

Analysis of Input Power, Energy Availability, and Efficiency during Deceleration for X-EV Vehicles

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ABSTRACT

The recovery of braking energy through regenerative braking is a key enabler for the improved efficiency of Hybrid Electric Vehicles, Plug-in Hybrid Electric, and Battery Electric Vehicles (HEV, PHEV, BEV). However, this energy is often treated in a simplified fashion, frequently using an overall regeneration efficiency term, ξ_{rg} [1], which is then applied to the total available braking energy of a given drive-cycle.

In addition to the ability to recapture braking energy typically lost during vehicle deceleration, hybrid and plug-in hybrid vehicles also allow for reduced or zero engine fueling during vehicle decelerations. While regenerative braking is often discussed as an enabler for improved fuel economy, reduced fueling is also an important component of a hybrid vehicle's ability to improve overall fuel economy. Much like energy captured through regenerative braking, engine fueling during deceleration is also often treated using an estimated deceleration fueling rate which is then applied to the total time of deceleration for a particular drive cycle.

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INTRODUCTION

Regenerative braking systems are often sized to accommodate vehicle decelerations close to those seen in common regulatory cycles, which may or may not effectively capture a significant portion of the braking energy available during real-world driving. Moreover, vehicle regenerative braking capability is often also dictated by issues related to vehicle stability and drive-ability. These limitations dramatically alter the efficiency with which braking energy can be captured depending on the vehicle speed and amount of deceleration requested, thus making ξ_{rg} a much more complicated calculation. For example, simply increasing battery input power may not directly correspond to an increase in recovered braking energy if other vehicle limitations are the determining factor for the amount of energy recovered during a particular deceleration event. Similarly, the net road load force acting on the vehicle during deceleration, which reduces the required braking system energy, can be reduced via more rapid deceleration. However, the required additional braking force could nevertheless result in reduced regenerative braking energy capture if the vehicle braking system's regenerative capability is exceeded.

Generalized Equations for Fueling and Braking Energy

Sovran and Blaser [1] discuss two particularly relevant quantities pertaining to the fuel and energy consumption of X-EV vehicles during deceleration events. More specifically, they discuss the fuel used during braking and the energy recovered by braking shown in Equations 1 and 2, respectively. The mass of fuel used during braking for a particular drive cycle is calculated as

$$m_{brkg} = \overline{(\dot{m})}_{brkg}(T - \tau - t_{idle}) \quad (Eq. 1)$$

Where $\dot{m}$ [kg/s] is the estimated fuel rate during vehicle decelerations and $(T - \tau - t_{idle})$ represents the braking time for a particular cycle of T total time with τ duration of powered driving and t_{idle} duration of idle.

In later work, Sovran and Blaser [2,3] move toward more deeply evaluating braking energy, calculating braking energy available for a particular drive cycle as

$$E_{BR} = E_k - (E_R - E_D) \quad (Eq. 2)$$

Where E_k represents the vehicle kinetic energy removed during deceleration; E_R and E_D represent the energies removed by rolling and aerodynamic resistances. When using a chassis dynamometer, the rolling and aerodynamic resistance terms in Equation 2 are typically represented by a single “road-load” equation that is a function of vehicle speed. Using Equation 3, the energy recovered by regenerative braking is defined using a simple efficiency term applied to the braking energy

$$E_{rg} = \xi E_{BR} \quad (Eq. 3)$$

With Equations 1 and 3 in mind, this work seeks to evaluate how well the terms work for a variety of recently evaluated vehicles and drive cycles.

Instrumentation and Selected Vehicle Overview

In collaboration with other national laboratories and the US Department of Energy, Argonne National Laboratory evaluates a wide range of vehicles using a chassis dynamometer. Results contained in this report are derived from 2WD vehicle testing on the chassis dynamometer at EPA specified road load and test weight class unless otherwise specified. The majority of testing was done using standard regulatory drive cycles including the Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HWFET or Hwy), and US06, which respectively represent city, highway under 60 mph, and aggressive driving conditions. Overall tractive force and vehicle speed in this work are calculated by the dynamometer and provided to the data acquisition system. Axle torque shown in this work was collected using half-shafts instrumented with an inductively coupled, strain gauge based measurement system [4]. Unless otherwise mentioned, fuel and electrical power measurements are taken using a direct in-line fuel scale and power analyzer [6] respectively. Engine speed is collected from the vehicle communication network (CAN).

