Overview of Evolutionary Electrification of Powertrains for More Efficient and Intelligent Vehicles

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The history of ground vehicles is, in a sense, largely representative of the modernisation 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. Since the advent of car manufacturers 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. More interestingly, electric cars and hybrid vehicles had also been around since the early 1900s. At that time, Ford made 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. However, in the publishing world, there was no specialty journal to archive innovations, progress and research in powertrain development until 2010, when the *International Journal of Powertrains* was initiated.

Humankind has learned costly lessons from the persisting and harmful environmental effects of early engine-driven automobiles. In the 1940s and 1950s, millions of people drove millions of cars in the Los Angeles area. There was a constant heavy smog hanging over the city. It wasn’t until the 1950s that scientific research identified emissions from vehicle engines as being one of the leading causes of the production of photochemical smog. Since then, the State of California has 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. California has been a global advocate for emissions regulation and fuel economy. Such effort has greatly promoted technological advances in the automotive industry: passenger car CAFE has risen from 18 mpg in 1978 to 45 mpg today; commercial vehicle NOx emissions have dropped from 10.7 g/bhp-hr in the early 1980s to the current 0.02g/bhp-hr. As human awareness of the environment increases, regulations have begun to shift towards the low-carbon era. Today, in addition to the eye-catching Silicon Valley, California's market support for new energy vehicles such as Tesla's EVs and Japan's fuel cell vehicles is at the forefront of the world again. While challenges with the environment and regulations continue, full electric and hybrid powertrains are hot research areas in both academia and industry. It can be expected that within the next few generations of vehicles, the use of internal combustion engines as the sole source of motive power will reduce dramatically. At this transformative point in time, research effort is focused on innovations in and the industrialisation of both refined powertrain technologies and alternative disruptive ones.

Electronics have played an important role in advancing engine technology. By the 1960s, internal combustion engines had entered large-scale industrial applications for vehicles. In the 1970s, electronic engine control systems emerged that commanded 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 from greatly enhanced engine efficiency and emissions control. With the invention and application of heated exhaust gas oxygen (HEGO) sensors in the 1980s, closed-loop air-fuel ratio control was successfully applied to engine system. Entering the 1990s, additional control actuators for internal combustion engines were explored to meet more stringent regulations. Multi-variable control technology facilitated engineering applications of exhaust gas recirculation (EGR) and variable valvetrain systems. Other advanced technologies were developed as well, such as variable direct injection, dual injection and variable compression ratio systems. 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 achieved through the further development of internal combustion engines within the framework of integrated powertrain systems. Holistic optimisation 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 such as artificial intelligence, will be a large contributor to re-inventing engines so that they continue to be an integral part of future powertrains.

Powertrain hybridisation is one of the highlights of today’s vehicle industry. Historically the powertrain is one of the core technologies for vehicle development. In fact, powertrain efficiency has always been the main focus of the automotive industry. It is well understood that 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 focuses of engine research is to boost 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 recognised that the energy efficiency of the whole vehicle can be significantly higher if the vehicle’s kinetic energy during braking is fully recovered and reused. Thus, recovery of braking energy is being studied widely to maximise energy efficiency during vehicle operation. In another approach, 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 industrialisation of commercial vehicle hybrid systems was launched by Eaton in 2002. Industry-wide, electrified powertrains range from micro-hybrid, light hybrid and full hybrid to plug-in hybrid to meet market and regulatory requirements.

In recent years, dedicated hybrid transmissions (DHTs) have been the subject of active research and development. The basic design principle is an integrated driveline system based on the respective characteristics of the engine and the electric motor. As such, the hybrid system can drive a vehicle more efficiently using fuel and electricity. Generally speaking, commercial vehicles apply five hybrid system architectures from P0 to P4 with regard to the position of motors in the driveline system. Each configuration has pros and cons, respectively. It is worth noting that DHTs are developed from the holistic approach by fully integrating various technologies to maximise the performance of powertrain systems. Unlike traditional gearboxes, DHTs require an innovative powertrain design that optimises engine efficiency and reduces overall vehicle energy usage. It is recognised that the efficiency of a hybrid system depends on power matching among the various components and the power sources to deliver optimised performance. Other performance aspects such as NVH, reliability and durability can be included in the design objective as well. Beyond that, safety is the key factor in the automobile industry. The development of hybrid vehicle systems needs to follow the electronic functional safety standard ISO26262.

Efficient and clean vehicles are required worldwide to preserve the environment. More and more renewable energy is being developed to meet increasing energy consumption. Alternatives to coal and petroleum ranging from solar and wind to hydro can move motive powers away from reliance on fossil fuels. The automotive industry is looking into hydrogen as an energy resource for vehicles. IEA reports that today hydrogen is produced by coal, natural gas and oil in the percentage of 57.3%, 23.0% and

19.7%, respectively. Furthermore, since hydrogen supply can be produced from fossil fuels, hydrogen can be recognised as one of the energy carriers of the future, like today's electricity. With the energy landscape shifting towards hydrogen, governments, industry and academia are coordinating to jointly advance fuel cell (FC) technology and work on the establishment of technological, safety and operational standards.

