A review on development of a lab scaled hybrid vehicle system for small gasoline engine

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Abstract. It is important to study the vehicle efficiency in order to have better performance and lower emissions. The sub-compact vehicle is powered by an internal combustion engine (ICE). Usually, the incomplete combustion in ICE gives out by-products of such carbon dioxide (CO₂), nitrogen oxides (NOx), unburned hydrocarbon (UHC), and water (H₂O). The electricity seems can solve the global warming issues contribute by the emission produce from the IC engine by reducing the dependence on the operating system from it. Electric vehicle via an electric motor (EM) give high efficiency compared to internal combustion engine but lower at average top speed. This paper will discuss more on developing the hybrid electric vehicle system, especially for the small gasoline engine. The process involves in the development of the small hybrid system is similar to other larger hybrid vehicle system. However, the system is more compact in size and no external gearing system or gearbox system. When developing this type of hybrid system, the drivetrain structure and the hybrid operating control system configuration is the main attention to be studied. Before developing the hybrid system, it is important to understand the basic component contains in a hybrid system, type of a hybrid electric vehicle, the hybrid drivetrain structure and the hybrid operating control system configuration first. By implement the hybrid system in vehicle system today, it will contribute to the environmental effect by decrease the emission release to the air. This paper will focus more on the type of the drivetrain design and the operating control system that suitable to implement on the small hybrid vehicle. Small gasoline engine in this paper refers to the single cylinder internal combustion engine with capacity below 150cc.

1. Introduction
The hybrid operating system can be described as a combination of two or more power source input operation system in a complete single operating system. Normally in the hybrid electric vehicle (HEV), there is a combination of an internal combustion engine (ICE) together with a hybrid electric motor (EM). In history at the year of 1995, the General Motor Corporation (GMC) introduces the first electric vehicle named as
“Saturn EV1” in California and Arizona [1]. With a limited market at that time, the production of the vehicle has been discontinued. The acceptable from the consumer market around is not ready to accept the vehicle that counters a problem with the range of distance travel on a fully charge of batteries [2]. The limited power consumes of the battery pack by the electric vehicles problems led the researchers and automotive industry players today to study and invent more for an alternative solution.

Then, Toyota plays an important role among the automobile manufacture player by introducing their first hybrid vehicle called “Toyota Prius” in 1999 in Japan. The early years of the electric hybrid vehicle (HEV) were discovered when the Faraday demonstrated the principle of the electric motor in 1820 through a wire rod carrying electric current and magnet. In 1831 he discovered the law of electromagnetic induction that enable the development of the electric motors (EM) and generator essential for electric transportation. The history of electric vehicles in those early years up to its peak period in the early 1900’s is summarized in Table 1 and Table 2 below [1]:

| Year | Pre-1830-Steam-powered transportation |
|------|---------------------------------------|
| 1831 | Faraday’s law, and shortly thereafter, the invention of DC motor |
| 1834 | Non-rechargeable battery-powered electric car used on a short track |
| 1851 | Non-rechargeable 19 mph electric car |
| 1859 | Development of lead storage battery |
| 1874 | Battery-powered carriage |

| Year | Early 1870s-Electricity produced by dynamo-generators |
|------|--------------------------------------------------------|
| 1885 | Gasoline-powered tricycle car |
| 1900 | 4200 automobiles sold: |
|      | • 40% steam powered |
|      | • 38% electric powered |
|      | • 22% gasoline powered |

From the table above, it can be seen that the early development of the electric car was on 1851 by 19mph electric car. After developing and testing the electric car, they seem facing the problem with the total distance travel or the power source which is batteries. After the invention of dynamo-generators, this problem had been countered. Refer to the table above, in 1900 there were about 4200-unit vehicle sold and 38% from that number assists from electric powered vehicles. It shows that the electric vehicle regains the attention from the market. Since that time, many automobile industry players start to invent and produce the electric hybrid vehicle.

2. Basic component of hybrid electric vehicle
Refer to basic internal combustion engine (ICE) components, the hybrid electric vehicle consists of two power source input functional to drive the drivetrain like an ICE and electric motor (EM). Refer to Figure 1 below the basic design of the hybrid electric vehicle component and parts [3]:

Table 1. Pre-1830-Steam-powered transportation
Table 2. Early 1870s-Electricity produced by dynamo-generators
3. Type of hybrid electric vehicle system

Hybrid electric vehicle can be classified according to the way in which power is supplied to the drive train and also based on the degree of hybridization [4][2][5][6] as shown in Figure 2. With many types of hybrid technology existed, is much interest in widespread conversion to hybrid transportation. With such a massive world population and high dependency on transportation, a significant switch to hybrids from gasoline and diesel vehicles must be met before any changes can be seen [7].

