

Methods of Measuring Regenerative Braking Efficiency in a Test Cycle

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ABSTRACT

In Hybrid Electric Vehicles, Regenerative Braking is an essential function to convert vehicle kinetic energy into electrical energy, which charges the battery during a braking event to make a portion of captured kinetic energy available for use later. In comparison, conventional vehicles use friction brakes only and kinetic energy is dissipated as heat and not made available for later use. This paper introduces methods of evaluating Regenerative Braking Efficiency, including multiple efficiency definitions that lead to different attributes. The paper proposes regenerative brake event definitions during the FTP cycle and how they are used for control strategy and calibration updates. Also, we apply the efficiency metrics to four different vehicles from four automotive manufacturers for comparison. The paper presents a sample comparison result. Finally, we compare our efficiency metrics with the Environmental Protection Agency (U.S.EPA) official Brake Energy Recovery efficiency evaluation process.

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INTRODUCTION

Hybrid Electric Vehicle technology makes a significant contribution to reduce the fuel consumption, which is the major trend in the automotive industry. With less fuel consumed, hybrid electric vehicles satisfy the demand from the customers with increasing environmental consciousness, reduce the pollution and Carbon-Dioxide emissions, and also, provide benefits for automotive manufacturers to comply with government mandated fuel economy regulations.

Regenerative Braking function (Regen) is a key feature in Hybrid Electric Vehicle technology [1]. During a deceleration, the vehicle kinetic energy difference between high speed and low speed is collected by the regenerative braking function into the battery instead of being wasted as heat loss using conventional friction brakes.

Hybrid Electric Vehicles have various architectures such as Series, Parallel, Power-split, etc [2]. While the concept of regenerative braking is the same across architectures, the different architectures will have different implementation of regenerative braking. In this paper we focus on one of the parallel architectures shown as in [Figure 1](#)- Parallel Hybrid Architecture.

Some research and analysis on regenerative braking efficiency during a drive cycle had been done [3]. Previous papers referenced show the energy available and energy collected calculation for the whole cycle. Also, regenerative braking efficiency results from different vehicle manufacturers are shown [4]. In this paper, based on the parallel architecture with a transmission shown above, we create "Event Based" regenerative braking efficiency definitions. In our calculations, not only the efficiency for the whole FTP City cycle is shown, but also the efficiency calculation for each vehicle

deceleration event and how different gears and different shift schedules would affect the efficiency. With the information in detail for events, gears, and shifts, we have much more capability to perform the analysis on the FTP City cycle, to dig into each possibility that affects regenerative braking efficiencies, and finally, to improve the overall regenerative braking efficiency.

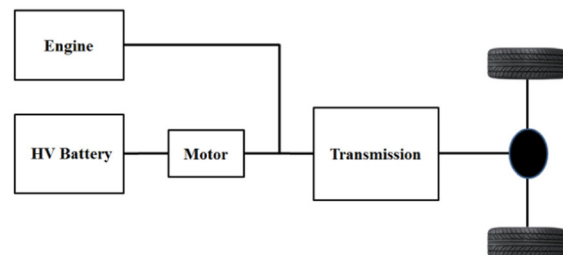


Figure 1. Parallel Hybrid Architecture

With the same regenerative braking efficiency metrics applied to different manufacturers' vehicles, including the braking events, in gear event, and in shift event, we have a clear understanding of the regenerative capabilities and performance, shift schedule design differences [5], etc, through the automotive industry.

The United States Environmental Protection Agency has a "Brake Energy Recovery Efficiency" definition [6], which is used to decide if a hybrid vehicle is a "Strong Hybrid" or "Mild Hybrid". The EPA efficiency defines the energy available and energy collected in a similar way with our metrics, based on the vehicle kinetic energy and the energy into the battery. However, compared with our metrics, the EPA definition does not separate any energy going into the battery from engine charging (engine fuel energy converted to electrical

energy via the electric motor to charge the battery), and it does not have any “Event Based” efficiency calculations. The difference between our method and the EPA method, and a sample EPA efficiency result with the same four manufacturers’ vehicles, are discussed in the EPA “Strong Hybrid” Definition section.

REGENERATIVE EVENT DEFINITIONS

Regenerative Braking performs the same function as the traditional friction braking for vehicle deceleration. Therefore, to evaluate the performance of Regenerative Braking, we need to select the time windows where the vehicle is decelerating so there is available kinetic energy for Regen to collect, and eliminate the time windows where the Regen function is off as the vehicle is accelerating. The time windows we select, in this paper, are called “Regenerative Events”, which includes: Braking Event, In Gear Event, and In Shift Event (see Figure 2 - Regenerative Events Definition).

