Design and development of split-parallel through-the-road retrofit hybrid electric vehicle with in-wheel motors

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Abstract. One configuration of the hybrid electric vehicle (HEV) is the split-axle parallel hybrid, in which an internal combustion engine (ICE) and an electric motor provide propulsion power to different axles. A particular sub-type of the split-parallel hybrid does not have the electric motor installed on board the vehicle; instead, two electric motors are placed in the hubs of the non-driven wheels, called ‘hub motor’ or ‘in-wheel motor’ (IWM). Since propulsion power from the ICE and IWM is coupled through the vehicle itself, its wheels and the road on which it moves, this particular configuration is termed ‘through-the-road’ (TTR) hybrid. TTR configuration enables existing ICE-powered vehicles to be retrofitted into an HEV with minimal physical modification. This work describes design of a retrofit-conversion TTR-IWM hybrid vehicle – its sub-systems and development work. Operating modes and power flow of the TTR hybrid, its torque coupling and resultant traction profiles are initially discussed.

1. Introduction

An HEV draws its propulsion power from an ICE and an electric motor, which also operates as a generator to re-charge the onboard battery pack. Depending on connectivity of the power sources to the load (wheels), an HEV has several possible configurations, which include series hybrid, parallel hybrid and combined series parallel hybrid. A parallel hybrid vehicle typically has the motor-generator on board the chassis. Alternatively, the electric motor can actually be part of the wheel itself, called an in-wheel motor (IWM).

In such vehicle, the ICE operates on one drive-shaft (e.g. front) while the in-wheel motors are fitted into the other pair of wheels (e.g. rear), resulting in a split-axle parallel architecture (figure 1) [1]. There is no dedicated mechanical device coupling the two propulsion sources. Instead, the sources are coupled through the road, giving rise to the term TTR hybrid. This paper describes specific operating modes, power flow, torque coupling and resultant traction profiles of the split-parallel TTR hybrid. It also explains sub-systems and development work for conversion of conventional vehicle into a TTR hybrid vehicle. The parallel HEV drive-train is a combination of two separate power-trains, each having an energy source/reservoir and an energy converter. The first power-train consists of the fuel...
tank (source) and the combustion engine (converter), while the second is made up of the battery bank (source) (or any electrical energy storage device) and the electric motor-generator (converter). As illustrated in figure 2, while power flow in the former is unidirectional, the latter allows for energy to be dispensed (electric motoring) and replenished (battery charging through electric generation and regenerative braking). In general, this results in nine possible operating modes for a parallel HEV. In a split-axle parallel hybrid vehicle with in-wheel motors, it is not possible for the ICE to directly charge the battery bank through the electric generator since the two sources are not coupled together [2].

Figure 1. Split-parallel through-the-road hybrid electric vehicle configuration.

Figure 2. Power flow paths of a parallel hybrid electric vehicle.
Rather the batteries can be charged only when the vehicle is moving – when the wheels and in-wheel motors are turning and operating as generators. Charging cannot occur when the vehicle is stationary. In a TTR hybrid, the ICE does not deliver power to the battery bank directly but through the load (vehicle mass) – when the vehicle is propelled by the ICE and power is delivered to the battery through the vehicle’s chassis, wheels and road coupling [1, 2].

Figure 3(a) shows configuration of the split-parallel hybrid vehicle, clearly showing the two power sources acting independently on different drive axles—there is no mechanical coupler as in the single axle parallel hybrid vehicle (shown in figure 3(b) and 3(c)). These results in only five possible operating conditions for the TTR-IWM hybrid, determined by the possible combination of energy flow paths, as depicted in figure 4:

1. **Mode A:**
   Similar to Mode 1, only the ICE is providing propulsion power to the vehicle. The in-wheel motors are not operating.

2. **Mode B:**
   Similar to Mode 2, only the motors are providing power to the vehicle. The ICE is idling.

3. **Mode C:**
   Similar to Mode 3, both the ICE and in-wheel motors are providing propulsion power to the vehicle.

4. **Mode D:**
   Similar to Mode 4, the in-wheel generator, to electrical power charge the battery bank, during regenerative braking.

5. **Mode E:**
   Similar to Mode 9, while the ICE is propelling the vehicle, the in-wheel generator converts the vehicle’s energy to charge the battery bank.

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**Figure 3.** Drive-train configuration: (a) TTR-IWM split-parallel hybrid, (b) single-axle post-transmission coupled parallel hybrid and (c) single-axle, pre-transmission coupled parallel hybrid
2. Torque coupling and resultant tractive profiles

A parallel hybrid vehicle has a mechanical-coupled drive train—it has some form of mechanical coupling device such as pulley, gear or chain assembly, which adds together mechanical powers from the two power sources. Due to power conservation, in a torque-coupled drive train, the torques from both sources adds up to give the final torque, while speed of the power sources cannot be individually controlled [2-4].

The split-parallel configuration is a torque-coupled vehicle, with torque contributions from the ICE and electric motor added up through the vehicle chassis, wheel and road—there is no dedicated coupling device. For the in-wheel motor hybrid vehicle, the electric motors care in the rear wheels; thus, the motor speed (rear wheel speed) is equal to the speed of the front wheels.

