ABSTRACT
An electronic continuously variable transmission (e-CVT) with integrated electric machines and planetary gears is widely used in the powertrains of hybrid electric vehicles (HEV). The e-CVT supports various promising hybrid powertrain designs, blending electric and mechanical drives with high efficiency and flexible energy sources. Identifying the peak performance characteristic of an e-CVT design for a given HEV, however, is a challenging task due to the complexity of hybrid propulsion system and the multi-disciplinary nature of hybrid powertrain design. In this work, model-based design and optimization methods are used to identify the peak synergistic performance of hybrid powertrains with an e-CVT. Four popular HEVs platforms have been studied: the Chevy 2-mode, Chevy Volt, Lexus RX450h, and Toyota Prius. The powertrains of these HEVs are modeled as nonlinear functions of several control variables, and their peak performances in both normal mode and electric-only mode are identified using simulation and a two-stage hybrid optimization method. To verify the results of the modeling and optimization from this work, comparisons are made with the results from the widely used Powertrain System Analysis Toolkit (PSAT), developed at the U.S. Argonne National Lab (ANL).

INTRODUCTION
PHEV PERFORMANCE CHARACTERISTICS AND CHALLENGES
The first electrical continuous variable transmission (e-CVT) introduced with the strong-hybrid electric vehicle consists of two major components: a planetary gear and an electric machine. It was initially used as a replacement of a conventional multi-gear transmission to improve fuel efficiency and reduce emissions of the internal combustion engine (ICE). With design improvement, an e-CVT is also used in a PHEV application with increased electrical propulsion ability. Such a PHEV oriented e-CVT design will effectively enable the vehicle’s energy diversity using both petroleum and electric energies, without much compromised vehicle functionality and affordability. The challenges for the PHEV and HEV powertrain design using an e-CVT also arise due to its multi-disciplinary nature and system complexity. To facilitate the design of an e-CVT hybrid system for a PHEV, this study applies a simulation and optimization based approach to identify and compare the peak powertrain performance of different operating modes on four hybrid powertrains. The two primary performance characteristics under comparisons are peak torque capability and electric drivability. The new modeling program provides more flexibility in modeling and optimizing newer powertrain architecture designs, comparing with the established powertrain modeling tool, PSAT.

Peak torque capability of a vehicle directly determines its acceleration and towing ability. Determining the peak torque capability of an existing vehicle, however, is not always straightforward. In a conventional vehicle (CV) with a discrete-ratios transmission, determination of the peak transmission output can be performed, by multiplying ICE output torque with gear ratios. In an e-CVT based powertrain configuration, however, there are multiple power actuators which creates numerous propulsive combinations. To produce a new design and associated control algorithm which fully utilize the powertrain's capability, substantial amount of developing time is needed even for an experienced engineers. The developed controller, however, is not necessarily capable of fully utilizing the best performance potential of the powertrain. The second performance characteristic under


### Table 1. Hypothetical Vehicle Energy Facts

<table>
<thead>
<tr>
<th></th>
<th>Battery Cap.</th>
<th>Utility Factor</th>
<th>Electric Propulsion Capability</th>
<th>MPG_{CD}</th>
<th>MPG_{CS}</th>
<th>MPG_{CD,UF}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle 1</td>
<td>20 kWh</td>
<td>0.6</td>
<td>50%</td>
<td>60</td>
<td>30</td>
<td>42.8</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>20 kWh</td>
<td>0.6</td>
<td>100%</td>
<td>Inf.</td>
<td>30</td>
<td>75</td>
</tr>
</tbody>
</table>

![FWD 2-mode Transmission Diagram](image)

**Figure 1. FWD 2-mode Transmission Diagram**

investigation, the electric only drivability, will significantly affect the electric energy usage and combined energy fuel efficiency, using the utility factor weight fuel economy calculation [1]. The combined energy usage of fuel and electricity is calculated using a utility factor (UF) based method, as shown in Equation (1). Taken two hypothetical vehicle factors created in Table 1 for example, the vehicle powertrain with a stronger electric drive gets considerable higher combined fuel efficiency rating than the other one does, with the same battery capacity onboard the vehicle.

\[
mpg_{CD,UF} = \frac{1}{UF + (1 - UF)} \cdot mpg_{CD} \cdot mpg_{CS}
\]

\[(1)\]

**REpresentative e-CVT POWERtrAINS**

Four representative PHEV/HEV hybrid powertrain configurations are studied. These include two mainstream PHEV/HEV hybrid platforms in different configurations: the Chevy EcoCAR and Chevrolet Volt using the GM 2-mode platform; and the Lexus RX450h and Toyota Prius based on the Toyota Hybrid System (THS) platform.

