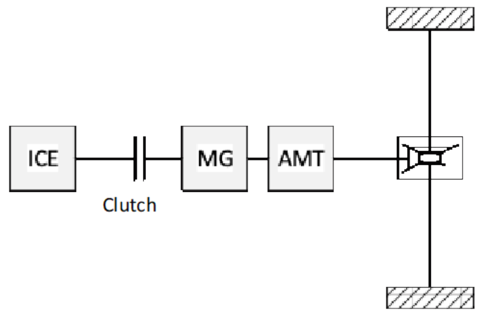


Figure 16. Parallel hybrid system for delivery truck

As the commercial trucks have many configurations for different unique applications, flexible architecture is critical for commercialization (Cornils, 2009). The hybrid system has flexibility to meet diverging needs by enabling electrification across many vehicle platforms while simplifying the integration effort. Engine can be gasoline or natural gas beyond diesel. Pure electric drive beyond vehicle launch might be required from the end customers so that a large pack of battery is needed for zero-emission drive. Unique functions of emergency power, anti-idle, reefer and others should be optional for further synergetic integration. Overall, it is important to enable OEM application differentiation while simultaneously maintaining commonality on core components for cost saving. Flexible technology boosts the volume, and the large volume contains the cost for commercialization success.

Among the full hybrids, the series hybrid has also been developed for commercial truck applications. Since the series hybrid decouples the engine and vehicle speeds, the engine can run at its most fuel efficiency region with minimized emissions. Due to the large power demands for sustained gradeability, traction motor and engine/generator (including battery pack) have to be sized up accordingly. This means inefficiency and added weight as well as significant cost. More efficient series hybrid solutions are still under exploration. Other cost-effective hybridization technologies can be micro-hybrid, which is typically a belt driven alternator-starter system on the engine. The engine can shut off as soon as the vehicle stops, and automatically restart as the driver presses the gas pedal. Fuel saving is about low several percent. In addition to accessory electrification on engines, mild hybrid integrates sufficiently powerful electric motor/generator to the engine so that the vehicle drive could be assisted with electric drive by using the recovered electric energy from decelerating or braking. That leads to fuel saving of around ten percent or more. In the publication (Benjey etc., 2015), an electrically assisted variable speed (EAVS) boosting system is presented as a cost-effective hybrid and downsize solution for classes 2b, 3 and 4 with aggressive duty cycles. Within a hybrid system framework, an electric waste heat recovery for heavy duty line haul applications is evaluated (Vinjamoor etc., 2015) as a source for electric energy through a high-speed generator. The electric energy (also from braking energy regeneration) can be used to reduce engine load during peak power requests to deliver the potential fuel economy benefits of commercial line haul vehicles. It is predictable that more innovative hybridization technologies will be developed as the legislative regulation becomes more and more stringent for protecting the environment.

5. DHT Development Challenges

Regardless of passenger cars and commercial trucks, electric hybrids have been accepted widely as a key enabler to improve fuel efficiency as well as high quality drive performance. The hybrid systems have similarities of coordinating engine and electric drive to accomplish the design objectives as well as meeting the end customer's expectations. For the application purpose, there are two major hybrid system categories, add-on and dedicated hybrid. The following sections discuss the key perspectives of DHT technology progress including industrialization challenges.

5.1 Architecture Challenge

The add-on architectures, as shown in Figure 17, include supplementation of the electric drive onto those production ICE based powertrains. Basically, no drivetrain components need to be re-designed. The location of the motor/generator defines the characteristics of these five hybrid powertrains. P0 and P1 are majorly used for the engine start-stop function as micro/mild hybrid systems. Both are applied to minimize the idling time. P0 prefers adopting a cost-effective 12/48 voltage system, while P1 may go with a higher voltage to provide drive-assisting. Usually P2/3/4 refer to full hybrids by offering the electric drive capability. P5 could be referred to as motors-in-wheel (WIM) for torque vectoring on wheels. The full hybridization can help to revolutionize efficient use of the combustion engines: create opportunities of zero-emission vehicle launch without need of involving an engine, provide more operation time of idling an engine as much as needed, avoid or reduce light-load engine running for minimizing emissions, and apply recuperated kinetic energy from decelerating or braking for vehicle drives. Overall, all these add-on hybrid architectures can simultaneously improve fuel economy, emissions, and performance to a different degree, but the system functionality intertwines much unnecessary redundancy between engine and electric drive with increased complexity and cost. Since up to date hybrids are mostly used for niche applications, modular addon solutions have advantage for a low volume market. It is noteworthy that P5 adds more unsprung mass which can compromise ride comfort and handling performance. Furthermore, the challenge for P0 to P4 architectures is that the heavy inheritance of production powertrain contents sets a boundary to further develop benefits of using electric drive systems, though such add-on hybrids take advantage of existing transmissions that have multiple transmission speeds and small ratio steps.

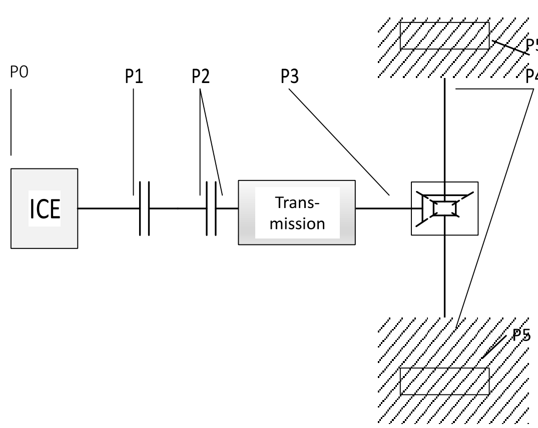


Figure 17. Add-on hybrid architectures

DHT systems have achieved a great success in the passenger car market, as detailed in Figure 18. The main contributions are made by eCVTs from Toyota and Honda. For commercial vehicle, the dual mode hybrid from Allison for the bus application is another successful case for DHT. Thus, a DHT seems to be of a choice. However, more effective hybrid architectures for industrialization are still under exploration. To deal with the existing challenges from combustion engines, DHT should be able to utilize the engine's sweet spots (areas of low specific fuel consumption) to best meet the driving cycles, down-size the internal combustion engines for better packaging, and down-speed the engine operations for higher efficiency with less friction losses (Fischer, 2015). DHT can embed the transmissions with larger ratio spreads and less speeds. The reduction of the number of speeds can definitely contribute to product cost reduction. Furthermore, DHT can become more compact design by adopting high-speed and -power-density motors. The eCVT based DHTs, discussed previously, demonstrate that the transmission can be gearbox-less or have a very limited number of fixed gear ratios. Figure 19 (retrieved from an SAE publication by Grewe etc., 2015) exemplifies the planetary gearset based DHT architectures. Actually, Toyota hybrids have evolved along a similar path. The earlier version of eCVT focuses on DHE development for higher efficiency, while the latest Toyota hybrids include fixed-ratios transmissions for more powerful drive-performance.