It is clear that both batteries and electric motors are two pillar technologies for electrification and hybridisation. Lithium-ion battery technology has developed very quickly for industrialisation over the past decade. LFP and NMC are used as energy storage for EV and PHEV applications while LTO and LMO for HEV as power battery. NMC offers the best energy density of about 250 Wh/kg. Today, higher-density battery technology will grow even more rapidly to support vehicle electrification. It is reported that solid-state lithium-ion batteries will be put into practical use in the next five years. For 2030, the lithium-sulfur battery is predicted, wherein the cathode material uses sulfur (S) and the lithium metal for the anode. Such battery chemistry can reach an energy density of 700Wh/kg. After 2030, the use of an "air electrode" as the positive electrode may become possible from an engineering point of view. This development could lead to energy densities as high as 1500Wh/kg, which is more than five times the current level. It is worth noting that battery performance is very sensitive to temperature. Thus a capable thermal management system should be able to accomplish the temperature controls on an electrified vehicle to meet both instantaneous and steady power requirements. Thermal management for better battery efficiency and safety is and will continue to be an active research area.

Today, there are four main types of electric motors: DC, (asynchronous) AC induction, synchronous permanent magnet (PM), and switched reluctance (SR). New energy vehicle motors mainly use the latter three. There is no doubt that motor technology has a lot of room for improvement. Both stator and rotor are mainly composed of a thin layer of (electromagnetic) steel. Generally speaking, increasing the number of thin steel layers can increase motor efficiency and also help to control internal temperatures. In terms of winding density, the amount of winding in the stator is an important factor in determining the power of the motor. In terms of coil type, there are mainly square and round types. Currently the square technology, since it has better space utilisation, is gradually replacing the circular to become the industry's preferred design. From the magnetic flux perspective, axial flux designs can deliver higher torque densities at low speeds, while radial flux motors can operate at very high speeds to achieve high power densities. One key challenge for mass production of electric motors is automated winding technologies that provide high quality control and production efficiency. Cooling systems are another key technology area for high-performance motoring systems. Since the magnetic force of the permanent magnet motor is weakened with temperature rises, the efficiency of the cooling system is critical for extended high-power operation. Mainstream cooling technology has evolved from air- and water-cooled to the current preference for oil cooling. Additionally, the power electronics between the battery, motor and charging systems are rapidly evolving. For example, silicon carbide is being developed for the next generation of power electronic devices to replace IGBTs.

At the same time, the mechanical components of vehicle powertrains have never stopped evolving. In response to more powerful motors and the evolution of consumer driving styles and efficiency regulations, conventional manual transmissions have given way to automatics and the hybridisation of AT, AMT, DCT and CVT. While the power split DHT (also referred to as eCVT) has proven successful in its application to planetary gears from Toyota, a new magnetic split technology is being developed as magnetic CVT ("mCVT") for vehicular applications. With electric motors having speed outputs of over 100,000 RPM, or in other cases microturbines being integrated into hybrid powertrains, there is a need for highly resilient and efficient bearings and gearboxes that can operate under such conditions, and a large amount of research and development effort is currently being undertaken in that direction by OEMs and transmission suppliers. Regarding electric propulsion, the integration of a flexible multi-speed transmission or continuously variable transmission (CVT) system can help to efficiently use battery capacity by moving the operating points of electric motors to their most efficient region. In that regard, high-speed traction motors at tens of thousands of RPM also pose a great challenge to developing and designing speed-reducing drivetrain components of such as gears and sealing.

While the vehicle industry moves towards highly automated and autonomous vehicles (AV), one further approach is to let vehicles be connected to each other, to transportation infrastructure and to cloud centers. Powertrains will be designed to deliver on-demand power requirements to work with intelligent vehicle operations. Vehicle connectivity can be used to send real-time trip information (e.g. average traffic speed, the timing of upcoming traffic lights, road conditions) to the on-board control system for minimising fuel consumption over the entire trip by optimising vehicle dynamics and powertrain through the use of model predictive control algorithms. Furthermore, vehicle connectivity also enables cooperative maneuvering wherein fleets of connected autonomous vehicles (CAV) jointly plan trajectories and decisions for creating a safer and more energy-efficient driving environment. For instance, vehicle platooning can lead to an energy saving of 5-20% in connected and automated vehicles. As such, big data analysis for powertrain research will be more dynamic than ever. This means that big data processing can help to offer deep insights into applied materials, components and propulsion systems. In addition, the data analytics can be utilised to improve vehicle powertrain operation by modifying powertrain ECU (electronic control unit) calibration tables, identifying faults and improving OBD (on-board diagnosis) strategies. The cutting-edge developments of powertrains will relate to artificial intelligence and deep/machine learning. This may lead to a new era of data-driven powertrain modeling and control that has the potential to reduce the development time of vehicles.

It is a significant milestone that the *International Journal of Powertrains* (*IJPT*) (www.inderscience.com/ijpt) was added to the SCOPUS database in August 2017. *IJPT* is progressively becoming recognised as an influential channel for powertrain research. Beyond establishing expert networks, a strong submission channel and operational outreach, the goal of *IJPT* is to emerge as an influential leader, though today it is still in its relatively nascent stages. The ultimate goal is to become a premier channel to distribute more effective and efficient communications among the powertrain community. Our mission is not only to preserve the development history of engines and powertrains, but also to disseminate knowledge of the rich and diverse innovations in powertrain electrification for more efficient and intelligent vehicles. *IJPT* provides a venue for disseminating knowledge of rapidly evolving powertrains, energy storage systems and motive power units.

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