For the TTR hybrid with in-wheel motors, the ICE is connected to a multi-gear transmission (existing) while there is no transmission for the motor (similar to a directly-coupled motor). The torques from both sources combines to give a final traction profile. The resultant tractive profiles of a TTR-IWM hybrid vehicle are shown in figure 5(a). As mentioned above, the traction profiles are
similar to device-coupled parallel hybrid vehicle with single-axle, post-transmission coupling as shown in figure 5(b) [4].

3. Retrofit-conversion TTR-IWM hybrid vehicle

The TTR split-parallel configuration enables an existing ICE-driven vehicle to be converted into a hybrid electric vehicle with minimal modification-by replacing the otherwise non-driven wheels with motors (IWM) and powering them with a battery bank located in the vehicle’s trunk. Along with controllers and an energy management system controller (EMS) that intelligently manages the vehicle’s energy and power flow, they form a TTR-IWM hybrid vehicle system [1, 5].

One such retrofit project is ongoing at Universiti Teknologi PETRONAS (UTP) in Bandar Sri Iskandar, Malaysia, to convert an existing conventional-drivetrain PERODUA MyVI into a TTR-IWM hybrid vehicle. The prototype shall be used for validation of TTR hybrid dynamic simulation model and investigation of different control strategies to achieve optimum fuel saving benefits. A retrofit-conversation TTR hybrid vehicle consists of several sub-systems, as explained below, with reference to the TTR hybrid vehicle development project at UTP.

![Diagram of TTR-IWM hybrid vehicle](image)

**Figure 5.** Resultant torque-speed profiles: (a) TTR-IWM hybrid and (b) single-axle, parallel hybrid with post-transmission, single-gear motor and multi-geared ICE.

In-wheel motors used in this project are sourced from Kelly Motor Controls (figure 6). Installation of the IWM system involves design and fabrication of a special adapter for attachment of the in-wheel motors into the rear axle (figure 6). The work consists of attaching two in-wheel motors for a split-axle hybrid drive train configuration and replacing the original drum brake system with a disc brake (figure 7).
The existing drum brake system needs to be replaced as it would have taken up a large amount of space at the center and will result in extending the wheels further outwards from the vehicle body. The disc brake system is preferable as it occupies less space, since the brake calliper mounting is located outside the central area and the disc itself has a much thinner profile. Braking performance of the rear tires is expected to be equal or better than the replaced drum brake system since it combines both mechanical braking and electrical re-generative braking (see separate section below).

Figure 6. In-wheel motor(left) and motor adapter (right) for attachment of IWM to the rear axle.

Figure 7. Motor adapter (left) and disc brake assembly for IWM (right)

This sub-subject consists of installation and configuration of motor controller hardware and power circuitry for the two in-wheel motors. The motor controller used in this project is sourced from the same manufacturer of the in-wheel motors: Kelly Motor Controls (figure 8). The work requires programming and commissioning of the controller, tuning for bench-top testing of motor speed control and interfacing to other parts of the hybrid system (figure 9).

If the existing vehicle has a mechanical-cable driven throttle valve body for the engine’s air-fuel intake, it can be replaced with an electric throttle body (ETB) to have electronic throttle-by-wire for vehicle. In this project, an ETB model BOSCH DV-E5 is tested for the electronic throttle (figure 10) [6]. The work requires configuration of the interface and power circuitry for the electronic throttle (figure 11), programming and configuration of the throttle controller and simulation and control tuning for the throttle position control.
Figure 8. In-wheel motor (left) and motor controller (right) from Kelly Controls.

Figure 9. In-wheel motor system (IWM) connectivity.

Figure 10. Electronic throttle body (BOSCH DV-E5) and throttle position control.
The energy management and supervisory control system (EMS) is the heart of the retrofit hybrid system. In this project, the EMS is developed on National Instrument’s CompactRIO embedded controller and LabVIEW Real-Time software platform (figure 12). The EMS functions as the primary vehicle controller whose objective is to achieve optimal operation of the hybrid propulsion system-reduced fuel consumption and self-sustaining on-board energy storage, since the vehicle is a non-plug in hybrid [7, 8].

The EMS reads the inputs of throttle position, vehicle speed, engine rpm and battery state of charge (SOC). Based on a certain control algorithm, it then determines the two sources operation status and power distribution and charging of the battery pack [8, 9]. A graphical driver interface is implemented on a tablet PC with a TCP/IP connection to the EMS controller. A LabVIEW-based interface appears on a dynamically-controllable HTML page hosted by the web server function of the CompactRIO, enabling the driver to monitor and override control of the hybrid vehicle. Figure 13 shows connectivity of the EMS to other sub-systems of the retrofit hybrid vehicle, showing the name, cable type and signal type of each input or output (I/O) parameter of the system.
5. Re-generative braking system (RBS)

R-generative braking is a major energy saving mechanism for a hybrid vehicle, since the vehicle’s kinetic energy which would otherwise be lost during braking is captured and converted to electrical energy—by operating the in-wheel motor as electric generator—to be saved in the onboard battery pack for later use. In a retrofit hybrid vehicle, a mechanism is required to incorporate electrical re-generative braking onto the existing mechanical braking system, which is retained in the vehicle for safety and maximum braking performance.