While certainly not exhaustive, vehicles used for this work were selected to span the range of vehicle type/electric utility from HEV to BEV. This range of vehicle types is important since electric traction capability and fueling during decelerations vary significantly as component and vehicle capability changes. Table 1 shows relevant system capabilities for the vehicles discussed in this analysis [7, 8, 9, 10, 11].

Table 1. Highlighted specifications for selected X-EV vehicles

	Traction Motor Max. Torque (Nm)	Traction Motor Max. Power (kW)	Max Battery Power (kW)	X-EV Type
MY 2010 Toyota Prius	207	60	27	HEV
MY 2011 Hyundai Sonata	200	30	34	HEV
MY 2012 Toyota Prius - PHEV	207	60	38	PHEV - Blended
MY 2012 Chevrolet Volt	370	110	110+	PHEV - EREV
MY 2012 Nissan Leaf	280	80	90	BEV

Fueling Modes During Vehicle Deceleration

Conventional Vehicles

While this work focuses primarily on hybrid vehicles, it is important to begin the discussion regarding behavior during deceleration with a conventional vehicle, i.e., not possessing a secondary propulsion pathway. In keeping with Sovran and Blaser [1], three possible scenarios with negative inertia are possible. In the first scenario, tractive force (F_{tr}), the force required by the vehicle at the road surface, is actually positive, which requires engine fueling (torque production) in order to provide positive traction power. Figure 1 illustrates the fueling behavior for two conventional vehicles during one of these events (824-830s). As expected, the engine is fueled despite the reduction in vehicle speed.

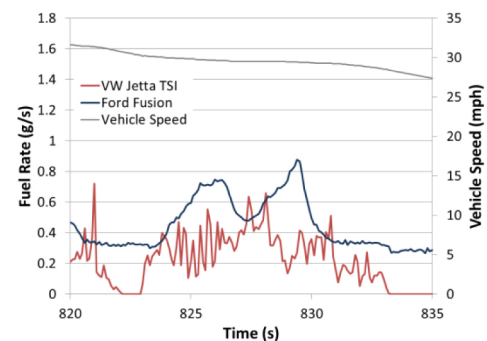


Figure 1. Example conventional vehicle fuel rate during powered deceleration

The next and much more prevalent scenario is that of negative F_{tr} and thus the need for a braking force applied at the tire/road interface. Sovran and Blaser also discuss a third, fairly unlikely, scenario where F_{tr} actually equals zero. This work focuses predominantly on $F_{tr} < 0$ events. Not only are these events the most prevalent deceleration events encountered during most driving styles, they also offer the opportunity to recapture braking energy, which allows for improved fuel economy.

Within the context of these negative tractive force events, two distinct vehicle behaviors can be observed for conventional vehicles. Figure 2 shows the fueling rates for two vehicles during a fairly nominal deceleration event from the UDDS cycle. The Ford Fusion shown in blue shows behavior that would be consistent with the estimated deceleration fuel rate discussed in Equation 1. In contrast, the VW Jetta TSI shown in red shows no fueling during the entire deceleration event. This deceleration without engine fueling is frequently referred to as Decel. Fuel Cut-off (DFCO). As the vehicle approaches zero speed, the engine fueling resumes, but during this deceleration event there is very limited fueling.

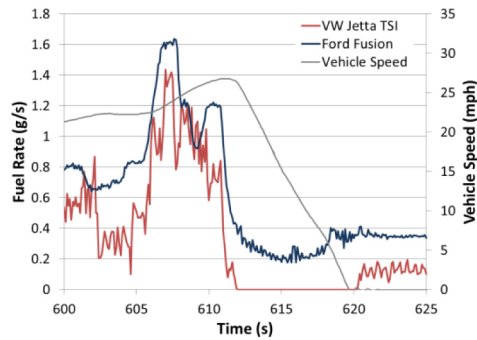


Figure 2. Example conventional vehicle fuel rates during normal deceleration

The second type of possible behavior is illustrated by the Ford Fusion (blue) in [Figure 3](#). In contrast to the previous cycle where the Fusion showed engine fueling during the entire deceleration event, this deceleration event shows no fueling for both the Fusion and the Jetta during a portion of the deceleration event. Specifically, at higher vehicle speeds, both vehicles show DFCO operation. Once the vehicle speed is decreased, the Fusion again begins to fuel the engine

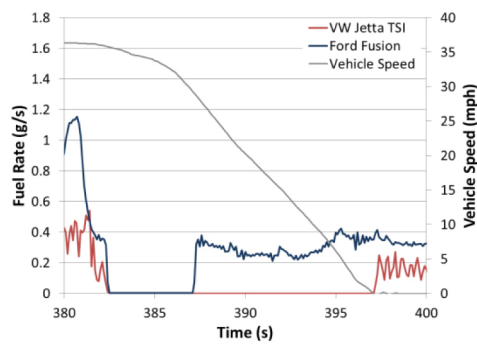


Figure 3. Example conventional vehicle fueling rates with some DFCO for both vehicles.