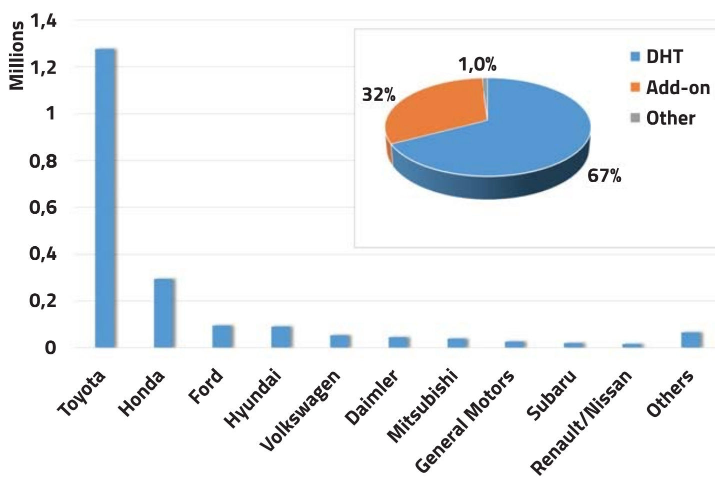
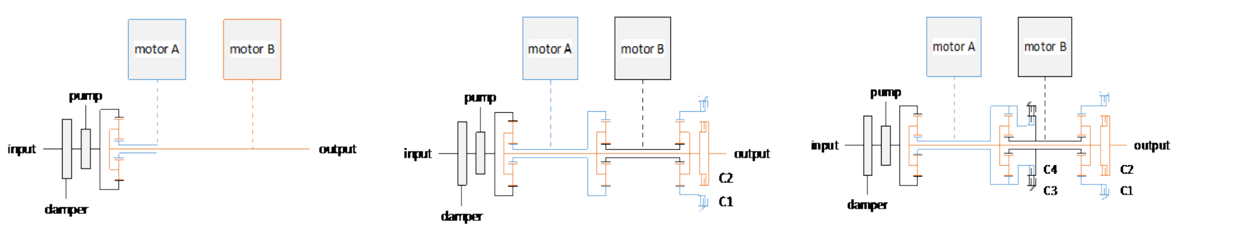


Figure 18. 2014 Full hybrids in the global market from IHS (from CTI MAG, 2015)



(a) One mode eCVT (b) Dual mode hybrid (c) Dual mode with fixed ratios

Figure 19. DHT architectures with eCVT application (Grewe et al., 2015)

Vehicle performance depends on the propulsion system configuration. The mild hybrid P0 architecture improves efficiency without frictional belt loss due to the absence of a belt drive; crankshaft-mounted concentric architecture (P1) can be more effective than P0 but with a limited torque capability; shaft mounted parallel hybrids (P2/P3) can provide more efficient drives from engine and motor through mechanically connecting or decoupling, but increases the axial length for packaging; P3 needs a much larger torque motor for competitive performance than P2; axle mounted motors (P4) can complement torque-vectoring AWD in addition to hybrid drives like the other hybrid systems, and the function safety design is formidable. Usually, locating motors closer to wheels would be able to provide more hybrid functionalities than standard functions of start-stop, recuperation and shifting of operating points of the ICE. As presented in (Atluri etc., 2014), in order to attain the hydrocarbon emission requirements of Tier 2 Bin 2 standards, three diesel hybrid architectures are studied by integrating hybrid strategy, combustion strategy and aftertreatment system control strategy. The results show that the benefits are subject to driveability, cost, the level of engine downsizing and the degree of hybridization. It is well recognized that by applying a holistic optimization the hybrid powertrains can offer many further potentials to meet stringent legislative regulations as well as containing complexity and cost. For the commercialization success, the architecture challenge is: what's the best configuration? With competing architecture, the DHT volume can be expected to exceed or even completely replace conventional powertrains.

5.2 Engine Technology Challenge

Dedicated hybrid engines offer a potentially unique opportunity to improve efficiency and emissions beyond simply adapting engine design optimization to the requirements of hybrid operation. Combustion research is one of the very core enablers for advancing the engine technology. Another imperative demand is to further promote compact design, especially for range extender applications.

5.2.1 Advanced Combustion Technology

Several advanced combustion strategies have been developed over the past few decades and are broadly categorized as low-temperature combustion (LTC). One of the reasons that an LTC strategy has yet to reach wide-ranging mass production is that they tend to be difficult to control in real-world transient operation. It has also proven difficult to achieve LTC combustion over the entire speed–load operating range of a given engine, which then requires two distinct combustion strategies. This 'dual-mode' approach further increases control complexity since the engine must automatically switch between LTC and a more conventional combustion strategy.

Early research into novel LTC strategies considered lean-homogeneous mixtures driven by chemical kinetics. Several research groups have demonstrated significant emissions and efficiency improvements compared to spark-ignited (SI) or compression ignited (CI) combustion for both two-stroke and four-stroke LTC variants (Onishi, 1979, Noguchi, 1979, Najt, 1983, Thring, 1989). Though different terms have been used, homogeneous charge compression ignition (HCCI) is the widely accepted term for this type of combustion. Although the potential efficiency benefit of HCCI is high, the limited range of operation is a substantial limitation. Hybridization has been shown to have a unique synergistic impact on improving efficiency beyond either hybridization or advanced combustion strategies alone (Lawler et al., 2011). Figure 20 depicts the results of a control strategy optimization for an electrified SI+HCCI powertrain. It can be observed that the coupling of hybridization and advanced combustion significantly improves fuel economy beyond either hybridization of an SI engine or an advance combustion strategy alone.