The University of Victoria (UVic) Chevy EcoCAR is a PHEV with full electric vehicle capability [2]. It is based on the Chevy EcoCAR prototype which is a strong hybrid SUV. The all wheels drive (AWD) UVic EcoCAR has its front wheels driven by a 2.4L Ecotec ICE and a 2-mode transmission, and its rear wheels driven by an added rear traction-motor. Since the front wheel drive component is an independent e-CVT configuration, only the performance of the front wheels drive is analyzed. The 2-mode hybrid system which has two continuous variable speed modes was developed by GM together with several other major OEMs. The Chevy EcoCAR and GM Volt [3] were both developed on the FWD version of the 2-mode transmissions with minor modifications [4]. The configuration layout for this transmission is shown in Figure 1, and the clutches engagement logic is listed in Table 2. The FWD 2-mode transmission can create several different modes, including power split, fixed ratio, or series hybrid configurations, with different clutch engagements. The Chevy Volt has a series-hybrid configuration using the same 2-mode CVT found in the Chevy EcoCAR with different electrical drives. The powerful electric propulsion system of the vehicle allows to be qualified as an Extended Range Electric Vehicle (EREV).

**Table 2. Clutch Logic Table**

<table>
<thead>
<tr>
<th></th>
<th>CL1</th>
<th>CL2</th>
<th>CL3</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM-2mode</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Mode1</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Toyota Prius and Synergy Drive was first introduced in late 1990s as a HEV powertrain with improved fuel efficiency [5]. It has gone through three generations till year 2010 since the first launch while the basic transmission configuration remains unchanged [6, 7]. Figure 2 is the powertrain configuration of the Toyota Synergy Drive in the Prius. The transmission is developed with a single planetary gear set. The Lexus 400/450h hybrids are developed with a second planetary gear set to increase the speed of the drive motor M/G B [8], as shown in Figure 3. The third and also the latest generation of the THS added an additional electric drive to the rear wheels to create an all-wheel-drive configuration (a similar concept as the UVic Chevy EcoCAR). The powertrain configuration on the front wheels remain unchanged [9].
HYBRID POWERTRAIN MODELING

To analyze the performance characteristics of these powertrains, the transmission, electric motors, and the ICEs are modeled.

TRANSMISSION MODELING

The mechanism of an e-CVT hybrid transmission is based on planetary-gear sets and clutches. Between the ICE input and the transmission output, the Chevy EcoCAR 2-mode has two variable speed modes and four fixed gear modes; the Toyota’s two hybrid systems have a single variable speed mode [10]; the Volt powertrain has no direct mechanical linkage between the two. The gear ratio for a planetary gear set is defined by the number of teeth on the ring gear divided by the number of teeth on the sun gear. The gear ratio for each of the hybrid transmission is listed in Table 3 [4, 11, 12].

Table 3. Gear Ratio of the Hybrid Transmissions with Planetary Gears

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Gear Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevy EcoCAR (2-mode)</td>
<td>k₁=60/44; k₂=97/43</td>
</tr>
<tr>
<td>Chevy Volt</td>
<td>k₁=60/44; k₂=97/43</td>
</tr>
<tr>
<td>Toyota Prius</td>
<td>k₁=78/30</td>
</tr>
<tr>
<td>Lexus RX450h</td>
<td>k₁=72/28; k₂=2,478</td>
</tr>
</tbody>
</table>

Chevy EcoCAR has two variable speed modes, Model and Mode 2. The transmission has two planetary gears and two Motor/Generators (M/G). Based on parameters in Table 3, the kinematic and kinetic equations for the two modes are derived and shown in Equations (2) and (3).

\[
\begin{align*}
T_{MG1} &= \frac{1}{1+k_1} \times T_{ICE} \\
T_{MG2} &= \frac{1}{k_2+1} \times T_{Out} - \frac{k_1}{1+k_1} \times T_{ICE} \\
\omega_{MG1} &= (1+k_2) \times \omega_{ICE} - k_1(1+k_2) \times \omega_{Out} \\
\omega_{MG2} &= (1+k_2) \times \omega_{Out} \\
\end{align*}
\]