Hybrid and Plug-in Hybrid Vehicles

Hybrid vehicles possess an alternative propulsion path, namely the electric traction system for a Hybrid Electric Vehicle (HEV), which enables significant amount of unfueled vehicle operation. Moreover, this work focuses on vehicles with a significant amount of electric operating capability and thus the ability to operate on battery power for a range of positive tractive power. With this capability in mind, [Figure 4](#) shows electric operation (no fueling) for an $F_{tr} > 0$ deceleration event. Similarly, [Figure 5](#) shows unfueled behavior for the same nominal deceleration event as shown in [Figure 2](#) for the conventional vehicle.

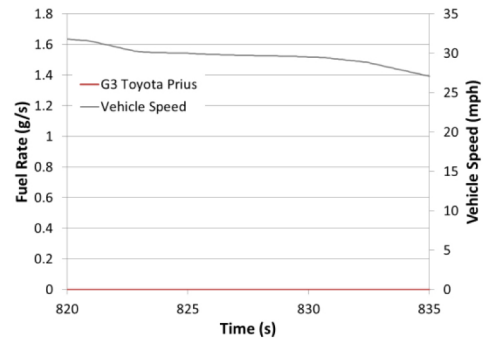


Figure 4. Example hybrid vehicle fueling during powered deceleration.

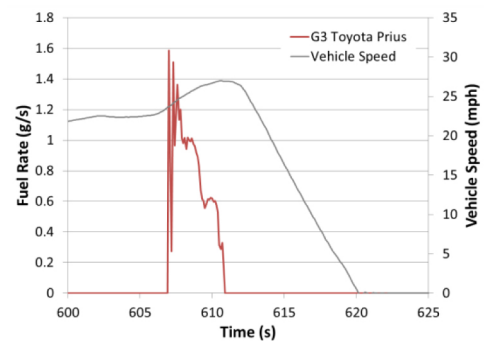


Figure 5. Example hybrid vehicle fueling rate during deceleration (~613 s).

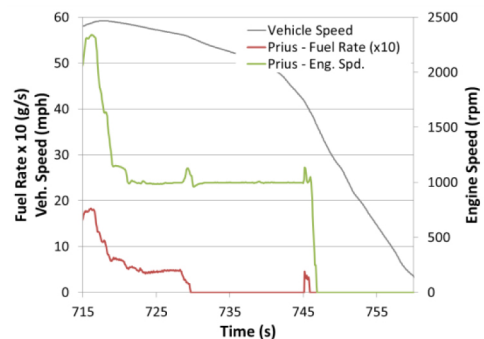


Figure 6. Example hybrid vehicle deceleration including restart protection

While hybrid vehicles do allow for a significant portion of decelerations to be accommodated by all-electric operation, there are some scenarios that do not do so. [Figure 6](#) shows a deceleration event beginning at a relatively high speed. Several unique behaviors can be seen in this figure. Engine speed, plotted in green, can be seen to be non-zero for a large portion of the deceleration event. Furthermore, fueling, in red near the bottom of the plot, can be seen to be non-zero for the initial portion of the deceleration event and then decreases to zero despite the non-zero engine speed. This behavior is typically observed in situations where engine restart

protection is prioritized due to the increased probability of a relatively high engine power request.

Battery size, generator/starter sizing, and powertrain architecture also factor into behavior during decelerations. Namely, these characteristics determine how quickly an engine can be spun-up and restarted as well as the maximum speed a vehicle can run with the engine at zero speed. While fueling during decelerations obviously decreases fuel economy, spinning the engine also reduces fuel economy by diminishing the energy recaptured through regenerative braking.

In addition to these basic issues regarding deceleration behavior for hybrid vehicles, many more vehicle specific behaviors that increase fueling and/or reduce regenerative energy capture exist. Issues such as driving dynamics, desired vehicle “feel”, and noise/vibration/harshness (NVH) often drive the fueling and engine speed behavior during deceleration for a particular vehicle.