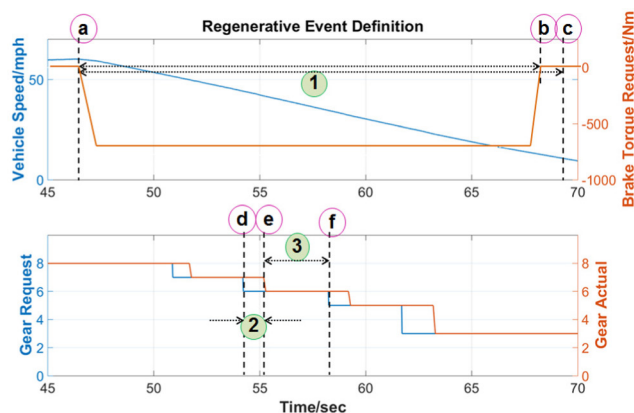


Figure 2. Regenerative Events Definition

Where:

- 1 Braking Event
- 2 In Shift Event
- 3 In Gear Event
- a Braking Event Start Trigger: Brake Torque < threshold_tq
- b Braking Event Stop Trigger1: Brake Torque >= threshold_tq
- c Braking Event Stop Trigger2: Vehicle Speed < threshold_spd
- d In Shift Start/In Gear Stop Trigger: Gear Request deviates from Gear Actual
- e In Gear Start/In Shift Stop Trigger: Gear Request == Gear Actual
- f Same as d

Braking Event

Braking Event starts when the brake torque request passes the pre-set torque threshold, which means the vehicle starts to decelerate, and thus kinetic energy needs to be collected or consumed; Braking Event stops based on two conditions: 1. When brake torque request is less than the pre-set torque threshold, meaning the vehicle is not decelerating any more, and no braking kinetic energy is available; 2. When vehicle speed is lower than the pre-set speed threshold. The speed threshold is used for practicality of testing procedures (some

braking tests do not go all the way to zero vehicle speed). The speed threshold is set low enough so the amount of kinetic energy not included is very small, for instance on the order of 1% of a typical Braking Event from 30 mph.

During a Braking Event, the powertrain may or may not be able to provide enough regenerative brake torque to meet the driver’s brake request. If the driver’s request is beyond the powertrain regenerative braking capability, the regenerative system would provide braking torque at its maximum limit, and friction braking must fill in to make up the difference. The powertrain regenerative braking capability changes with transmission ratio, where more regenerative wheel torque is available with higher transmission ratios. The system tends to be able to satisfy the driver braking request at lower gears (higher ratios) and not satisfy it at higher gears (lower ratios).

As vehicle speed gets very low during Braking Event the powertrain regenerative braking wheel torque must “blend out” while (some) friction braking wheel torque “blends in” (in order to replace this powertrain torque that “blends out”). This is done for a few reasons: brake system traction stability limits on powertrain torque at very low vehicle speed; to hold the vehicle stationary while stopped; some system architectures such as discussed in this paper have a lower limit on the motor speed – the transmission cannot stay in a locked state all the way down to zero speed and must unlock before that, thus regen braking must be blended out before unlocking the transmission.

In Gear Event

In Gear Event starts when a shift finishes, for example, when the Gear Actual equals the Gear Request; In Gear Event ends when a shift starts, which is when the Gear Request starts to change. Also, the start of a Braking Event could also be the start of In Gear Event if it falls inside the “In Gear” region (i.e. if a Braking Event happens while in 8th gear, then the Braking Event start point is also the start of the In 8th Gear Event); the same rule applies to the end point of a Braking Event.

As we discussed in the Braking Event section, the regenerative braking capability is limited in higher gears and while vehicle speed is very low (in lower gears), so at first friction braking maybe used in higher gears, then removed after some downshifts, and finally filled in again in low gears. With the In Gear Event definition, we could keep track of the efficiencies in different gears, which helps us modify our shift schedules to stay in more efficient gears longer to get better efficiency for the entire braking event. It can also help us find the exact gears in which the friction brake starts to fade out or come in, which provides more information for the calibration process.

In Shift Event

In Shift Event starts when the Gear Request changes, and ends when Gear Actual and Gear Request match. Notice that the In Shift start point does NOT require the Gear Request to change from the match point with the Gear Actual, as there are situations where one shift happens right at (or even before) the previous shift end point. In this case, there is no In Gear Event in between two consecutive In Shift Events.

