

The GM “Voltec” 4ET50 Multi-Mode Electric Transaxle

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Michael A. Miller, Alan G. Holmes, Brendan M. Conlon and Peter J. Savagian
General Motors Company

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ABSTRACT

The Chevrolet Volt is an electric vehicle (EV) that operates exclusively on battery power as long as useful energy is available in the battery pack under normal conditions. After the battery is depleted of available energy, extended-range (ER) driving uses fuel energy in an internal combustion engine (ICE), an on-board generator, and a large electric driving motor. This extended-range electric vehicle (EREV) utilizes electric energy in an automobile more effectively than a plug-in hybrid electric vehicle (PHEV), which characteristically blends electric and engine power together during driving. A specialized EREV powertrain, called the “Voltec”, drives the Volt through its entire range of speed and acceleration with battery power alone, within the limit of battery energy, thereby displacing more fuel with electricity, emitting less CO₂, and producing less cold-start emissions than a PHEV operating in real world conditions.

The Voltec powertrain architecture provides four modes of operation, including two that are unique and maximize the Volt's efficiency and performance. The specialized electric transaxle, known as the 4ET50, enables patented operating modes both to improve electric driving range when operating as a Battery Electric Vehicle (BEV) and to reduce fuel consumption when extending range by operating with the ICE.

Historically, most EVs have used a single-speed electric transaxle with one motor and a fixed gear reduction. The single-speed gear reduction is a simple arrangement that takes advantage of the wide speed range of electric motors. While this arrangement can work well, the wide speed range of most electric motors comes at the price of a well known loss of efficiency at higher motor speeds for most types of motors. Consequently, two-speed transmissions have been proposed

for BEVs that can improve both tractive effort and efficiency although with the attendant additional extra gear shift hardware and controls.

The Voltec 4ET50 multi-mode electric transaxle introduces a unique two-motor EV driving mode that allows both the driving motor and the generator to simultaneously provide tractive effort while reducing electric motor speeds and the total associated electric motor losses. This new operating mode, however, does not introduce the torque discontinuities associated with a two-speed EV drive. For ER operation, the Voltec transaxle uses the same hardware and controls that enable one-motor and two-motor EV operation to provide both the completely decoupled action of a pure series hybrid, as well as a more efficient powerflow with decoupled action for driving at light loads and high vehicle speed.

Construction of the GM Voltec 4ET50 transaxle employs significant re-use of the GM front wheel drive Two-Mode Hybrid 2MT70 transaxle with modifications to enable all-speed and full-power EV operation. A new high power driving motor, optimized generator, and modified control elements allow the two EV driving modes and the two ER driving modes to be realized in the Chevrolet Volt.

INTRODUCTION

VEHICLE TYPES AND ELECTRIC UTILITY

Hybrid Electric Vehicle (HEV)

A hybrid is defined by SAE [1] as: “A vehicle with two or more energy storage systems both of which must provide propulsion power - either together or independently.” In practice, hybrid vehicles typically require a combination both sources to provide full vehicle capability. The engine is also

typically the larger of the two propulsion sources, being sized to provide most of the power during high power vehicle events. The motor is typically the smaller of the two propulsion sources, being sized for transient events to maximize the amount of energy that can be captured during braking and for limited low speed EV operation.

The powertrain of an HEV incorporates significantly large electric motors, power electronics and a battery pack (or RESS - Rechargeable Energy Storage System), to make a more efficient vehicle. However, the HEV does not directly displace petroleum with electrical energy for driving the vehicle. Electric Driving Utility is defined as percentage of real world driving where propulsion power is provided by energy that comes from the electric grid. The electric utility of an HEV is 0% for all driving.

Plug-in Hybrid (PHEV)

A PHEV has been defined by SAE [1] as: “A hybrid vehicle with the ability to store and use off-board electrical energy in the RESS.” These systems are, in effect, an incremental improvement over the HEV, with the addition of a large battery with greater energy storage capability, a charger, and modified controls.

