Comparative Analysis of Single and Combined Hybrid Electrically Variable Transmission Operating Modes

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ABSTRACT

Electrically variable transmissions divide power between the electrical and mechanical paths using input, output, or compound split schemes. When combined with an electrical energy storage element such as a battery, these systems allow numerous fuel saving and performance benefits. This paper examines the design tradeoffs in each of the three topologies in order to balance fuel economy, system performance against requirements, and electrical component size. A general EVT analysis method is presented and used to study the fuel economy and performance sensitivity of the three configurations to motor, inverter, and battery constraints, and planetary gear ratios. To evaluate fuel economy, the three systems are assessed for each of the primary fuel economy mechanisms enabled by hybridization. To evaluate performance tradeoffs, system performance against typical vehicle performance design points is compared. The effects of combining two modes that are optimized for individual speed ranges vs. a single mode covering all ranges are also discussed. The use of 2 modes provides significant advantages over a single mode design including reduced motor power for a given vehicle performance.

INTRODUCTION

It is known that hybrid vehicles provide the potential for significant fuel economy improvement as compared to conventional automatic transmission vehicles. However, to satisfy the automotive customer, this fuel economy improvement should not come at the cost of vehicle drivability or performance. The refined state of development of conventional automatic transmissions provides a good benchmark against which potential hybrid systems must be compared.

At a minimum, hybrid vehicles typically incorporate engine-off at idle, a moderate level of coast down or braking regeneration, and possibly acceleration assist. As the level of power available increases and becomes a larger percentage of total power, increases in regenerative braking and engine boost are possible as well as other functions such as electric-only operation and high voltage accessory power. With the higher percentage of total power and additional functions, the potential for effect on vehicle drivability, both positive and negative, is increased.

Various hybrid architectures have been proposed and implemented over the past 10 years. The series hybrid is conceptually the simplest hybrid and is capable of providing all hybrid functions. However, poor efficiency and the large electric machine size that is necessary limits its applicability to specific drive cycles and vehicle types. Parallel hybrids, which use 1 or more electric motors that provide power additively with the engine are a better use of electric machine capability due to the fact that the machines need to be sized only for the desired functions rather than the full engine power. In these vehicles, the integration of the electric and mechanical transmission systems becomes complex, especially if strong hybrid functionality is desired. In addition, continuous control over engine operating speed is possible only with a CVT transmission.

The Electrically Variable Transmission (EVT) has the potential to combine the continuous control and urban drive cycle efficiency of the series hybrid with the high power capability and highway efficiency of the parallel hybrid. Both single mode and multi-mode EVT transmissions have been developed. A single mode EVT is typically implemented with a single planetary gearset and is conceptually closer to a series hybrid, while a multi-mode EVT contains multiple sets of gears and clutches, and is conceptually closer to a parallel hybrid. Both types of systems are capable of full hybrid functionality.

This paper studies the strengths and weaknesses of the possible EVT modes in conjunction with electric drive systems, focusing in particular between the tradeoffs between the electrical and mechanical systems. Both single mode and multiple mode systems are considered.
FUNDAMENTALS OF EVT SYSTEMS

The design and optimization of an EVT system is a complex problem in which the engine, transmission, electric motor, and power electronics must be balanced. In particular, the tradeoffs in design of an EVT between the mechanical transmission and electric drive system are important because there is a direct relationship and tradeoff between the torque, speed, and power requirements of the electric drive and the gear ratios and mode spacing of the mechanical power split elements.

POWER SPLIT TRANSMISSIONS

The EVT is based on general power split modes that were originally developed for hydraulic systems. The EVT (as well as the CVT) is distinguished from the conventional transmission by the number of degrees of control freedom. Conventional step gear transmissions are 1 degree of freedom systems, i.e. for each operating mode, the speed of the input is determined from the speed of the output. Consequently, there are linear equations relating the speeds and torques of the input to the output. Electrically variable transmissions have 2 degrees of freedom, i.e. independent control of the input and output speeds and torques. This results in a 2-D system of equations that must be solved to determine the transmission torques and speeds.