Basic Restrictions on Regenerative Energy Capture

While an extensive theoretical discussion about the various limitations on regenerative energy capture is outside the scope and intent of this work, several basic limitations and issues will be addressed to provide context to the regenerative braking envelopes shown later in this work. The three main limitations to regenerative braking are shown in Figure 7.

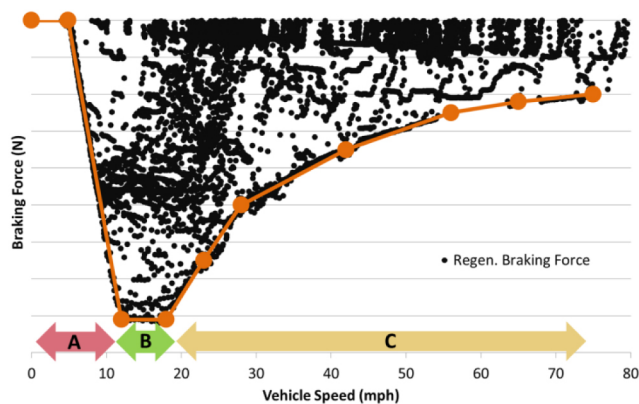


Figure 7. Example Regenerative Braking Envelope.

Area A represents the ramp-in of regenerative braking from 0% of maximum regenerative braking force at very low speeds to 100% of maximum braking force, still at relatively low speeds. This ramp-in is primarily due to the fact that for efficiency reasons the friction brakes will eventually be applied at zero or near-zero vehicle speeds. Thus, in order to have a suitably acceptable pedal feel and vehicle smoothness, the regenerative braking force is gradually reduced as the vehicle slows [12], thus the ramp-in, or rather ramp-out of regenerative braking in the case of decreasing speed, as the vehicle slows. Regardless of system capability, Area A will dramatically reduce the amount of braking energy recaptured

during low speed operation. Although the energy available at low speeds is relatively smaller, it may or may not be significant depending on the mix of low versus high speed operation for a particular drive cycle or real-world operation.

Area B represents “maximum” regenerative braking force. This region could represent the maximum torque capability of a particular electric traction system, but in practice and especially for PHEVs and BEVs with larger electric traction capability, this limit is often below the traction capability of a particular vehicle. There is a preponderance of literature attributing this effect to various mechanics, but the crux of these issues relates to the limits of braking force balance between front and rear axles and vehicle stability. For a non-four-wheel-drive vehicle, regenerative energy capture is done exclusively on a particular drive axle (front or rear). This skewed balance offsets the traditional front/rear balance which has been optimized for vehicle handling/dynamics [13]. For a front drive system, braking force can be applied exclusively on the front axle up to a particular limit which depends on several vehicle parameters such as mass, center of gravity, and weight distribution. Above this limit and without a minimum level of rear braking, the front wheels will lock and road adhesion will be greatly diminished, an unfavorable condition to be avoided. In fact, ECE R13H [15] provides guidance related to the minimum rear braking required to avoid loss of adhesion. While additional regenerative braking force could be utilized with supplementary rear braking, it is the opinion of the author that this condition is not likely to be used because in the event of a regenerative braking system failure (or dramatic change in capability) the rear braking force will be much greater than the front braking force, which leads to the rear wheels locking and dangerous vehicle instability. The actual limits for several recent vehicles will be discussed later in this document.

While the subject vehicles in this work are all front-wheel drive, it is worth mentioning that rear-drive vehicles typically allow for regenerative braking using the rear axle exclusively, which is a much more restricted case. As mentioned previously, with significant braking force on the rear axle, vehicle instability is likely, thus a rear drive vehicle must either brake with both front and rear brakes, or utilize rear-only regenerative braking within a much smaller envelope. In fact, 0.15g maximum exclusive rear braking appears to be suggested in ECE R13H. As vehicle electric traction capability increases, this “maximum” regenerative braking force constraint, Area B, becomes increasingly important. While the example in Figure 7 has a very small Area B, analysis later in this work shows that PHEVs and BEVs are limited across a fairly wide range of vehicle speeds. With this issue in mind, increasing battery and/or electric traction capability alone will not increase regenerative energy recaptured in Area B and thus the benefit of adding increased capability may be overstated for a particular driving style if this constraint is not properly assessed.

Area C in Figure 7 represents power based limitations of the electric traction system. This may be due to either traction