(2)

\[
\begin{align*}
T_{MG1} &= \frac{k_2}{1+k_2} \times T_{Out} - \frac{1}{1+k_1} \times T_{ICE} \\
T_{MG2} &= \frac{1}{1+k_2} \times T_{Out} - \frac{k_1}{1+k_1} \times T_{ICE} \\
\omega_{MG1} &= \frac{1+k_1}{1-k_1} \times \omega_{ICE} - \frac{k_1(1+k_2)}{1-k_1} \times \omega_{Out} \\
\omega_{MG2} &= \frac{1+k_2}{1-k_1} \times \omega_{Out} - \frac{k_1(1+k_2)}{1-k_1} \times \omega_{ICE} \\
\end{align*}
\]

(3)

Disengagement of one of the clutches in the 2-mode transmission creates a series hybrid configuration as used in the Chevy Volt. The ICE coupled with an electric motor generates electricity and another electric motor independently drives the vehicle. The kinematic and kinetic relations for Volt hybrid is shown in Equation (4).

\[
\begin{align*}
T_{MG1} &= -T_{ICE} \\
T_{MG2} &= \frac{1}{1+k_2} \times T_{Out} \\
\omega_{MG1} &= \omega_{ICE} \\
\omega_{MG2} &= (1+k_2) \times \omega_{Out} \\
\end{align*}
\]

(4)

For the THS transmission of the Prius, there is a single planetary gear and two M/G, where the carrier gear is connected to the ICE, the sun gear is connected to the M/G A, and the M/G B and the output shaft shares the same connection with the ring gear. Equation (5) presents the relations.
Table 4. Performance Characteristics of the Electric Motors

<table>
<thead>
<tr>
<th></th>
<th>Speed range (RPM)</th>
<th>Peak Torque (Nm)</th>
<th>Power Range (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevy EcoCAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M/G A</td>
<td>7600</td>
<td>201</td>
<td>60</td>
</tr>
<tr>
<td>M/G B</td>
<td>9100</td>
<td>234</td>
<td>50</td>
</tr>
<tr>
<td>04 Toyota Prius</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M/G A</td>
<td>10000</td>
<td>153</td>
<td>25</td>
</tr>
<tr>
<td>M/G B</td>
<td>6200</td>
<td>400</td>
<td>50</td>
</tr>
<tr>
<td>Chevy Volt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M/G A</td>
<td>4500*</td>
<td>363*</td>
<td>53</td>
</tr>
<tr>
<td>M/G B</td>
<td>15000*</td>
<td>370</td>
<td>111</td>
</tr>
<tr>
<td>Lexus Rx450h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M/G A</td>
<td>13000</td>
<td>88</td>
<td>116</td>
</tr>
<tr>
<td>M/G B</td>
<td>13500</td>
<td>335</td>
<td>123</td>
</tr>
</tbody>
</table>

* Estimated values

\[
\begin{align*}
T_{MGa} &= \frac{1}{1+k} T_{ICE} \\
T_{MGB} &= T_{Out} - \frac{k}{1+k} \times T_{ICE} \\
\omega_{MGa} &= (1+k) \times \omega_{ICE} - k \times \omega_{Out} \\
\omega_{MGB} &= \omega_{Out} \\
\end{align*}
\] (5)

Lexus RX450h is similar to the Prius with some modifications. A second planetary gear is added to the transmission to increase the speed for the M/G B. The kinetic and kinematic relations are shown in Equation (6).

\[
\begin{align*}
T_{MGa} &= \frac{1}{1+k_1} T_{ICE} \\
T_{MGB} &= \frac{1}{1+k_2} T_{Out} - \frac{k_1}{(1+k_1)(1+k_2)} \times T_{ICE} \\
\omega_{MGa} &= (1+k_1) \times \omega_{ICE} - k_1 \times \omega_{Out} \\
\omega_{MGB} &= \omega_{Out} \times (1+k_2) \\
\end{align*}
\] (6)

**ELECTRIC DRIVE MODELING**

The torque and speed characteristics of the electric motors are modeled. The torque of an electric machine is characterized by the near-flat peak torque period followed by an isoclines power curve. The modeled motor characteristics are shown in Figure 4. Each of the vehicles has two electric motors M/G A and M/G B. The speed, torque, and power range of the studied motors are obtained from various sources and summarized in Table 4 (4, 13). Limited data was found on the Chevy Volt platform. As a result, hypothetical speed and torque range of the motors are used from the known vehicle power range and speed range of the Volt. The performance characteristics of these motors are plotted in Figure 4. It should be noted that the peak motor performance modeled here is different from the continuous motor capability. For continuous motor capability related vehicle performance analysis (such as towing capacity), the peak motor torque is reduced for continuous operation purposes.