Figure 1. Schematic diagram of a hybrid electric vehicle [3]

For the standard hybrid electric vehicle, it consists of an ICE, fuel tank, electric motor, battery, power electronics, power transmission and gearbox. Basically, this is the main component and part of a standard hybrid electric vehicle system.

3.1. Plug-in-hybrid

This type of hybrid system sometimes called Plug-in Hybrid-Electric Vehicles (PHEVs), are hybrids with large charging system storage or high-capacity batteries that can be charged by plugging them into an electrical outlet or charging station [8]. In this type of hybrid system, it can run individually whether in electric motor mode or with an internal combustion engine mode that run to charge the battery pack. They can store enough electricity from the power grid to significantly reduce their gasoline consumption under different typical driving conditions [1]. Refer to Tony Markel, he states that the plug-in hybrid electric vehicle (PHEV) is a hybrid electric vehicle (HEV) with the ability to recharge its electrochemical energy storage with electricity from an off-board source such as the electric utility grid [8]. The vehicle can then drive in a charge-depleting (CD) mode that reduces the system’s state-of-charge (SOC), thereby using
electricity to displace liquid fuel that would otherwise have been consumed [9]. Thus, this type of hybrid electric vehicle can be operating efficiently based on their battery capacity.

3.2. Mild hybrid
The second type of HEV called mild hybrid system that cannot propel a vehicle on electric power alone. The used of electric motor was to start the combustion engine like start-stop function, thus to offer a boost function during acceleration or to enable for regenerative braking to recuperate energy [10]. The required voltage from the battery can be reduced compared to the fully hybrid or electric vehicles as the electric motors used in mild hybrid vehicles have a limited power less than 20kW, in order to reduce costs of the different components [10].

3.3. Fully hybrid
Fully hybrid vehicle can operate using just battery power without using an internal combustion engine. This makes this type of hybrid system more fuel efficient compared to the other type of hybrid vehicle. At the low speed, the electric motor is used because the electric motor is more efficient than the internal combustion engine [11][12]. The fully hybrid configuration allows for the pure electric drive under certain conditions. Hence, the ICE can be turned OFF, while the vehicle is moving. The ICE ON/OFF operation allowed by the full hybrid configuration contributed to qualifying this vehicle as the most fuel efficient midsize class vehicle by U.S. EPA in 2012 [11]. This type of HEV has a different type of operating mode based on the different function.

3.4 Small electric hybrid vehicle
Refer to basic three type of hybrid system above, it can be concluded that the most suitable hybrid system for small vehicle type was plug-in hybrid system. This result was supported by the design of plug-in hybrid system itself which is it can be an external source to charge the electric storage system. In this type of hybrid system, it can run individually whether in electric motor mode or with an internal combustion engine mode that run to charge the battery pack. They can store enough electricity from the power grid to significantly reduce their gasoline consumption under different typical driving conditions [1]. For the small vehicle system, the space was too limited with no external gearbox system that can design to charge the system like the dynamometer mechanism installed.

4. Type of hybrid electric vehicle drivetrain structure
In a hybrid electric vehicle, generally, there are four type of drivetrain structure which are series, parallel, series-parallel and complex hybrid [2][11][13] as shown in Figure 3. Commonly there are two type of hybrid electric vehicle drivetrain use nowadays especially for small gasoline engine which is series and parallel drivetrain. The hybrid vehicles do not require the change in the existing transmission and fuelling infrastructure compared with the introduction of electric vehicles, hydrogen or other alternative energy sources [14].
4.1. Series hybrid drivetrain

The internal combustion engine drives the electric motor and usually a three-phase alternator with rectifier instead of directly drives the wheels in a series hybrid system as shown in Figure 4 and Figure 5. The uses of the electric motor are only to providing the extra power to the wheels. The charging system for the batteries and power up the electric motor are commonly generated from the generator to move the vehicle [15]. P.Kamper state that series hybrids can be assisted by ultra-capacitors or a flywheel: KERS=Kinetic Energy Recuperation System, which can improve the efficiency by minimizing the losses in the battery [11].

Figure 3. Type of hybrid drivetrain operational system edited from [11]

Figure 4: Structure of a series hybrid vehicle drivetrain [11].

Figure 5: Structure of a series hybrid vehicle drivetrain with the flywheel as peak power unit [11][16].
They deliver peak energy during acceleration and take regenerative energy during braking. Therefore, the ultra-capacitors are functioning to keep charged at low speed and almost empty at top speed. Deep cycling of the battery is reduced, the stress factor of the battery is lowered [16].