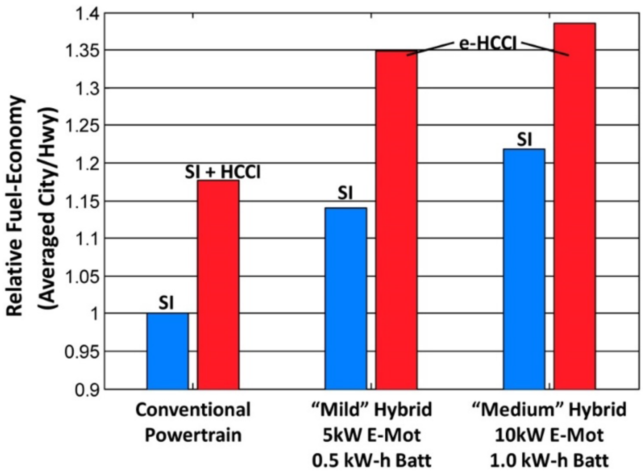


Figure 20. Fuel economy comparison with various combustion strategies (Lawler et al., 2011)

Several strategies have emerged that at least partially mitigate many of the obstacles facing HCCI. Researchers have investigated the use of a spark discharge to increase ignition energy (Urushihara et al., 2005). The in-cylinder conditions can be tuned such that the spark produces a flame kernel and a propagating flame. The additional energy from the deflagration flame then triggers autoignition in a significant portion of the charge. This two-stage combustion (spark-initiated flame propagation, then compression ignition) is called spark-assisted compression ignition (SACI). This strategy leverages the slow burning of the flame to reduce peak pressure rise rates and the heat release from the flame to augment ignition energy, enabling a wider range of operation than HCCI (Robertson, 2019). Control of combustion phasing is achieved using a spark plug, allowing the engine controller to achieve transient operation and quickly respond to transient in-cylinder conditions.

Mazda has recently introduced the SACI concept which is marketed as spark-controlled compression ignition (SPCCI), as shown in Figure 21 (Nakai et al., 2019). Three different regions are indicated in the figure which require the engine controller to switch among these modes. The power density and speed range of SACI combustion are insufficient to meet the total performance requirements, and a mode shift to SI is required at high loads and high speeds. Mode switching increases the control complexity as the charge preparation requirements (e.g., EGR, air-fuel ratio, effective compression ratio) can vary significantly between combustion strategies. The Mazda SACI engine is paired with a mild hybrid system, which reduces the need for mode switching and enables fast torque response. While the authors did not state that mild hybridization was *required* for SACI to be feasible for production, hybridization contributes to the production viability of advanced combustion modes by reducing the demands on the engine. As such, this controls challenge can be mitigated with hybridization.

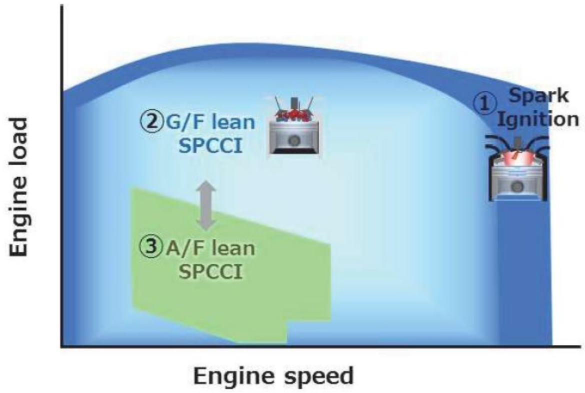


Figure 21. Engine combustion strategy diagram for Mazda's SACI design (called "SPCCI")

5.2.2 Compact Power Plants and Range Extenders

In recent years, there has been an approach for extending vehicle mileage range, favoring simplicity and compactness, at the expense of reduced efficiency and increased emissions. Despite the somewhat poor efficiencies of these engines when compared to their EV counterparts, they do display very high-power densities.

AVL showed a two-cylinder unit and a 15 kW Wankel with minimum fuel consumption of 260 g/kWh. Also, Capstone presented a range extender (RE) 30 kW microturbine with low volume and weight (56 x 15 x 28 cm, 91 kg), but with low efficiency (260 to 350 g/kWh). Based on these engines, some concepts of extended-range electric vehicles (EREV) have also been presented. Some of the vehicles with this concept include a twin microturbine (2x 70 kW) Jaguar C-X75, and 15 kW Wankel engine Audi A1 e-Tron (Green car reports, 2010). Wankel engines, while significantly more silent and compact than their reciprocating piston counterparts, suffer from relatively low efficiency when burning gasoline, although this problem is removed when switching to hydrogen as fuel. Combustion chamber sealing during the warm-up phase is also an issue.

On the other hand, microturbines, despite their extreme compactness and very low requirements for cooling, have some considerable drawbacks, such as low efficiency (25% for ambient temperature – although waste heat recovery can help to offset this), and high acquisition cost (Capstone, n.d.). Operating at significantly higher speeds of the order of several tens of thousands rpm, and capable of using a variety of fuels, from kerosene and diesel to natural gas, and with the ability to control their CO_2 emissions by using filters, they are useful both in the role of primary engine and to recharge the battery – a role that can help operate them at optimal efficiency. Importantly, with power capacity easily reaching 500kW, microturbines lend themselves well to heavy duty applications, such as HEV trucks and buses. Heat and noise management remain key challenges in the development of this technology, which is also sensitive to its use context and weather conditions, which will dictate the use of the produced waste heat.

5.3 Drivetrain Technology Challenge

The various hybrid architectures not only place unique demands on the various system components and on the evolution and refinement their respective technologies, but also create needs and opportunities for the (re)introduction of alternative technologies potentially conferring unique advantages and affordances. Transmission elements needing to accommodate complex power flows; alternative power plants as range extenders; the redefinition of the importance and perception of noise and vibration of various components in the context of the virtually silent electromotors; and, not least, the technology of the electromotors themselves, aiming for more compactness, efficiency, complexity and robustness.

5.3.1 Transmission

The development of EMs (electric motor) and hybrid operation of the engine has opened up new potential for the powertrain operation. Across the board of mechanical transmissions, innovations include gear tooth modifications to improve durability and NVH, hard finishing for NVH-critical gears only and also advanced torsional vibration absorbers and lower drag loss in clutches.