**INTERNAL COMBUSTION ENGINE MODELING**

The torque and power characteristics of the ICE are modeled using a similar approach as the modeling of electric machines. The performance characteristics of the four ICES are listed in Table 5 and plotted in Figure 5. Limited information on the ICE is obtained from the Chevy Volt and Lexus RX450h, and the estimated parameters are marked in Table 5. These empirical and hypothetical models are fitted using 4th or higher order polynomials so that models are scalable to support the design optimization.

**A TWO-STAGE HYBRID OPTIMIZATION APPROACH**

**PROBLEM FORMULATION**

With the hybrid powertrain model identifying the peak powertrain performance remains a challenging task, due to the numerous possible propulsion combinations. In this work, an optimization method is used to automatically identify the design with peak performance. The design is aimed at identifying the peak driving or output torque of the powertrain, under various given vehicle speeds, leading to the maximum powertrain power output.

According to Equations (2), (3), (4), (5), (6), the transmission output torque is a function of three torque sub-functions: torque of the ICE and the two electric machines, as represented by Equation (7). The values of these torque sub-functions further depend upon four speed variables of the ICE, the electric machines and the vehicle, \( V_{ICE} \), \( V_{MGA} \), \( V_{MGB} \), and \( V_{veh} \). These components, as shown in Figure 4 and Figure 5, and represented by Equation (8). As only two of the four speed variables are independent and the vehicle speed \( V_{veh} \) is
treated as a constraint, as shown in the last equation in Equation (8), one additional variable is added to the objective function, given in Equation (7) to produce the updated objective function in Equation (9). Consequently, the original optimization problem is transformed to $n$ sub-problems (SP) of design optimization, where $n$ is the number of different vehicle speed to be scanned through. The updated objective function in Equation (9) can have up to 4 independent variables, depending upon the specific configuration of the c-CVT.

$$
\text{Maximize } T_{\text{output}} = f(T_{\text{ICE}}, T_{\text{MGA}}, T_{\text{MGB}})
$$

subject to:
Table 5. Performance Characteristics of the ICEs

<table>
<thead>
<tr>
<th></th>
<th>Speed Range (RPM)</th>
<th>Peak Torque</th>
<th>Power Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chevy EcoCAR LE9</td>
<td>6750</td>
<td>230 Nm @ 4700 RPM</td>
<td>130 kW @ 6300 RPM</td>
</tr>
<tr>
<td>04 Toyota Prius (1NZ-FXE)</td>
<td>4500</td>
<td>102 Nm @ 4000 RPM</td>
<td>42.7 kW @ 4500 RPM</td>
</tr>
<tr>
<td>Chevy Volt</td>
<td>5500*</td>
<td>140 Nm @ 4000 RPM*</td>
<td>74 kW @ 5500 RPM*</td>
</tr>
<tr>
<td>Lexus RX450h</td>
<td>6000*</td>
<td>317 Nm @ 4800 RPM</td>
<td>183 kW @ 6000 RPM</td>
</tr>
</tbody>
</table>

*Estimated Values

\[
\begin{align*}
    f_1(V_{ICE}) & \leq T_{ICE} \\
    f_2(V_{MGA}) & \leq T_{MGA} \\
    f_3(V_{MGB}) & \leq T_{MGB} \\
    V_{veh} & = V_{veh}(i)
\end{align*}
\]

Maximize \( T_{output}(i) = f(T_{ICE}, T_{MGA}, T_{MGB}, V_{ICE}) \) \hspace{1cm} (8)

where, \( i = n_{in}, \ldots, n \), represents different given vehicle speeds.

In our previous design optimization study, several global optimization search schemes, including GA, PSO, and meta-modal based methods have been used [14]. These optimizations involve intensive computation and present no assured search quality. In this work, a new two-stage hybrid optimization approach is used.

A TWO-STAGE HYBRID OPTIMIZATION SOLUTION

As previously discovered in Equations (2), (3), (4), (5), (6), the objective function of each SP given in Equation (9) can be separated into two parts: a linear component and a nonlinear component. The linear function component can be solved using various linear programming (LP) approaches and it is the nonlinear component that led to the solution complexity. The two-stage hybrid optimization approach solves the linear and nonlinear component at two separated stages. The principal of this approach is to separately solve the linear component of the problem using linear programming [15] and solve the remaining nonlinear component of the problem using other techniques.