In addition to the number of degrees of control freedom, it is also helpful to consider the number of degrees of design freedom of the transmission gear scheme, which includes the gears and their interconnections, as well as the corresponding higher level powerflow. Since a number of transmission gear schemes may provide equivalent power flow, designs may be analyzed at the level of the power flow. For example, in a single planetary gear stage the number of teeth on the ring, planets, and sun may be set independently. From a powerflow standpoint, the design may be considered to have a single degree of freedom, the ratio of the ring teeth to sun teeth, which determines the power split between the three shafts.

Lever Analogy for EVT Transmission Analysis

It is common practice in transmission design to represent a set of planetary or fixed gears by a lever diagram [1]. For the EVT, the lever can be drawn with point 0 at the output shaft and point 1 at the input shaft. The length of the lever, which may be positive or negative, determines the kinematic relationship of the electric machine to the input and output shafts. In the lever analogy, lever length ratio is analogous to gear ratio; hence, static forces are analogous to steady state torques. In this analysis, parameters $\alpha$ and $\beta$ will represent the lever lengths of the unit A and B power split planetary gears. An example lever diagram is shown in Figure 1.

Note that a lever length of 1 represents a motor that is directly connected to the input power path, and a 0 represents a motor that is directly connected to the output power path. With this convention, it can be seen that an input split is characterized by a set of parameters where either $\alpha$ or $\beta$ are zero, and an output split by a set of parameters where either $\alpha$ or $\beta$ are 1.

Conditions for Forward Power Flow

Since the electric drive is capable of bi-directional power conversion, power flow is possible in either direction. One of the conditions for useful application of an EVT is that the power flow be in the forward direction. Operation is possible with power flow in the reverse direction, but efficiency is generally poor due to additional circulating power subject to conversion losses.

By examining the lever diagram, it can be seen that for positive lever lengths the electric machine will absorb power whenever its speed is positive and supply power...
whenever its speed is negative. For negative lever lengths the opposite is true. Enumerating the possible combinations of speeds and lever lengths yields the following possibly useful hybrid configurations listed in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>α</th>
<th>β</th>
<th>A Motor Speed</th>
<th>B Motor Speed</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Split Low Ratio</td>
<td>&gt;0</td>
<td>0</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td></td>
</tr>
<tr>
<td>Input Split High Ratio</td>
<td>&lt;0</td>
<td>0</td>
<td>&lt;0</td>
<td>&gt;0</td>
<td></td>
</tr>
<tr>
<td>Output Split Low Ratio</td>
<td>1</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td>&lt;0</td>
<td></td>
</tr>
<tr>
<td>Output Split High Ratio</td>
<td>1</td>
<td>&lt;0</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td></td>
</tr>
<tr>
<td>Compound Split</td>
<td>&gt;0</td>
<td>&lt;0</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td>Limited usefulness due to restricted ratio range</td>
</tr>
<tr>
<td>Compound Split High Ratio</td>
<td>&lt;0</td>
<td>&lt;0</td>
<td>&lt;0</td>
<td>&gt;0</td>
<td>Limited usefulness due to restricted ratio range</td>
</tr>
<tr>
<td>Compound Split Low Ratio</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td>&lt;0</td>
<td>Limited usefulness due to restricted ratio range</td>
</tr>
</tbody>
</table>

Table 1 – Possible Hybrid Configurations

Conditions for Forward Power Flow

In order to easily analyze transmissions that include electrical paths, a general analysis method for 2 degree-of-freedom systems is used. Using the lever analogy, the ratio design space may be analyzed independently of the underlying gear sets that implement the powerflow. It can be shown that ratio design space of a 2 DOF, EVT transmission mode can be represented by 6 parameters, regardless of the gearing that implements the powerflow:

- \( R_{ia} \): Ratio between input and motor A power split
- \( R_{ib} \): Ratio between input and motor B power split
- \( R_{oa} \): Ratio between output and motor A power split
- \( R_{ob} \): Ratio between output and motor B power split
- \( \alpha \): Lever length of Motor A power split
- \( \beta \): Lever length of Motor B power split

The torque equations for this model can be written as:

\[
T_i = -\frac{\alpha}{R_{ia}} T_a - \frac{\beta}{R_{ib}} T_b \quad (1)
\]
\[
T_o = (1 - \alpha) R_{oa} T_a + (1 - \beta) R_{ob} T_b \quad (2)
\]

and the speed equations as:

\[
S_a = \frac{\alpha}{R_{ia}} S_i + (1 - \alpha) R_{oa} S_o \quad (3)
\]
\[
S_b = \frac{\beta}{R_{ib}} S_i + (1 - \beta) R_{ob} S_o \quad (4)
\]

The speed equations can be solved for the mechanical point ratios by setting \( S_a \) and \( S_b \) = 0:

\[
R_{ma} = \frac{\alpha - 1}{\alpha} R_{ia} R_{oa} \quad (5), \quad R_{mb} = \frac{\beta - 1}{\beta} R_{ib} R_{ob} \quad (6)
\]

Torque, Speed, and Power Relationships

In order to compare the three configurations, it is useful to use normalized input and output torques and speeds, where a value of 1 is equal to the engine torque or speed. The speeds, torques, and powers can be plotted against transmission ratio.

Input Split Mode

The input split configuration has one mechanical point \( (R_{ia}) \) where the input motor speed is zero. Power flow is in the forward direction above this ratio and reversed below this ratio. The fraction of power through the electrical path depends only on the ratio relative to the mechanical point and can be expressed as:

\[
P_{elect} = \frac{(r_n - 1)}{r_n} \quad (7)
\]

where \( r_n \) is a normalized ratio defined as:

\[
r_n = \frac{S_i}{S_o R_{ma}} \quad (8)
\]

Figures 4 and 5 show unit A and B torque, speed, and power plotted vs. ratio, for various values of \( \alpha \). While the input split is capable of infinite ratio spread with forward power flow, the upper ratio at which the engine can be run at full speed and power will be limited by unit A speed, unit B torque, or power. A usable ratio range equivalent to a ratio spread can be defined as a ratio range from the mechanical point up to the point at which the input split can no longer operate at full input speed and torque. It can be seen that ratio spreads on the order of 4 are obtainable at the expense of a high fraction of power through the electrical path (75%), high unit A speed (2-3X input speed for typical values of \( \alpha \)), and high unit B torque (2X input torque if \( R_{ob} = 1 \), could be reduced with gear ratio between unit B and output).
Output Split Mode

The output split configuration has one mechanical point ($R_{mb}$) where the output motor speed is zero. The direction of the power flow is forward below this ratio and reverse above this ratio. Again, as with the input split, the machine powers depend only on the ratio relative to the mechanical point and can be expressed as:

$$P_{\text{elect}} = 1 - \frac{S_i}{S_0 R_{mb}}$$  \hspace{1cm} (9)

Figures 6 and 7 show unit A and B torque, speed, and power plotted vs. ratio, for various values of $\beta$.

For the output split configuration, note that the power is symmetric about the mechanical point. It can be seen that an output split has a practical upper bound of about 1.5 $R_{mb}$ due to the increasing circulating power. Similarly, there is a practical limit on the low side of about 0.5 $R_{mb}$ due to increasing unit B speed. These limitations make it infeasible to design a single mode output split with the needed level of ratio coverage.