By integrating planetary gear sets (PGS) in the transmission it is now possible to combine power flows (speed and torque) from the EMs and internal combustion engine. This allows the vehicle to operate in many different areas than when it is only driven either by the EMs or engine. The several existing concepts can differ in terms of applicability, even though each of them can deliver the required number of driving modes. Two concepts with indistinguishable number of driving modes can still very significant in different operational areas.

In Figure 22 a representation of the demand map of a vehicle is plotted for all operational areas (Mitsche et al., 2014; Fischer et al., 2015; Li et al., 2019). The demand map is limited by the maximum vehicle speed and gradeability. When taking into consideration real customer operation, it occurs between these two limited conditions. The area of the demand map where the vehicle is able to be driven is termed as "operational area". For the same EMs and engine, different operational areas are attained for different DHTs. This difference in operational area is a result of the differences of structures of the DHTs.

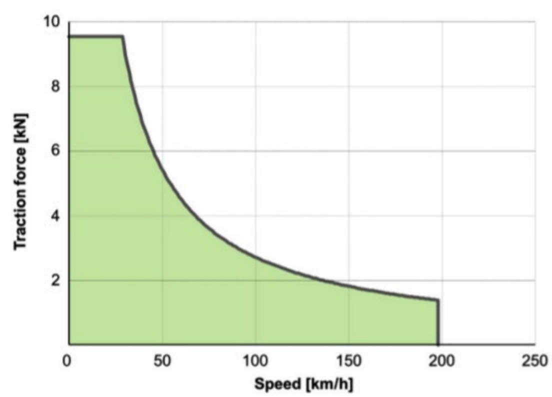


Figure 22. Vehicle demand map. (Li et al., 2019)

For the vehicle to be applicable, it is essential that the transmission operational area cover the entirety of the vehicle demand map, since the demand map illustrates real life driving situation that drivers may encounter. This implies that the drivetrain generates large traction force at low speeds and adequate torque at high and middle speeds. A study by (Li et al., 2019) demonstrated the operation areas of various concepts, where the vehicle is subjected to all driving resistances. Via measurements on vehicle in series production, a characteristic map was obtained, which was used to model EM and ICE. In each driving mode, full iteration of ICE and EM of the transmission output speed and torque was done. Through this it became possible to determine all assessable driving forces and vehicle speeds. From these two terms, the operational area of a specific driving mode was defined.

The results from the simulation shown in Figure 23, represent the operational areas of a high state of charge (SOC), where the battery charge permits the EM to use full power and torque. For this case the following modes are available: ICE-solo, electric driving (ED), and electric continuous variable transmission (eCVT). Comparing the operational areas of the modes of driving and the demand map (dotted lines), it clearly shows that this DHT cannot cover the entire demand map. In the driving situation when the driver desires low speed and high traction force, the drivetrain cannot generate the desired torque (red area), making this operation not feasible.

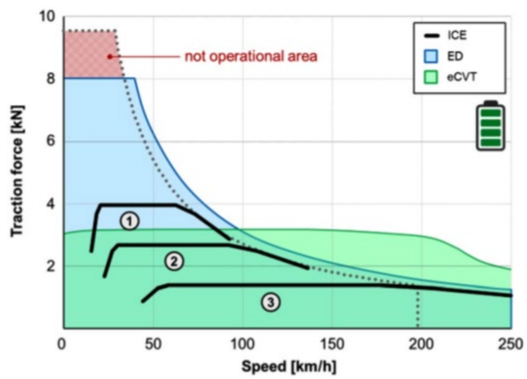


Figure 23. Operational areas of a DHT at a high SOC with all modes (Li et al., 2019)

On the contrary, Figure 24 shows the results of the simulation for a low SOC, where it is not possible for the vehicle to electrically drive due to very low battery charge. Also, the limited power of the EMs affects the operational area in the eCVT mode. Overall, the operational area of the modes when the SOC is very low is leading to small demand map coverage.

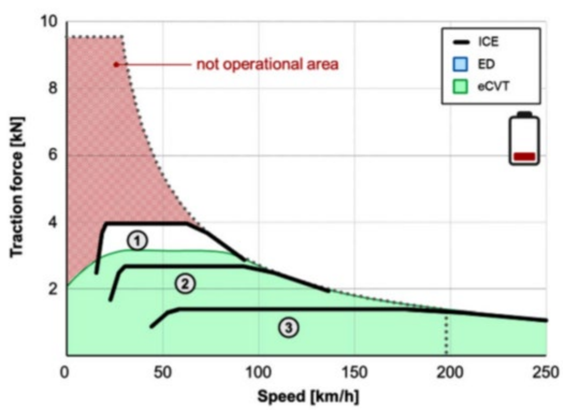


Figure 24. Operational areas of a DHT at a low SOC with all available modes (Li et al., 2019)

Besides eCVT transmissions, the introduction of high efficiency high ratio fixed transmissions has been under investigation in recent years. High speed compact brushless electro-motors rotating at 80,000-100,000 rpm coupled with fixed ratio gearboxes could deliver a more compact solution than current EV powertrains, provided that the cost, weight, complexity and reliability problems of current technology candidates, such as magnetic gear drives and cycloidal drives, can be overcome. This type of architecture will be particularly attractive if coupled with high speed range extender technologies, such as microturbines. In spite of the ongoing investigations, sufficiently mature solutions are not readily forthcoming.

On the other hand, distributed architectures using independent traction motors in the wheels do much to simplify the powertrain, essentially removing most of the mechanical transmission elements, although with less optimal torque-speed characteristics for the resulting system.

5.3.2 Gears and Bearings

Gears and bearings are highly critical parts for the integrity and efficiency of any transmission system including DHT. Statistically, rolling element bearings are responsible for a majority of drivetrain failures (SMMT, 2018). In induction electric motors only, 51% of all failures are due to failure of rolling element bearings. The wear issue of bearings is further triggered in the modern electric drives, tending to run at high speeds in excess of 10000rpm. Under these conditions, contacts may be lightly loaded while operating at high speed. This causes significant changes in the tribological conjunctions for a wide range of load-speed combination which is critical for durability and reliability of the whole system.