The system is designed as follows: when the pedal is depressed, only re-gen braking occurs initially (no mechanical braking) up to a certain stroke of the pedal. Beyond this pre-set position, mechanical braking is applied along with re-gen braking, until the end of the stroke. This ensures that more braking energy is re-captured through re-gen, before mechanical braking takes place. This requires modification of the existing brake pedal (figure 14).

The main criterion in re-design of the brake pedal is to ensure its ergonomic position and pedal travel while in operation. By maintaining as much of the original design as possible, the mechanism is incorporated without major change to the brake pedal’s initial position. The strategy of the integrated braking mechanism consists as following (figure 15):

1. Applying re-gen braking to harvest electrical energy from the IWM for the first 30% of the pedal travel and
2. To continue with mechanical braking using standard OEM braking mechanism for the remaining 70% of the travel.

If the vehicle is required to stop abruptly, such as in an emergency situation, the EOM brake will still be fully functional. Additionally, actual amount of re-gen braking energy depends on the battery
pack’s state-of-charge (SOC)—if the battery is almost full, very little re-gen is possible and thus braking that can be applied to the vehicle also becomes reduced, which affects effectiveness of braking.

Figure 14. Brake pedal adaptation to incorporate re-generative braking.

Figure 15. Travel pattern of brake pedal: original OEM brake pedal (left) and modified brake pedal to incorporate re-gen braking (right)—a free-travel zone is created to retard mechanical braking, whereby only re-gen braking is activated in this zone.

Thus mechanical braking remains a significant braking component for the retrofit vehicle, to ensure safety and maximum braking performance. Apart from pedal modification to enable delay in mechanical braking, the system requires installation of a brake pedal position sensor and an electronic interface circuit for the brake sensor’s connection to the motor controller and EMS.

6. Thermal management system (TMS)

The vehicle IWM system is subject to high temperatures. This sub-project consists of design and fabrication of a thermal management system and a fire-retardant enclosure for the motor controller and battery pack, which are located in the vehicle’s trunk (rear boot space—figure 16). The thermal system’s function is to maintain the batteries and motor controller at their optimum operating temperature, which is important not only for safety objectives but also to prolong the batteries life and performance.

Figure 16 shows the rear view of the vehicle which indicated two main areas with different temperature profile. Interior cabin space will have lower temperature due to the vehicle’s air condition system. It cooler air is blown into the rear boot space via fans to cool the battery pack and motor controller located within. A basic model for temperature profile in the battery pack is as equation (1).

\[
C_c T_{c,i} = I^2 R_{in} + \frac{T_{xi}-T_{ci}}{R_e}, \quad (1)
\]
where $C_c$ is lumped heat capacity, $T_{c,i}$ is the cell core temperature, $I$ is current applied to the cell, $R_{in}$ the internal electric resistance of the cell, $T_{s,i}$ is the cell surface temperature and $R_c$ is the thermal resistance between the core and surface of the cell.

An active thermal management system is built based on this equation to predict the battery core temperature. For the retrofit vehicle, an air-cooled system with two fans is selected for the cooling system since it requires less modification in the vehicle’s interior and it can maintain of the battery cells and motor controller for temperature monitoring. The readings are fed to a closed-loop temperature control system, in which a temperature controller (CAREL) will adjust the speed of one of the fans to keep the system temperature about a set point.

![Figure 16. Rear view of prototype retrofit hybrid vehicle.](image1)

The driver also has the option to manually activate further cooling in the event of over-temperature, by turning on the second fan. The thermal management system’s control schematic is shown if figure 17.

![Figure 17. Schematic diagram of thermal management system.](image2)
Figure 18 indicates air-flow direction in the two areas, showing hot air being blown out of the rear boot compartment via a separate exhaust fan. Thus in this design, cooler air from the cabin plays an important role to cool down the vital system components. This is further illustrated in figure 19, which also shows a vertical cross section of the system.

![Diagram](image1)

**Figure 18.** Component position and direction of air flow (vertical cross-section of system).

![Diagram](image2)

**Figure 19.** Thermal management system for battery pack and motor controller (vertical cross-section of vehicle trunk)

An in-house designed fire-retardant material (figure 20) is used as coating for and enclosure which houses the battery pack and motor controller to prevent flames from spreading to the vehicle cabin in the event of a fire. This coating suppresses flame by releasing CO\(_2\) when it is in contact with the flame. It can withstand surrounding temperatures of up to 1000°
7. Conclusion
A split-axle parallel HEV configuration enables existing ICE-powered vehicles to be retrofitted into a hybrid electric vehicle with minimal physical modification. This paper describes specific operating modes, power flow torque coupling and torque profiles of the split-parallel, through-the-road hybrid vehicle. Design and development of sub-systems for a TTR hybrid vehicle with in-wheel motors are provided as part of a retrofit-conversion hybrid electric vehicle project.

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