Since PHEVs, commonly referred to as blended PHEVs, do not offer full electric driving capability, there are limits to EV driving based on the power capacity of the battery, electronics, interconnects, motors and associated thermal systems, as well as the kinematics of the hybrid transmission. Accordingly, there are different types of PHEV operating limits and strategies. This means a “charge depleting” mode exists where the engine comes on as the battery is discharging and both energy sources are blended to drive the vehicle. Typically, the utility of electric driving is limited in PHEVs, and the full effects of and benefits of using grid energy instead of fossil fuel can only be partially realized as analyzed and discussed in [2],[3], and[4].

Over the charge depleting range, electric energy utility, or the percentage of total energy supplied to the output from the battery during depletion, was limited to about 70% for a PHEV in real world driving [4].

Extended-Range Electric Vehicle (EREV)

SAE has not yet established a definition for an EREV. However, several automakers describe them using the definition provided in [2], “A vehicle that functions as a full-performance battery electric vehicle when energy is available from an onboard RESS and having an auxiliary energy supply that is only engaged when the RESS energy is not available.”

An EREV has 100% electric energy utility over the charge depleting range. To do so, the EREV must have sufficient

motor, inverter, interconnects, RESS, and thermal system power capacity. While depleting in EV mode, the engine does not assist in propulsion. Rather, an EREV relies on 100% electric energy for all wide open throttle events, high-speed freeway cruising, and extended grade conditions.

Battery Electric Vehicle (BEV)

the SAE [1] defines a BEV, or more plainly, an EV, as “A vehicle powered solely by energy stored in an electrochemical device.”

The BEV is the simplest form of the electric vehicle, and has 100% electric energy utility for all driving distances and as such, like the EREV must have sufficient power capacity in the driving motor, inverter, interconnects, RESS, and thermal systems.

However, the driving distance of the BEV is severely limited to only that energy that is available in the RESS.

Table 1. Attributes of Electric Vehicles

Vehicle Type	Electric Power	Onboard Electric Storage	Grid Recharge	Electric Energy Utilitiy	Range Limit
HEV	Low to med	low	no	0%	Gasoline
PHEV	med	med	yes	~70%	Gasoline + Battery
EREV	high	high	yes	100%	Battery + Gasoline
BEV	high	highest	yes	100%	Battery

Table 1 shows a summary of HEV and BEV vehicle attributes. Full Electric Driving Capability is an attribute that defines the EREV, just like a BEV. But unlike the BEV, the vehicle's total range is not limited by the energy in the battery; rather the energy in the battery *combined* with the fuel in the tank.

EREV SYSTEM REQUIREMENTS

In order to meet the customer's expectations, the EREV system must provide excellent performance in both EV and ER modes. Table 2 lists key requirements that help to define the system.

Table 2. EREV System Requirements

Vehicle Requirement	EV Req't	ER Req't
Vehicle Acceleration	X	X
Vehicle Top Speed	X	X
Launch Acceleration	X	X
Sustained Gradeability	X	X
Fuel Economy		X
All-Electric Range	X	
Extended Range		X

Peak Tractive Effort

The requirements for vehicle acceleration, top speed, and launch acceleration together define a tractive effort curve that is required to be achieved both in EV and ER modes, as shown in Figure 1. To meet these requirements, the system should be capable of transmitting a large amount of power from either the battery or the engine during acceleration over a large range of vehicle speeds.

Continuous Tractive Effort

The requirements for Gradeability and Top Speed also define an envelope of continuous operation. Under these conditions, the system must be able to operate for long durations with adequate cooling of components. By determining the torques and powers of the electric machines under these conditions, the selection of the transmission powerflow determines both the peak and continuous sizing of the motors, inverters, and gearing.