Figure 25 shows the variation of the lubricant film thickness between a roller and a race of bearing in a Permanent Magnet Synchronous Machine (PMSM), ramping over a speed sweep from stationary to 15000rpm. These results which are experimentally obtained in the tribo-dynamics lab of Loughborough University, reveal an order of magnitude difference in the thickness of lubricant film. Such a wide range of variation in contact conditions results in components and contacts working under different regimes of lubrication from hydrodynamic and elasto-hydrodynamic fluid film to mixed and boundary regimes undergoing direct interaction of surfaces. Such a variation brings along significant challenges in terms of durability of bearings.

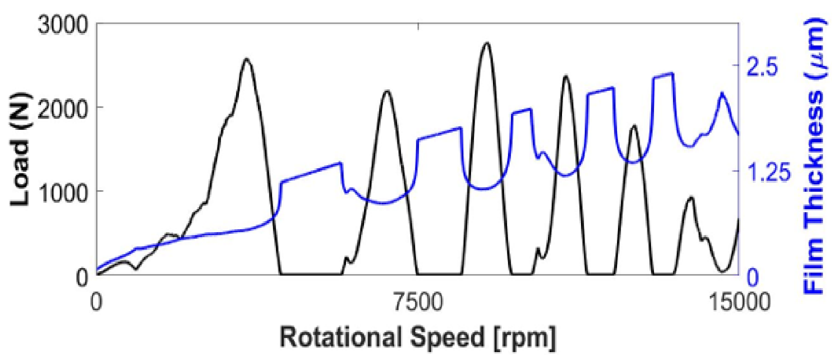


Figure 25. Variation of the load and lubricant film thickness in contact between a single roller and the race of rolling element bearing

According to UK data (Patterson, 2012), increasing the average life of each car by 10% due to enhanced durability of bearings can contribute 0.935 tons of CO2e saving for each car. As well known, any increase in the active life of these critical components and consequently the DHT systems as well as other powertrain systems can lead to enormous savings in the vehicle-utilization carbon footprint per macro-economy.

5.3.3 NVH Considerations

The noise, vibration and harshness (NVH) problem in automotive transmission affects vehicle driving comfort (Li and Wang, 1997). The five main types of noises produced are: rattling, shifting, whining, clunking and bearing noises. The rattling noise is caused by the backlash of loose parts, for example, the forward and backward vibration of unloaded synchronizers and gear pairs (Bellomo et al., 2002). Besides, the shifting noise is induced when there is improper operation of the clutch or the synchronizer (Wang el al., 2008). The two main reasons for the whining noise is time-varying mesh stiffness and transmission error. The clucking noise occurs due to the collision of the flanks of active components (Crowther et al., 2005). Bearing noise is always concealed by other types of noises except if damage occurs, and the magnitude of the noise increases as the damage level grows (Chaturvedi and Thomas, 1982).

To improve the NVH quality, often active and passive measures are implemented. Active measures are used mainly for tackling noise sources. The gear whining noise can be reduced with high-contact ratio gear, modified tooth profile, helical gear, high-quality tooth surface, misalignment-tolerant designs, and in some cases stiffness function optimization by power splitting (Lei et al., 2018; Yue et al., 2016; Beisekenov et al., 2019; Spitas et al. 2019). Also, the rattling noise can be lowered with the optimization of the synchronizer design, minimizing torsional vibration from the ICE and reducing the backlash and the inertia of loose parts (Bile et al, 2013; Spitas et al. 2016). Furthermore, to decrease the fluctuation and vibration from the ICE, often a dual mass flywheel, torsional damper or pendulum absorber is placed between the engine and the transmission, effectually suppressing the vibration and the rattling noise of the gearbox. Passive measures are concerned with the structure-borne noise to the car body. Instances of passive measures include stiffening of gear bodies, bearings, housing and shafts (Campbell et al., 1997).

As for the HEVs, with their advancement, there is a paradigm shift in the NVH arena. Even the most refined and smoothest combustion-engine and hybrid have considerably different harmonic spectra than EVs. Experts have asserted that EVs are anything but silent, but they do have their own acoustic challenges. In terms of total harmonic noise, traction motor in low and mid frequencies are relatively quiet, but the whine noise along with various other sounds in the gear within the propulsion system are much more noticeable. Also, there can also be a relative cacophony of heating, ventilation, and air conditioning (HVAC), compressor cycling and tire noise. During the electric drive (for instance EV mode or electric vehicles), sounds from electrical switching and battery coolant can be heard, even when the vehicle is at rest.

Despite customers not complaining about the EV cabin noise, and this may likely not change in the years to come, leading experts in the NVH-reduction field are already trying to make progress through up-front solutions. After all, the qualities of the sound in the vehicle form an integral part of the user experience for both driver and passengers.

6. Synergistic Technologies for DHT

The fuel economy regulation on light vehicles has been implemented globally for several decades. Hybridization and electrification are becoming well-accepted for light vehicles with a gross vehicle weight rating (GVWR) of 8,500 pounds or less. In order to reduce emissions and GHG from big rigs and work trucks (i.e., commercial vehicles), vehicle electrification is recognized as important and essential technology. The optimization of both endogenous fuel and exogenous electricity can begin from innovative idea, engineering design, product implementation, to actual product usage. From technology perspective, simulation and control are key enablers to develop powertrain electrification to meet all of the requirements as a successful product.

6.1 Simulation Technology

Dated back to 1980's, design analysis was facilitated with the advent of personal computers. One remarkable development was transitioning from Basic and C languages to symbolic programming languages (such as Matlab/SIMULINK). Concomitantly, the vehicle industry began to shift the focus on emission and fuel economy. Since the 1990s, hybrid and electric powertrain solutions have been re-visited due to pollution reduction demands. With aided design and analysis through computers, the number of physical prototypes is reduced and therefore the technology/product development cost is decreased. The advancement of software tools has significantly improved the efficiency of engineering design and shortened the product lead time for competitiveness in the market.