During an In Shift Event, in addition to providing the regenerative brake torque, the motor also has to reduce the input torque to make the wheel torque smooth as the torque ratio changes. Also, in most cases, In Shift Events do not last long (~1sec). Therefore, the available energy during a shift is not as “significant” as that during an In Gear Event. Actually, the smoothness of a shift is more critical, and the In Shift Efficiency is mostly used as a reference to ensure regenerative braking is functioning.

EFFICIENCY DEFINITIONS

Two main efficiency definitions to help us evaluate our regenerative braking system performance were built: Overall Efficiency and Powertrain Efficiency. The efficiency definitions can be easily applied to our benchmarking vehicles so we have identical calculations for different vehicles to get reasonable comparisons.

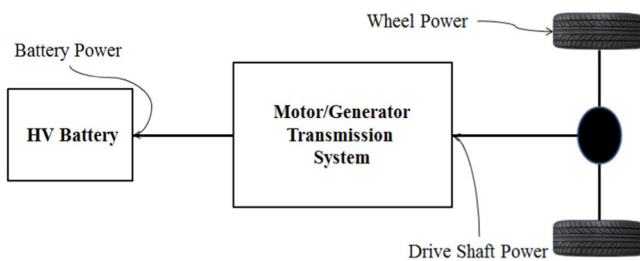


Figure 3. Power Definition with P2 Architecture

To perform the efficiency calculations, we need two main elements: energy available and energy collected. The following sub-sections introduce the appropriate energy calculations we used (See Figure 3 – Power Definition with P2 Architecture).

Wheel Power/Energy

We apply the force analysis on the vehicle longitudinal axis assuming the ground is flat: Total force acting on the vehicle consists of two parts: the drive force from the vehicle powertrain, and the resistant roadload force from the environment. Environmental Protection Agency (EPA) has regulations for roadload force calculation, and provides the “F-Terms” needed for each test vehicle [7]. Using the EPA information, we have the roadload force:

$$F_{RoadLoad} = (f_0 + f_1 \times v_{mph} + f_2 \times v_{mph}^2) \times Unit_{lbf \rightarrow N} \quad (1)$$

Where, f_0 , f_1 , f_2 are F-Terms from EPA, v_{mph} is the vehicle speed in mile/hour, Unit converts Force from lbf to Newton.

To get the total force acting on the vehicle, we take the derivative of the vehicle speed to get the vehicle acceleration/deceleration, and use Newton’s Second Law with the test vehicle weight M_{veh} :

$$F_{Total} = M_{veh} \cdot \frac{dv_{m/s}}{dt} \quad (2)$$

Then, we get the drive force based on the roadload force and total force. With the vehicle speed in m/s, we get the time based drive power, and we call it “Wheel Power” in the paper:

$$F_{Wheel} = F_{Total} - F_{RoadLoad} \quad (3)$$

$$P_{Wheel} = F_{Wheel} \cdot v_{m/s} \quad (4)$$

We have discussed the Regenerative Braking Events in the previous section. For each of the Braking Event, In Gear Event, and In Shift Event, we have an event start time and an event end time: t_{start} and t_{end} . By integrating the Wheel Power through each event time span, we are able to get the amount of Wheel Energy for each event. This wheel energy is defined as “Total Energy available during an event”.

$$E_{Wheel} = \int_{t_{start}}^{t_{end}} P_{Wheel} \cdot dt \quad (5)$$

Battery Power/Energy

Battery Power calculation is straightforward: we multiply the battery current and battery voltage to get the battery power.

$$P_{Battery} = I_{Battery} \cdot V_{Battery} \quad (6)$$

However, when we consider regenerative braking event, we want to know how much battery power is from braking using the powertrain only. In this case, if the engine is running during a regenerative event and is charging the battery, we would have to remove that portion from the battery power:

$$P_{Battery} = I_{Battery} \cdot V_{Battery} - P_{engine} \times \eta_{motor} \quad (7)$$

Where, P_{engine} is Engine Power, η_{motor} is the motor efficiency

Again, integrating the battery power using the start and end time of each event, we are able to get the amount of Battery Energy for each event. This Battery Energy is defined as “Energy collected during an event”.

$$E_{Battery} = \int_{t_{start}}^{t_{end}} P_{Battery} \cdot dt \quad (8)$$

Overall Efficiency (Event/Cycle)

For each event (Braking, In Gear, In Shift), we have the Battery Energy and Wheel Energy calculated as the energy collected and energy available. The overall efficiency for each event is calculated below:

$$Eff_{Overall} = \frac{E_{Battery}}{E_{Wheel}}$$