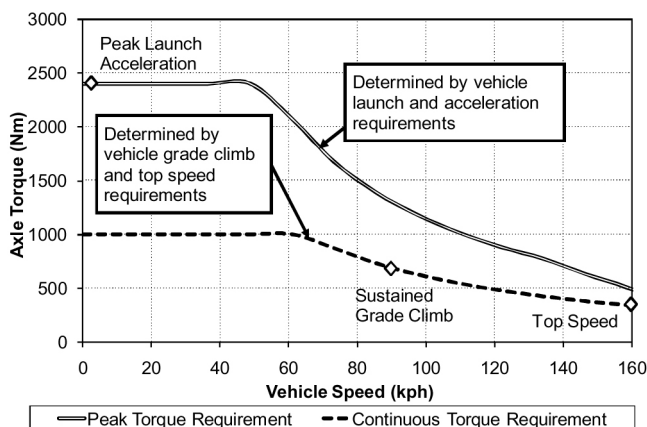


Figure 1. EREV System Torque Requirements

EV Range and ER Fuel Economy

Since range and fuel economy requirements apply under different system operating modes, tradeoffs can occur where some systems are optimized for EV range at the expense of fuel economy, or vice versa. A design goal of the system is to provide good efficiency as an EV drive, thus efficiency should be comparable to a system designed as a BEV drive unit. On the other hand, when operating in range extending mode, the system should have fuel economy comparable to the best IC engine systems available. In this situation, highway fuel economy could be expected to be particularly important to the customer, as trips which exceed the EV range are likely to involve highway driving.

EV Drive Character

An EREV has two distinct operating modes: EV and ER. When operating as an EV, the system is capable of providing quick, smooth response to driver commanded torque due to the wide constant power characteristics and inherently fast transient response capability of electric drives. It is desirable to maintain these characteristics when operating in electric drive mode and to also allow similar drive feel when in ER mode.

ELECTRIC DRIVE POWERFLOWS

One-Motor EV Drive (Single-Speed)

One-motor, single speed drives have been used on most modern BEVs. The prototypical system for a BEV uses a single motor and a fixed single-speed gear reduction connected to a differential output as was developed for the first modern BEV, the GM EV1[5].

Lever diagrams are useful, simple representations of driveline kinematic arrangements, where torque and rotating speed relationships are represented with forces and displacements using a schematic linear linkage and free-body diagram scheme [6]. They provide a linear analog to the rotational reference system of a powertrain that many find easier to comprehend. The kinematic arrangement, or *powerflow*, of the single speed EV drive is shown in Figure 2 in the form of a lever diagram.

A typical single-speed One-Motor EV drive combined (inverter $\times$ motor $\times$ gear reduction) efficiency map is shown in Figure 3 in the axle torque - vehicle speed domain. This figure uses a 7.0:1 overall gear ratio from the motor speed to the wheel speed. The efficiency was defined as traction power delivered to the axle divided by the DC electric power input as shown in Equation 1.

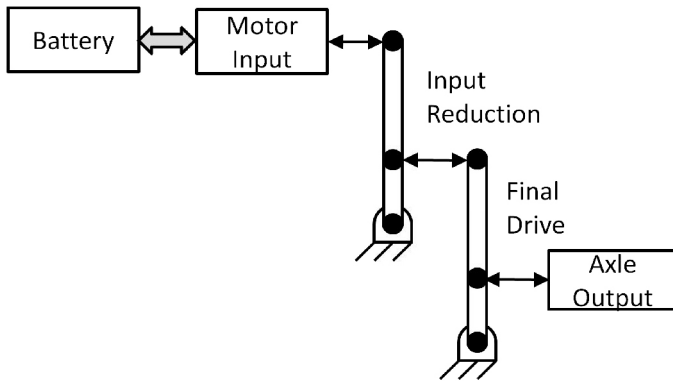


Figure 2. One-Motor EV Drive (Single-Speed) Powerflow

$$\eta_{EV \text{ drive type}} = \frac{P_{traction, \text{ net output}}}{P_{electrical, \text{ net input}}} \quad (1)$$

Efficiency was calculated for the entire tractive effort envelope using correlated, modeled component data and the same motor controls. Each mechanical and electrical component was separately modeled, including each torque transmitting and spinning element.

The level road load line of a reference BEV, assumed to be similar to the Chevrolet Volt, was overlaid on the efficiency. From the figure, a BEV with a single-speed drive experiences the most efficient point of operation at approximately 75 kph (47 mph) at loads that are much higher than the road load.