In the automobile industry, design with computational optimization has become more integrated in product development, and simulation-based R&D is becoming a principal approach (Tammi, etc., 2018). The simulating technology has evolved from in-house platforms to widely accepted commercial software tools. The simulation tools are generally based on Matlab or Modelica. Simulink (2002-) and Simscape (2007-) in Matlab provide the library packages for PSAT, ADVISOR, and Autonomie, while Dymola, SimulationX, OpenModelica, and JModelica are derived from Modelica. Other Modelica based effective tools are AMESim (Siemens PLM Software), Dymola and CATIA (Dassault Systemes), and MapleSim (Maplesoft). All these can readily handle complex systems of electric and hybrid propulsion systems. The following discussion focuses on application of Matlab/Simulink and its derivatives.

ADVISOR was published in 1994 as freely distributed software. The model represents quasi-steady vehicle dynamics and uses basic kinematic equations to describe the powertrain dynamics. ADVISOR based on empirical data is an analysis tool rather than a design tool. The simulation process involves both backward and forward path in the flow stream of calculations without need of iterations. Since the transient dynamics is not considered, there might be numerical difficulties incurred in simulation. One case is reported in a study of the numerical improvement of ADVISOR through simulating commercial vehicles with conventional powertrains (Song, etc., SAE 2007-01-4208). In the early 2000s, AUTONOMIE built off of Powertrain System Analysis Toolkit (PSAT). This tool is developed to evaluate the energy consumption, performance and cost of advanced powertrains (i.e., conventional, hybrid electric, plug-in electric, and fuel cell hybrid), component technologies, and control algorithms in a wide range of driving conditions (www.energy.gov). The Matlab-based framework can allow AUTONOMIE to co-simulate with other commercial software tools of GT-POWER, AMESim, CarSim, and AVL-DRIVE.

It should also be noted that Matlab/Simulink-based simulation usually requires a significant effort to model the physics correctly. For example, the challenge of friction models for Simulink based commercial vehicle simulation is presented in (Song and Smedley, 2010). The static friction models of a clutch are studied through Simulink with application of fixed and variable step sizes to explore numerical tractability and the fundamental friction characteristics of both stick-slip and

correct friction predictions. The observed conclusion is that an improved Karnopp model for clutch modeling is essential for capturing computationally smooth friction dynamics.
Comparable to Modelica, a relatively new Simulink tool "Simscape" has been introduced since 2007 to provide non-causal model notations and physical domain libraries. Simscape uses the Simulink environment to model physical systems directly and efficiently in more than 10 physical domains, such as mechanical, electrical, two-phase fluids, or electrical systems. In 2016, the Powertrain Blockset for Simscape was introduced for modeling and simulation of electrical and hybrid powertrains beyond traditional powertrains. This toolbox makes all the components work together uncomplicatedly, and enables to unblock the design and implementation of innovative features. The complex hybrid powertrains can be developed symbolically and so efficiently.

Continuous advancement of powertrain designs and innovations requires sophisticated tools, application of advanced data analytics, and large computational studies. As is driven by the challenges of complexity, connectivity and electrification of vehicles to meet more and more stringent requirements, the number of components in powertrains increases continuously. Multi-physics modeling and simulation packages can be integrated to facilitate modelling a component/powertrain detail to a full vehicle system. As such, the needs of co-simulating Simulink models with various applications of ADAMS, Saber and SIMPLORER continues to rise. In the electric vehicle (EV) study (Wang, etc., 2013), vehicle electrification with direct drive and multi-speed gearbox architectures is investigated through co-simulation. Direct drive scenario offers simplified drivetrain system, however requires a large and powerful electric motor. Multi-speed transmission system provides an opportunity to reduce motor size and optimize its operating points, but increases complexity from the architecture and controls point of view. The simulation results demonstrate the advantages of EV drivetrain system employing a multi-speed transmission over direct drive approach for demanding city-bus duty cycles. One coexistent challenge is that since a wide selection of components and subsystems are validated and parameterized by software vendors the user is responsible for identifying or selecting the right parameters for the application in hand (Tammi, etc., 2018). Others can be related to improving model exchange and reuse of model components and sub-models for more efficient modeling of complex systems such as hybrid powertrains. Today, since the computational analysis can be even quicker than real-time, fast transients and sophisticated controls can be simulated from modeling a detail to a full vehicle system. Consequentially, controls can be developed and validated through the virtual reality without need of involving physical prototypes.

6.2 Model Based Design

Model-Based Design is a model-centric approach to the development of embedded systems. The MBD development can be completed by using either model-in-the-loop (MiL), software-in-the-loop (SiL), hardware-in-the-loop (HiL), or vehicle-in-the-loop (ViL). The model-centric approach utilizes system- and component-level design and simulation, applies the automatic code generation, and implements continuous test and verification to develop and validate control, signal processing, and communications. There are eight core concepts of MBD (Aarenstrup, 2015):

- Executable specification
- System-level simulation – break boundaries
- What-if analysis - easy to explore multiple design ideas without risk
- Model elaboration

- Virtual prototyping
- Continuous test and verification – enable iterative development
- Automation
- Knowledge capture and management

MBD implementation provides the flexibility to adopt the best approach for a development task. There are six frameworks: Waterfall, V-model, Iterative and incremental development (IID), Spiral, Scrum, and Extreme programming (XP). The MBD processes are categorized as two types: plan-driven (waterfall, V-model) and agile (scrum, XP, and IID). Spiral is kind of a mixture methodology.

Each type has a home ground, i.e., areas of special strength or competence in the perspective of the above eight core concepts. Please refer to (Aarenstrup, 2015) for their explanation. Plan-driven methodologies can be applied to iterate production powertrains generation by generation with stable and targeted requirements. Agile methodologies are better suited to developing new powertrain or propulsion systems with a relatively small team for inconstant requirements and aggressive deadlines, which can allow more freedom to explore further. A model-assembled repository is a key enabler to unite cross-functional or geographically scattered teams to work on the same SMART objectives (specific, measurable, achievable, relevant, and time-bound). Data analysis needs to deliver right information, the team can acquire knowledge through sharing data and information, and ultimately the organization can benefit from the collective wisdom to stay innovative and competitive. A routine engineering practice to develop a new supervisory control system for a hybrid vehicle can be accomplished by applying the core concepts of Model-Based Design to enable team members to try new ideas. The full system simulation can be run to evaluate the new controls. This MBD process shall be time-efficient and cost-effective, because there is no need of expensive hardware or resource coordination. However, Model-Based Design enables teams and organizations to capture, leverage, preserve, communicate, reuse, and create knowledge from such iterative development. In the early investigation of dual clutch based transmissions (DCT) for medium duty (MD) trucks (Song, Liu, etc., 2005), a single clutch-based transmission (SCT) and an automatic transmission (AT) are also developed for comparative study. The simulation results tentatively show that DCT technology is a cost-effective avenue to achieve smooth shifting and avoid engine flaring while exhibiting some beneficial features of both AT and SCT. It is noteworthy that the different DCT control strategies can be tried with numerous parametric studies through the digital simulation.