At the first stage, with the vehicle speed and the ICE speed pre-assigned, the speed of M/G A and M/G B become fully determined. Consequently, the torque constraint will be known and the nonlinear components in the constraints can be removed. Applying this strategy, the continuous changing ICE speed is converted to a group of finite, discrete values using a fixed step size. With the variable of ICE speed pre-assigned, each SP consequently generates 600-800 linear sub-sub-problems (SSP), based on a step size of 10 RPM of the ICE speed between 600-8000 RPM. At the second stage, the maximum result among all SSPs is identified, presenting the global optimum of each SP, subject to the resolution of the step size.

Linear Problem Solving - Stage I

With the ICE speed pre-assigned, the objective function of a SSP for the EcoCAR 2-mode system is given in Equation (10).

\[
    T_{output} = (1 + k_2) \times T_{MGB} + \frac{k_1(1 + k_2)}{1 + k_1} \times T_{ICE}
\]

(10)

The constraints on the variables are known when the ICE speed and the M/G B speed are determined.

\[
\begin{align*}
    \text{Min ICE torque} & \leq T_{ICE} \leq \text{Max ICE torque} \\
    \text{Min MGB torque} & \leq T_{MGB} \leq \text{Max MGB torque}
\end{align*}
\]

(11)

Using the same approach, objective functions are set up for other hybrid powertrains, as shown in Equation (12), Equation (13), Equation (14), Equation (15).

\[
    T_{EcoCAR-output} = \frac{1 + k_1 + k_2 + k_3}{1 + k_1} \times T_{MGB} + \frac{k_1(1 + k_2)}{1 + k_1} \times T_{Engine}
\]

(12)

\[
    T_{Prius-output} = (1 + k_2) \times T_{MGB}
\]

(13)

\[
    T_{Prius-output} = T_{MGB} + \frac{k}{1 + k} \times T_{Engine}
\]

(14)
Nonlinear Problem Solving - Stage 2
Solving a SSP using LP can lead to a guaranteed optimum for each case. The optimum for all SSPP solutions is best solution of each SP. As there are 600–800 discrete variable values in the design space for the nonlinear component of a SP, an exhaustive search approach is used to compute the function value at every feasible point, to ensure the optimization results when the shape of the nonlinear objective function is unclear.

RESULTS AND SUMMARY
COMPARISON WITH PSAT RESULTS
The proposed method can quickly identify the peak torque performance of a hybrid powertrain with an e-CVT. To verify the solution obtained using this optimization-based approach, it is compared with the simulation results obtained from the widely used Powertrain System Analysis Toolkit (PSAT), developed at the Argonne National Lab (ANL) [16]. The Prius platform in PSAT was selected to carry out simulations and comparisons due to the existence of a high fidelity model, which has been verified against experimental results within 5% of difference on different driving cycles with different SOC [17].

The Prius model in PSAT is based on the 2004 vehicle with the powertrain configuration explained in Section 2. The PSAT vehicle controller model of Prius was developed based upon extensive knowledge on hybrid powertrain and the intent to reach peak vehicle performance. However, the heuristics based control logic cannot ensure the maximum performance available from the powertrain. The proposed optimization based method, on the other hand, can quickly identify the maximum performance available from the powertrain, without a complex model for the vehicle controller. The quality of the simulation and optimization results, however, is subject to the model accuracy. In this comparison, a standard 0–100 km/h acceleration drive cycle was applied to simulate “near-peak” torque delivery for the specified speed range. Comparisons are made on the speed and torque of the ICE and M/G, as shown in Figure 7. There are two results match well when the vehicle speed is greater than 20 km/h. At lower vehicle speed, the PSAT model simulates the transient of the engine starts accurately; the optimization based powertrain model assumes the engine is kept on at all time.

M/G-A functions as an ICE starter as well as an electric generator. Similar to the engine simulation results, the match is better when the vehicle speed is greater than 20 km/h, as shown in Figure 8.

M/G-B is the primary drive electric motor. The PSAT model contains more transient details where the optimization results provide a closer estimation, as shown in Figure 8.

