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Effect of battery state of charge on fuel use and pollutant emissions of a full hybrid electric light duty vehicle

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HIGHLIGHTS

- On-road measurements performed on a full hybrid vehicle.
- Data analysis using the Vehicle Specific Power methodology.
- Analysis of internal combustion engine ON and OFF operation.
- Quantify the impact of battery state of charge on fuel use and pollutant emissions.
- Quantify effect of internal combustion engine OFF periods in pollutant emissions.

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ABSTRACT

This research work focuses on evaluating the effect of battery state of charge (SOC) in the fuel consumption and gaseous pollutant emissions of a Toyota Prius Full Hybrid Electric Vehicle, using the Vehicle Specific Power Methodology. Information on SOC, speed and engine management was obtained from the OBD interface, with additional data collected from a 5 gas analyzer and GPS receiver with barometric altimeter. Compared with average results, 40–50% battery SOC presented higher fuel consumption (57%), as well as higher CO_2 (56%), CO (27%) and NO_x (55.6%) emissions. For battery SOC between 50 and 60%, fuel consumption and CO_2 were 9.7% higher, CO was 1.6% lower and NO_x was 20.7% lower than average. For battery SOC between 60 and 70%, fuel consumption was 3.4% lower, CO_2 was 3.6% lower, CO was 6.9% higher and NO_x was 24.4% higher than average. For battery SOC between 70 and 80%, fuel consumption was 39.9% lower, CO_2 was 38% lower, CO was 33.9% lower and NO_x was 61.4% lower than average. The effect of engine OFF periods was analyzed for CO and NO_x emissions. For OFF periods higher than 30 s, increases of 63% and 73% respectively were observed.

1. Introduction

According to SAE, a hybrid vehicle is "a vehicle with two or more energy storage systems both of which must provide propulsion power – either together or independently" [1]. Regarding Hybrid Electric Vehicles (HEV) there are two inboard power sources, namely an electric battery – charged by the vehicle means – and an internal combustion engine (ICE). These vehicles can overcome some of the drawbacks of conventional technologies, namely operation at partial loads, especially on spark-ignition engines. Electric energy is generated by the vehicle means (internal combustion engine, regenerative braking, etc.) and is stored on an on-board electric battery.

There are three basic hybrid electric designs: parallel, series and parallel/series or full hybrid configurations. Parallel HEV available on market use the internal combustion engine and electric motor to move the wheels, with ICE as the main power source and electric assist, according to the driving condition. Battery energy flows to drive wheels via an electric motor that also can act as generator, recharging the battery [2,3]. Series HEV configuration use the ICE as generator and an electric motor to provide movement to the vehicle. This system can run with a small engine output with a stable operation efficiency region, supplying and generating electricity to the electric motor end being efficient in charging the battery [3–5].

In 1997, the Toyota Motor Company launched its mass production hybrid vehicle, the Toyota Prius. This vehicle uses the Toyota

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Hybrid System (THS), adopting a dual configuration, parallel/series design which can be called as "Full Hybrid". This architecture uses a planetary gear set – power split device – that allow the vehicle to be driven only by the ICE, only by the electric motor or by both simultaneously. The 2nd generation of THS, introduced in 2003, compared with similar conventional Toyota's vehicle, represented an improvement in fuel efficiency of 21% [6]. The current THS generation (2009) uses an ICE with 1.8 L capacity, 4 cylinders, Atkinson cycle engine with some electric auxiliaries, such as the water pump for improved efficiency [7]. The full hybrid configuration allows for pure electric drive under certain conditions, hence, ICE can be turned OFF, even while the vehicle is moving. The ICE ON/OFF operation allowed by the full hybrid configuration contributed to qualify this vehicle as the most fuel efficient midsize class vehicle by U.S. EPA in 2012 [8].

Internal combustion engine ON/OFF operation is very important when analyzing energy and pollutant emissions, either in this work using on-road data or during certification. United States HEV certification is based on continuous cycles performing charge sustaining tests (CST), weighted in order to measure exhaust emission and fuel economy [9]. Some approaches quantified the ICE ON/OFF operation defining rules in order to develop a fuel and exhaust emissions model for the full hybrid vehicle [10], concluding that the ICE is usually OFF at combinations of low acceleration and low to moderate speed or moderate speed and low acceleration. It is also OFF in cruising modes at low speed and at deceleration [10], which suggests the practical use of the full hybrid design to avoid the use of the ICE in partial loads regimes.