Another highlight is that MBD approach can offer Lean Software Development. With the significant progress of computing technology, the modeling tools can provide generic component libraries, the sophisticated simulation tools can model the increasingly complex electrified vehicles, and the analysis tools can disclose details of the actual physics involved. Model-Based Design automates procedures such as report generation and code reviews. As such, Model-Based Design can deliver ceremony requirements without affecting cycle time. MBD can minimize bureaucracy and build integrity into the process to eliminate waste and amplify learning. The hardware-independent MBD procedure can allow to elect the target hardware (such as a DSP, FPGA, or ASIC) as late as possible in the development process. That means the developmental results can be delivered efficiently. The gradual evolution from dedicated single-domain simulation tools towards general tools brings about the model-based development procedure to effectively and efficiently manage complexity of both multi-domain physics and cross-functional teams. For instance, friction devices of clutch and inertia brake are commonly available as actuating mechanism for the commercial vehicle drivetrain systems. The researches from (Song and Liu, 2013 and 2014) have shown these kind of friction devices can be used with semi-active controls to suppress the driveline vibrations. The development process involves the MBD process and then move to the vehicle environment for validation. The procedure is highly efficient without much of capital investment.

In the long term, MBD design automation will be increased in modeling and simulation. The automated features will merge together with development of data-driven models and artificial intelligence. Data analytics and advanced data analysis methods will change the simulation post-processing to acquire deep insights and gain new knowledge to advance the technology. Looking into the future, further fusion will come with integration of software with communication possibilities through 5G and Internet of Things (IoT). The co-simulation will be able to stream data to a virtual simulating world for parallel processing as digital twin. In that way, MBD can become more interactive to the real world for more productive development in the virtual reality. Regardless, Model-Based Design continues to significantly reduce risk and save time and cost. The seamless integration between research, development, and production increases confidence in innovative designs.

6.3 Powertrain Controls

New regulations on emissions, fuel efficiency and driving cycles pose a demanding challenge to develop novel powertrains and advanced control strategies. Similar to simulation progress, computational power allows to develop and adopt highly sophisticated powertrain control algorithms for better performance and drivability. Conventionally, powertrain controls are primarily based on gas pedal and brake pedal to make adjustment on engine and transmission to meet the driver's requirements, such as comfort and fuel efficiency. With the progressive applications of vehicle connectivity and HD maps, advanced controls like MPC are being developed to optimize the energy management of engine-driving and hybrid vehicles. Architecturally, a gearbox-less DHT can be more efficient mechanically and the control strategy should focus on the energy management by using all sensing signals and received information.

There is an abundance of automatic transmission related publications. The book by (Bai, etc., 2013) elaborated the basic working principle and the mechanical construction of various automatic transmissions (AT), continuously variable transmissions (CVT), and dual clutch transmissions (DCT). Gear shifting mechanics and the principles of hydraulics are presented mathematically. The gear-shifting control process involves synchronized torque transfer from one clutch to another, smooth engine speed change, engine torque management, and minimization of output torque disturbance. Novel control strategies are relentlessly explored and developed to improve shift comfort, calibration efforts and shift timing significantly. DHT systems might include a multiple-speed gearbox for boosting performance. As such, learning algorithms for achieving consistent shift quality, friction launch controls, shift scheduling and integrated powertrain controls could be also applicable to step-ratio involved DHT systems.

The paper from (Robinette and Orlando, 2019) studies the non-torque interrupted clutch to clutch or self-synchronized mode shifting transmission controls with a simplified gray-box model. A dedicated hybrid transmissions have power-split and fixed gear modes of operations. With the total rotating inertia lumped upstream of the automatic transmission input shaft, a gray-box modeling approach for effective control design is proposed to represent the clutch-to-clutch step gear transmission by using a 2x2 lumped inertia matrix and a small 2x3 kinematic matrix. The inertia matrix corresponds to input and output shaft accelerations, while the relevant kinematic information contains a vector of net input, output and control clutch torque. The values are acquired through a physical test of the transmission on a non-firing dynamometer or through mathematical models. Since the studied DHT with fixed gear ratios has two motor/generators, the system model with multiple modes consists of 2x2 lumped inertia matrix, and 2x4 kinematic matrix which embraces net input, output and two motor torque. Shifting smoothness can be optimized through control adjustment of torque-phase filling and inertia-phase torque reduction, while the regenerated energy during the mode transition can be quantified. In this paper, the control development is also applied to simulation investigation of an electric vehicle with a two-speed clutch-to-clutch transmission. The gray-box modeling methodology simplifies the gearbox transient dynamics to two linearly dependent equations of motion with the purpose of predicting the required torques of the controlling clutch or prime movers to achieve a desired shift feel and transient time of the output torque. The study of (Ngo, et al., 2015) analyzes the effect of the energetic loss models involved with gear shift and engine start on energy management strategies with in an AMT-based parallel HEV. The finding is that parallel HEV has a superior fuel-efficient advantage over the AMT, and AMT can improve fuel efficiency noticeably by reducing the torque interruption time in the gear shift process. The research (Song, DETC2011-47548) presents utilization of the HEV motor to actively abate the unwanted engine vibrations during the hotel mode for long-haul commercial vehicles. A pole placement control (PPC) is developed to smooth engine crank and shutdown. The PPC uses the motor speed as a feedback control signal to create a desirable motor torque control. The field-testing data from a prototype hybrid truck demonstrates the effectiveness.