Finally, the combined powertrain output is compared in terms of the torque delivery from the final drive, as shown in Figure 9. The optimization based solution successfully identified the peak torque performance from the powertrain despite of the missing transient details during the engine starts. The PSAT powertrain model and its controller achieve a “near-peak” performance close to the maximum performance from the powertrain. The PSAT model also provides better transient details during the engine starts.
PEAK POWERTRAIN PERFORMANCE CHARACTERISTICS

Following the same approach, the performance characteristics of four hybrid powertrains were investigated. In the normal mode when both the ICE and electric motors are utilized for vehicle propulsion, the powertrain's performance is compared in terms of maximum torque and maximum power. As shown in Figure 10, the Lexus RX450h powertrain has the highest available torque and power among the compared vehicles powertrains, largely taking advantage of the largest 123 kW electric motor and the most powerful 3.5L ICE. The UVic Chevy 2-mode system with the 2.4 L ICE is second high in performance overall; the mode-shift creates a noticeable torque value plunge; at middle to high vehicle speed, the 2-mode system can provide a high peak torque plateau. The Volt's powertrain uses a 111 kW electric motor independently to drive the vehicle. The electric motor has comparable high power output at vehicle speed 30 km/h or lower; as the vehicle speed increases, the performance drop is more significant, as compared with the RX450h and the Chevy 2-mode powertrain. The powertrain from a Prius outputs the lowest torque and power; the pattern of the output curve heavily resembles that of the RX450h powertrain, due to the similar powertrain configuration in nature.
EV MODE PERFORMANCE CHARACTERISTICS

In the EV mode while the ICE is turned off, the powertrain’s performance is determined by the performance of three major components: electric motor(s), batteries, and transmission. Since this study mainly focuses on how the transmission and the electric motors could affect the vehicle's performance, the power and energy capability of the ESS is assumed to be unlimited. Therefore, the all electric range (AER), which is largely determined by the battery capacity, is not compared.

The vehicles’ EV performance characteristics are shown in Table 6. All vehicles, except the 2-mode, have peak EV

<table>
<thead>
<tr>
<th></th>
<th>Peak EV Speed</th>
<th>Speed Limiting Factor</th>
<th>Peak EV Power</th>
<th>Power Limiting Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-mode</td>
<td>73 km/h</td>
<td>MGA speed</td>
<td>59 kW</td>
<td>MGB power</td>
</tr>
<tr>
<td>THS</td>
<td>164 km/h</td>
<td>MGA speed</td>
<td>49 kW</td>
<td>MGB power</td>
</tr>
<tr>
<td>RX450h</td>
<td>160 km/h</td>
<td>MGB speed</td>
<td>122 kW</td>
<td>MGB power</td>
</tr>
<tr>
<td>Volt</td>
<td>191 km/h</td>
<td>MGB speed</td>
<td>110 kW</td>
<td>MGB power</td>
</tr>
</tbody>
</table>

Table 6. Vehicle Performance in EV Mode

Figure 9. Final Drive Output Torque Comparison

Figure 10. Powertrain Torque and Power Comparison of four Selected Vehicles
speed over 160km/h. The peak vehicle speed with the 2-mode transmission is limited to 73 km/h due to the speed constraint on MGA. Only the first mode (Mode 1 or Low Mode) in the 2-mode transmission can be used as EV mode. The THS has the potential to run the vehicle at a speed up to 164 km/h. However, the vehicle's performance at higher vehicle speed in the EV mode is considerably compromised because of the limited peak EV power of 49 kW. Therefore, neither the Prius nor the 2-mode has full EV capability. The speed vs. power performance of the four vehicles in EV mode is shown in Figure 11.

![Vehicle Performance in EV mode](image)

**Figure 11. Vehicle Performance in EV mode**

### SUMMARY/CONCLUSIONS

The proposed model-based design and optimization method can quickly identify the synergistic powertrain output of e-CVT based transmissions of different configurations. Four representative e-CVT powertrains were used as case studies. The performance characteristics in both normal mode and EV mode are revealed. The THS hybrid powertrain from a Lexus RX450h vehicle have the potential to deliver highest torque and best EV performance among the compared selections, taking advantage of its larger ICE and electric motors. Applying this method, design optimization can be performed in the initial powertrain design phase to ensure desired peak powertrain output is fully achieved.

One of the main factors that limited the optimization speed is the exhaustive searching algorithm applied at the second stage of the 2-stage optimization approach. With better understandings of the objective function, more efficient optimization techniques could be applied without compromising the quality of the search result. With further improvement, the approach can also be applied to design optimization of different powertrain configurations.

### ACKNOWLEDGMENTS

Supports from the Natural Resource of Canada (NRCan), Natural Science and Engineering Research Council of Canada (NSERC), Auto21 Network of Centres of Excellence of Canada, US Department of Energy (DOE) and GM through several related programs are gratefully acknowledged.

### REFERENCE