Hybrid strategy, ICE management, fuel use and emissions are explored in this work, making use of on-road measurements, providing better insight on full hybrid, regarding energy and environmental impacts. On-road data is analyzed using the vehicle specific power (VSP) methodology to provide an estimate of the power per mass (W kg^{-1}) demand, according to vehicle dynamic (speed and acceleration) and road grade. Using VSP methodology is possible to group point of similar power demand and assign the respective fuel consumption rate and pollutant mass rate.

The current research work presents both a macro analysis of energy and emission characterization – independently of the power source – but also focuses on ICE ON/OFF operation, according to the driving demands and battery state of charge (SOC).

The objective of this study is to analyze the impact of battery SOC on fuel use and emissions using the VSP modal analysis. Therefore, on-road monitoring was performed to characterize and analyze the vehicle powertrain in energy and environmental scope, focusing on hybrid energy management, ICE and battery operation, according to the driving conditions and SOC.

2. Experimental

Road test measurements were carried out with a vehicle provided by Toyota Caetano Portugal during 3 days. Data was collected at 1 Hz, using a portable emission measurement system (PEMS), comprehending more than 15,000 s (more than 4 h) of driving data, under urban, extra-urban and highway conditions around the Lisbon metropolitan area, for almost 180 km. Vehicle on-road, regular operation, was collected in 6 trips, each divided in 3 segments.

2.1. PEMS description

A PEMS system was installed in the vehicle in order to collect data in a 1 Hz basis, acquiring engine parameters, state of charge (SOC), exhaust gas composition, road topography and vehicle dynamics [11,12]. Information is acquired from several equipments, connected to a laptop and using purposely developed software. This way was possible to receive, integrate, synchronize and record data along the trips. The ICE data is acquired by a multi-protocol OBD port reader. The information obtained from the OBD port reader are vehicle speed, engine speed and load, airflow mass, manifold absolute pressure, intake air temperature, throttle position and coolant temperature. Battery SOC was also collected from the OBD, using a specific parameter identification code (PID), Hybrid/EV Battery Pack Remaining Charge, defined as "the percent remaining level of charge for the hybrid battery pack, expressed as a percentage of full charge, commonly referred to as State Of Charge (SOC)" [13].

A GPS receiver with integrated barometric altimeter is used to collect latitude, longitude and altitude along the trip for posterior calculation of the road grade. Tailpipe emissions were measured with a portable five gas analyzer. It provides simultaneous information about carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC), nitrous monoxide (NO) and oxygen (O_2). Non-dispersive infrared chambers are used to evaluate CO_2, CO and HC concentrations, while oxygen and NO are measured with electrochemical sensors.

Data collected allows estimating ICE fuel consumption and mass of pollutants present in the exhaust in a second by second basis.

2.2. Vehicle Specific Power methodology

The Vehicle Specific Power methodology is commonly used to perform an energy and environmental analysis [14–16]. This analysis provides an estimate of the power per mass unit that is necessary for a driving condition, based on a combination of vehicle dynamics (speed, acceleration, rolling and aerodynamic resistance) and road grade. Thus, each point of the trip is given the correspondent VSP, according to (Eq. (1)).

$$\mathrm{VSP} = v\cdot(1.1\cdot a + 9.81\cdot grade + 0.132) + 3.02\cdot10^{-4}\cdot v^3 \quad (1)$$

where: v: vehicle speed (m s^{-1}); a: vehicle acceleration (m s^{-2}); *grade*: road slope (m m^{-1}).

On-road data is grouped in a modal analysis, where each mode has statistically different fuel consumption values and none of them is dominant in the estimation of the trip total fuel consumption, resulting in 14 modes for Light Duty Vehicles [17].

2.3. Vehicle description

The tested vehicle is the 3rd generation of Toyota Prius, 2011 model year, which comprehends Toyota Hybrid Synergy (THS) Drive technology following the concept of full hybrid, providing parallel and series configurations of ICE and electric motor. Different strategies of propulsion could be arranged according to

Table 1
Summary of the characteristics of the vehicles tested.

	Toyota Prius T3 1.8 VVT-I Hybrid E-CVT
Fuel	Gasoline
ICE displacement (cc)	1798
ICE compression ratio	13:1
ICE power (kW RPM^{-1})	73/5200
ICE torque (Nm RPM^{-1})	142/4000
Electric motor type	Synchronous, permanent magnet
Electric motor (kW RPM^{-1})	60/–
Electric motor torque (Nm RPM^{-1})	207/–
Battery type	Nickuel metal hydride (Ni–Mh)
Battery capacity (Ah)	6.5
Battery nominal voltage (V)	201.6
Combined maximum power (kW)	100
Vehicle gross mass (kg)	1725