Energy management is a pivotal constituent of the powertrain controls. The paper (Biasini et al., 2013) inquires into a rule-based energy management strategy for a medium duty hybrid truck. The DP algorithm is applied to extract near-optimal rules to minimize the fuel consumption. Drivability metrics such as frequent clutching and engine on/off behavior are also included in the control design. With a pre-transmission parallel medium-duty hybrid truck, the simulation results show that the proposed near-optimal rule-based strategy falls within 3% of the global optimal fuel efficiency derived from DP. Another study by (Marx et al., 2014) investigates an ultracapacitor heavy hybrid vehicle with application of an MPC energy management strategy. DP techniques are used to find out the upper limit to the potential fuel saving. The forward-looking MPC method makes use of statistical information for a given cycle to better represent the future expected demands. A consistent improvement in fuel economy of around 30% can be achieved with respect to the conventional vehicle. It is pointed out that same improvements may not be achieved in ‘smoother’ driving cycles. As indicated in (Yolga, and Bachinger, 2019), powertrain control is typically composed of energy management (hybrid control) and transition management (transmission control, which is discussed earlier). Energy management deals with static driving cases. During the hybrid control, the energy management provides a driver demand torque and control the battery state of charge (SOC). In order to fulfill the driver demand torque, the powertrain control might involve transmission control to execute the gear shift conjointly.

Fuel saving technology for vehicles can be pursued with preview information in addition to self-contained powertrain system optimization. The study (Ngo et al., 2015) with preview-based MPC algorithm finds out that minimum prediction horizon of 5 s is required to maximize the fuel economy under the impact of the engine start loss. The research from (Marx et al., 2014) shows that the use of simulated telematic preview information signals can improve another 1% more with the basic telematic and GPS data. A parallel hybrid configuration with a high power density ultracapacitor is studied for fuel economy of a heavy transport vehicle in (Schepmann, and Vahidi, 2016). With full and a-priori knowledge of the future driving cycle, the optimal control technique DP calculates the 'best possible' fuel economy. The observation is that simulated telematic preview information can help to further save fuel closer to the DP-calculated maximum saving, even though ultracapacitor storage provides a limited energy buffer. The paper (Song, etc., DETC2015-46206) presents a self-contained system architecture that integrates the digital map database, radar senor, V2x, and mobile traffic data from the wireless network for commercial vehicle driver assistance. A single board computer (SBC) based architecture is utilized to integrate these preview channels with the powertrain system as a cost-effective implementation. The field-testing data does show the benefits of using look-ahead information to improve the freight efficiency.

As an innovative DHT design can have strong flexibility and applicability of effective mode-shifting functionality, hybrid powertrain control algorithms can more efficiently fulfill driveability targets within the propulsion component limitations, which might be due to battery SOC, maximum charge/discharge currents, or maximum available torques with motor/generators. It is expected to develop novel control algorithms according to distinguished DHT systems. For system optimization with preview information, future powertrain control strategies that are able to make use of vehicle weight estimates and road grade information can provide more accurate torque demands so that fuel efficiency could be further improved. In order to validate the applicability of new controls, model-based design will continue to be a principal approach to refine the development process. In fact, real route information (containing speed limits, traffic conditions, and signal locations and timings) can be integrated into a simulation platform. As such, any kind of new powertrain controls can be more comprehensively assessed for the potential benefits in a high-fidelity simulation environment.

In principle, powertrain controls include gear-shifting control and energy management. Novel control algorithms for handling shifting dynamics more effectively or working out energy flow more efficiently are those of the many control inventions in this powertrain domain. The novel control algorithm not only offers opportunity to enhance the powertrain performance of such as shift quality and component durability, but also brings new ingredients to powertrain automation and expands new horizons of developing various DHTs.

7. Summary

Generic powertrains include motive powers of engine and battery, transmissions, motors and axles. Each of these elements involves multi-physics perspective as an independent system or module as an integral part of the vehicle propulsion systems. It is clear that DHTs can bring many benefits on drivetrain efficiency, packaging, weight reduction, and enhanced durability. Powertrains based on DHTs can offer unique opportunity of downsizing the propulsion elements and reducing the number of gear/mode ratios to meet the complete range of vehicle operations. Engines find new horizons to advance thermal efficiency and uplift durability because of motors being able to take care of low-speed and transient propulsions. Waste heat recovery (WHR) should be a part of the electrification solutions to attain higher efficiency engines. From developmental perspective, several virtual platforms can be extended to investigate material properties of such as friction, lubrication, thermal characteristics, and electrochemistry properties as the powertrain elements operate consistently per design specifications. Resultantly, innovations can become more effective.

Consequently, with deeply studying the dedicated hybrid transmissions, further benefits can be profoundly conceived. With dual motive powers on-board, torque interruptions with AMTs can be resolved through innovative design of DHT systems. In the other hand, the conventional low-efficiency torque converters for AT can be removed from the electrified powertrains, because the motors can provide large torque at 0 and relatively low speeds. DHTs can take advantage of integrated motors to penetrate further holistic optimization of the powertrain controls such as distinguished shifting controls, BSFC-optimized engine controls, and vehicle-level energy management, to name a few. As a further matter, survey of other DHT constituents of advanced power electronics, fuel cell technologies, advanced battery, motor/generators, and thermal management systems will be worked out in the near future.

The noteworthy is that internal computing engine (ICE) is becoming the heart of a new *computing ICE* age for vehicle industry as well, though the *combustion ICE* "internal combustion engine" has dominated as a key enabler for vehicle value and innovation since the advent of human transporter "car" (KPMG, 2019). Today, there is a conspicuous change that just like smart phones vehicles begin to be differentiated by functionalities defined by software, semiconductors and electronics. As the vehicle development is entering a completely new stage of electrification, autonomy, connectivity and mobility as a service, such four megatrends also pose a challenge to innovate powertrains (i.e., propulsions) for future vehicles by using on-board supercomputing capability for more potential merits. Correspondingly, the automobile industry continues to apply more software-based digital abilities to create a digital replica of a physical entity. The virtual development approach can integrate existing data to physical materiality to facilitate processes and reduce marginal costs. The development of electrified powertrains through simulation can be more realistic than ever. With completing virtual validations, the design optimization of hybrid vehicles can be transferred to a mature industrial stage. To the expectation, digital twin can facilitate vehicle development and optimizations of both electrified vehicles and powertrains as the model-based design has helped out for several decades now.

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