Weaknesses of series hybrid vehicles:
  i. The ICE, the generator and the electric motor are dimensioned to handle the full power of the vehicle. Therefore, the total weight, cost, and size of the power train can be excessive.
  ii. The power from the combustion engine has to run through both the generator and the electric motor. During long-distance highway driving, the total efficiency is inferior to a conventional transmission, due to the several energy conversions.

Advantages of series hybrid vehicles:
  i. There is no mechanical link between the combustion engine and the wheels. The engine generator group can be located everywhere.
  ii. There are no conventional mechanical transmission elements (gearbox, transmission shafts). Separate electric wheel motors can be implemented easily.
  iii. The combustion engine can operate in a narrow rpm range (its most efficient range), even as the vehicles change speed.
  iv. Series hybrids are relatively the most efficient during stop-and-go city driving

4.2. Parallel hybrid drivetrain

In parallel drivetrain hybrid system, the internal combustion engine and electric motor are individually operated as shown in Figure 6 and Figure 7. Both of the internal combustion engine and electric motor are in parallel connection to a mechanical transmission.

Figure 6. Structure of a parallel hybrid electric vehicle drive train [16]  

Figure 7. Structure of a parallel hybrid vehicle drive train with the flywheel as peak power unit [16].

Most designs combine a large electrical generator and a motor into one unit, often located between the combustion engine and the transmission, replacing both the conventional starter motor and the alternator (see figures above). The battery unit can be recharged during regenerative braking, and during cruising (when the ICE power is higher than the required power for propulsion). As there is a fixed mechanical link between the wheels and the motor (no clutch), the battery cannot be charged when the car isn’t moving [17].
Weaknesses of parallel hybrid vehicles:
  i. Rather complicated system.
  ii. The ICE doesn’t operate in a narrow or constant RPM range; thus efficiency drops at low rotation speed.
  iii. As the ICE is not decoupled from the wheels, the battery cannot be charged at a standstill.

Advantages of parallel hybrid vehicles:
  i. Total efficiency is higher during cruising and long-distance highway driving.
  ii. Large flexibility to switch between electric and ICE power.
  iii. Compared to series hybrids, the electric motor can be designed less powerful than the ICE, as it is assisting traction. Only one electrical motor/generator is required.

4.3 Series-parallel combination drivetrain
In these type of combination hybrids, the internal combustion engine is also used to charge the battery as shown in Figure 8. Even though HEVs basically evolved as series or parallel drive, manufacturers then realized the advantages of a combination of the series and parallel drivetrain configurations for practical road vehicles. The recently available Toyota Prius is an example of such a hybrid, where a small series element is added to the primarily parallel HEV. The small series element ensures that the battery remains charged in prolonged wait periods, such as at traffic lights or in a traffic jam. These type of combination hybrids can be categories classify under parallel hybrids because they remain the parallel structure of a component arrangement[2].

![Series-parallel drive train structure HEV.](image)

The ICE drives the power split device to the wheel through the driveshaft and the electric generator is depending on the driving condition. The batteries are charged from the generator power. The electric motor can also transmit the power to the front wheels in parallel to the ICE. The inverter is bidirectional and is used to condition the power for the electric motor or to charge the batteries from the generator. The power control unit (PCU) regulated the power flow for the system by using multiple signals from the various sensor[2].

4.4 Complex hybrid drivetrain
The complex hybrid drivetrain consists of a complex configuration which cannot be classified into the other types of the drivetrain. The complex hybrid is similar to the series-parallel hybrid drivetrain. The generator and electric motor remain to function as electric machines. However, the key difference to this kind of
drivetrain is due to the bi-directional power flow of the electric motor in a complex hybrid structure and the unidirectional power flow of the generator in the series-parallel hybrid. The major disadvantage of a complex hybrid is higher complexity. The bidirectional power flow allowed the multifunction of operating modes, especially the three propulsion power operating mode. This type of mode cannot be offered by the other type of series and parallel hybrid drive train[18].

4.5 Small hybrid electric vehicle drivetrain
As referred to the development of a hybrid vehicle system for a small gasoline engine, the parallel type of drivetrain structure was the most suitable type of structure to be used. The advantage of this structure of the electric motor abilities can be less powerful than the ICE and it is assisting traction[18]. It only need a single electric motor to operate this hybrid system. The condition for as small vehicle which is smaller in size and limited spaces contributed to this finding of selection for parallel structure. The operating system for this type of structure also contribute to this selection factor which is the power input can be driven independently or separately.