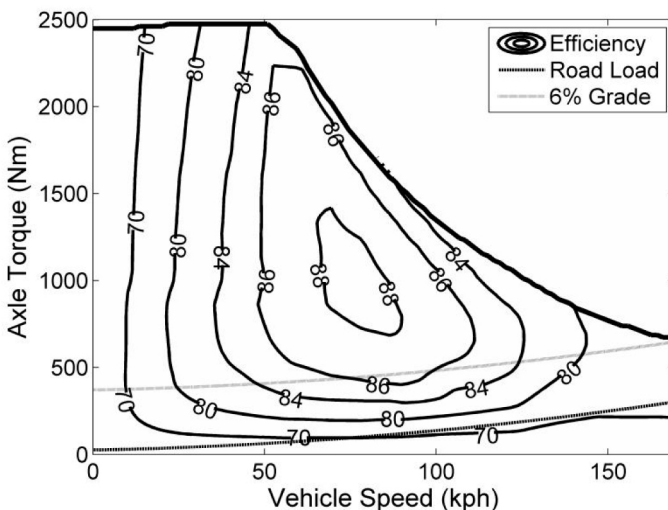


Figure 3. One-Motor EV Drive (Single-Speed) Efficiency Map

Figure 4 shows the same efficiency map with operating points added that represent time durations of the US urban, US highway, and higher intensity US06 Schedules. This

figure shows that many of the US urban and highway schedule driving points are at speeds and loads below the most efficient operating point, and only the highway and US06 schedules spend a significant portion of time at speeds higher than the most efficient operating point.

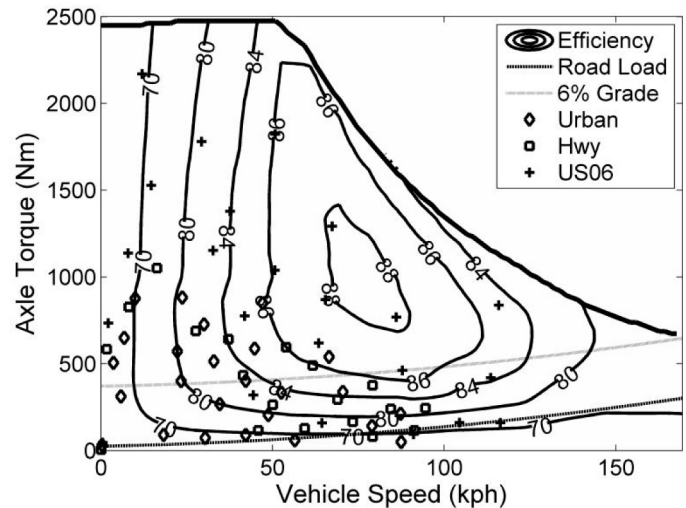


Figure 4. One-Motor EV Drive (Single-Speed) Efficiency Map with Operating Points

$$\eta_{EV \text{ drive, sched.}} = \frac{E_{traction} + E_{regen capture}}{E_{electrical} + E_{braking}} \quad (2)$$

Schedule-averaged efficiencies of a single-speed drive in the reference BEV on the three schedules were calculated according to Equation 2. This calculation is similar to Equation 1, but in addition to including the conversion from input (electrical) to output (traction) energy for propulsion, the energy capture efficiency from mechanical (braking) to electrical (regen capture) energy during regenerative braking was also included. As a sign convention, all energies in Equation 2 are positive for a typical drive schedule. This equation integrates the power over the entire operating envelope of the referenced schedule. For the single-speed EV drive, the following efficiencies were found:

$$\eta_{EV \text{ Single-speed, Urban}} = 77.2 \%$$

$$\eta_{EV \text{ Single-speed, Hwy}} = 75.5 \%$$

$$\eta_{EV \text{ Single-speed, US06}} = 80.9 \%$$

It is interesting to note that while component peak efficiencies can be in the mid or even high 90 percents, the reality of their application yield much less. Relevant measures of an EV drive must account for all the losses in the driveline over a defined and useful driving envelope, like the