5. Hybrid operating control system configuration
Hybrid operating control system can minimize some energy losses associated with engine operation mode either at some speed or load combination where the engine is inefficient by using the energy storage device. This allows the internal combustion engine to operate only at certain speed and loads where it is most efficient. When the system is stopped, it is better running the engine at the idle, where it is extremely inefficient. The control system may either shut off the engine or with the storage device providing auxiliary power. Due to the variations in HEV configurations, different power control strategies are necessary to regulate the power flow to or from different components [11]. All the control strategies aim to satisfy the following goals:

i. Maximum fuel efficiency [1][11][19]
ii. Minimum emissions [11][19]
iii. Minimum system costs [20][11][19]
iv. Good driving performance [11][12][21][22]

5.1 Operational mode by the load control
In operational mode by load, the systems will sensitive to the throttle. When the throttle is open too wide, the ICE will operate the system while the throttle is closed open, the electric motor will take place the operating system. At this type of operational mode, there are 5 phase of the system operating as bellow [23][24]:

i. Phase 1: At startup, the battery solely provides the necessary power to propel the vehicle and the ICE remains in off mode.
ii. Phase 2: During full throttle acceleration, both the ICE and the EM share the required traction power.
iii. Phase 3: During normal driving, the required traction power is provided by the ICE only and the EM remains in the off state.
iv. Phase 4: During normal braking or deceleration, the EM acts as a generator to charge the battery.
v. Phase 5: To charge the battery during driving, the ICE delivers the required traction power and also charges the battery. In this mode, the EM acts as a generator.
5.2 Operational mode by the speed control
This type of operational mode, the systems will sensitive to in vehicle speed. At every change of speed occur, the control system will receive the signal from the speedometer then convert the reading to the system. There are 4 type of phase for this type of operational mode that stated as below [19][23]:

i. Phase 1: During startup or full throttle acceleration both the ICE and the EM share the required power to propel the vehicle. Typically, the relative distribution between the ICE and electric motor is 80-20%.

ii. Phase 2: During normal driving, the required traction power is supplied by the ICE only and the EM remains in off mode.

iii. Phase 3: During braking or deceleration the EM acts as a generator to charge the battery via the power converter [13,14].

iv. Phase 4: Under light load condition, the traction power is delivered by the ICE and the ICE also charges the battery via the EM.

5.3 Operating mode for small hybrid vehicle system
From this two type of operating mode, it can be concluded that the operating mode by speed control is the most suitable for the small vehicle. This type of mode, the electric motor assists the ICE system when there is a drop in vehicle speed. That’s mean, the electric motor supports the ICE system at the higher load condition. As to develop the hybrid system for a small vehicle, the operating mode design is depending on the hybrid objective design. Small gasoline engine does not have any extra external gearbox system, thus from this type of operating mode, the system can function individually in the same system. For the example, the ICE can remain to drive the rear wheel while the electric motor can drive the front wheel.

6. Environmental effect from hybrid vehicles
Whenever a vehicle is started, sitting idle or in the driving condition it is producing emissions that are filling our atmosphere [7]. These emissions releases contain nitrogen gas (N2), carbon dioxide (CO2), water vapor (H2O), carbon monoxide (CO), hydrocarbons or volatile organic compounds (VOCs), and nitrogen oxides which is NO and NO2, together called NOx [26][27][28]. Many of these emissions are naturally occurring compounds but the concerning part about them is the levels in which they are produced by vehicles. According to the Environmental Protection Agency (EPA), the average surface temperature of the Earth has increased by about 1.2°F to 1.4°F in the past 100 years [7][20][3]. Experts predict that the average could, and most likely will increase to around 3.2°F to 7.2°F by approximately the year 2100 [7]. As the invention of the hybrid vehicle system aimed to minimize the global warming problem caused by the vehicle emission. Nowadays, most of the automotive industry player put more important objective of their company production to minimize the gas emission release by implementing the hybrid concept. Gases produced by vehicle should be controlled and proactive measures should be implemented as to minimize these type of pollutant emissions. The automotive industry has introduced hybrid cars, such as the Honda Insight and the Toyota Prius that minimize the use of combustion engines by integrating them with electric motors [6]. The environmental impact related to the vehicle production stage is associated with material extraction and processing, manufacturing and end-of-life utilization steps. Referring to R. Dhingra et.al, data on the gaseous emissions accompanying a typical vehicle are taken and presented in Table 3 below [26][29]:

Table 3(a): Environmental impact associated with vehicle production stages [26]
In this study, environmental impact is considered by examining air pollution (AP) and greenhouse gas (GHG) emissions. GHG and AP emissions also emanate from fuel production and utilization stages. The corresponding environmental impact has been evaluated in numerous life cycle assessments of fuel cycles. The environmental impact related to the vehicle production stage is associated with material extraction and processing, manufacturing and end-of-life utilization steps. Data on the gaseous emissions accompanying a typical vehicle are taken and are presented in Table 3(a) and Table 3(b). The \( AP_m \) emissions per unit curb mass of a conventional car are obtained by applying weighting coefficient’s to the masses of air pollutants in accordance with the formula:

\[
AP_m = \sum_i m_i w_i
\] (1)

Where \( i \) is the index denoting an air pollutant (CO, NOx, SOx, VOCs), \( m_i \) is the mass of air pollutant \( i \), and \( w_i \) is the weighting coefficient of air pollutant \( i \). The results of the environmental impact evaluation for the vehicle production stage for the vehicle types considered are presented in Table 3(a) and Table 3(b) above. We assumed that GHG and AP emissions are proportional to the vehicle mass, but the environmental impact related to the production of special devices in hybrid, electric and fuel cell cars, e.g., nickel metal hydride (NiMeH) batteries and fuel cell stacks, are evaluated separately.

### Table 3(b): Environmental impact associated with vehicle production stages [26]

| Type of car   | AP emissions per 100km of vehicle travel (kg per 100 km) | GHG emissions per 100km of vehicle travel (kg per 100 km) |
|--------------|--------------------------------------------------------|----------------------------------------------------------|
| Conventional | 0.00362                                                | 1.490                                                    |
| Hybrid       | 0.00419                                                | 1.722                                                    |
| Electric     | 0.00625                                                | 1.972                                                    |
| Fuel cell    | 0.0178                                                 | 4.074                                                    |

7. **Hybrid efficiency**

All hybrid vehicle system has their own operating efficiency based on hybrid design. As to obtain the hybrid operating efficiency result for this hybrid system for a small gasoline engine, the system must meet some criteria and parameter needed to find its efficiency. Refer to basic general efficiency equation for the general condition as mention in the equation below:

\[
\text{Efficiency} (\%) = \frac{P_{out}}{P_{in}} \times 100
\] (2)

Where:

\( P_{out} = \) total output power deliver from system
\[ P_{in} = \text{total input power by the system} \]

Where \( P_{out} \) is power output from the hybrid system and \( P_{in} \) power input from the hybrid system. \( P_{out} \) and \( P_{in} \) can be determined by the power produced by the hybrid system in terms of system performance or fuel consumption of the hybrid system.

\[
\begin{align*}
    P_{in1} &= P_{ice} \\
    P_{in2} &= P_{em} \\
    P_{in} &= P_{ice} @ P_{em} \\
    P_{out} &= P_{hybrid} = P_{ice} + P_{em} \\
    \text{Hybrid Efficiency (\%) } &= \frac{P_{ice} + P_{em}}{P_{in}} \times 100
\end{align*}
\] (3)

For example, the power input for the hybrid system denotes by fuel consumption. For load condition, the fuel consumed by the ICE is very higher, thus when support by turning on the electric motor system, the fuel consumed by the ICE will decrease automatically. Then, the hybrid efficiency in terms of fuel consumption can be measured by calculating the initial fuel consumption of the ICE before the electric motor assists \( P_{ice} \) and after assist. After assist will become the \( P_{hybrid} \).

8. Conclusion

Throughout certain condition based on hybrid operational mode designed such as idling state, the hybrid vehicle used no energy or less energy than a gasoline engine. At lower speeds, no emission is released maintaining its sustainable advantage. At the lower speed, the car operates on the electric motor and on cruising speed, it runs on IC engine [17]. They offer greater mileage or total distance travelled than the conventional vehicles [30]. Noise pollution and emission of CO2 is considerably reduced. However, they are quite expensive than conventional cars, are more complex in construction and working compared to IC engine cars. It can be concluded that the hybrid vehicle technology is the best way to reduce the global warming issues by reducing or eliminating the emission release from vehicle today.

Basically the development of standard hybrid electric vehicle and hybrid electric vehicle for small gasoline engine seen to have the similar method and component. For the drivetrain structure, the difference between it was the transmission system in term of combing gearbox. For a small gasoline engine, to implement the external gearing system for combining the electric motor together with internal combustion engine seem to be more complex. As to show the basic hybridize system, the system just runs separately in one closed system. The ICE drives the rear wheel while the EM drive the front wheel. To show the hybrid efficiency from this system, the electric motor must design to support the ICE at higher load condition. The operating system for this small hybrid vehicle system has shown in operational system subtopic.

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