Compound Split Mode

The compound split has a mechanical point at which each of the two electric machines is at zero speed. The direction of the power flow is forward between these two ratios and reverse outside of this range. For the compound split, the ratio spread may be defined as the ratio between the two mechanical points, and can be expressed as:

$$\phi = \frac{R_{mb}}{R_{ma}} = \frac{\alpha(\beta - 1)}{\beta(\alpha - 1)} R_{mb} R_{na}$$  \hspace{1cm} (10)

There is a tradeoff between $\alpha$ and $\beta$ for a given ratio spread. The power transmitted through the electrical path follows a characteristic curve with a peak value that is a function of the ratio spread. The fraction of power through the electrical path can be expressed as:

$$P_{\text{elect}} = \frac{\left(\frac{S_i}{S_0} - R_{ma}\right) R_{mb} - S_i}{R_{mb} - R_{ma}} S_i$$  \hspace{1cm} (11)
Figures 8 and 9 show unit A and B torque, speed, and power plotted vs. ratio, for two compound split designs covering a ratio spread range from 2 to 4. Note that in the forward power flow region the electrical power peaks at a low fraction of the engine power. However, the sharp increase in power in the reverse power flow regions limits the operation to near the mechanical points. It can be seen that ratio spreads on the order of 4 are obtainable at the expense of high unit B torque; however, for the example shown the ratio ranges from 0.5 to 2.0 rather than the normal transmission design range of 0.75 to 3.0.

The combination of an input and compound split has a number of advantages:

- Electrical path power under wide open throttle conditions is reduced by limiting operation in the input split mode to ratios less than 2 times the mechanical point.
- Electric machine maximum speeds are reduced
- Unit B serves as both the launch motor in low range as well as the generator during highway cruise. During highway cruise the transmission ratio is near the lower mechanical point which allows unit B to be the primary supply of holding torque. Because unit B is always at low speed under cruising conditions, it may be optimized for high torque, low speed condition.

EvT Electric Drives

The electric drive for an EvT utilizes two electric machines and two inverters in order to transmit a portion of the power through the series path. Three types of electric machines that are commonly used are surface permanent magnet, interior permanent magnet, and induction motors. Electric machines have a number of design variables that may be optimized in conjunction with an EvT transmission. These variables determine the machine's torque, power, and loss characteristics.
Electric drives have several sources of losses:

- Copper losses are ohmic losses proportional to the square of current through the windings.
- Iron losses are a function of the speed of the machine and the strength of the magnetic flux and are due to hysteresis losses and eddy currents within the laminations.
- Inverter losses are a function of the motor winding current and include conduction and switching components.

While the mechanical losses in the transmission depend to a large extent on the detailed design and transmission layout, the losses in the electric drive are determined primarily by the machine size and the required torque and speed, which are functions of the selected powerflow and ratios. It is helpful to decompose the losses into quadratic functions of speed and torque in order to gain insight into the interaction between the powerflow and electric drive design. In general, a tradeoff exists between speed based and torque based losses for permanent magnet type machines, with stronger PM machines biased towards higher speed based losses. Induction machines have very little speed based losses at the expense of higher torque losses. A tradeoff also exists between motor size and either type of losses.

**Electric Drive Scaleability**

There are several design parameters which allow scaling of electric drives. If the length of a machine is changed the torques will change proportionally, but the peak powers will be similar since the current rating of the inverter is unchanged. Alternately, the machines may be scaled by inverter current, in which case the length is unchanged but the silicon area in the inverter is split unequally between the machines, resulting in unequal currents which results in unequal torques and powers.

Additionally, systems may be scaled by increasing the operating voltage of the electric drive. This may involve increasing the number of battery modules in the pack, and/or increasing the voltage rating of the silicon. In this case, the torque of the motor is unchanged but the base speed and power are increased.

**FUEL ECONOMY MECHANISMS**

Hybrid vehicles save energy by means of various fuel economy mechanisms. Hybrid architectures and individual EVT modes vary in the degree to which they are able to execute the different mechanisms. It must be noted that a hybrid vehicle starts out “in the hole” relative to a conventional vehicle if none of the hybrid mechanisms are enabled due to the additional mass and possibly increased accessory power demands, and the savings must first make up this difference before a net gain may be achieved. Since total motor mass is constant for all EVT powerflows for the purpose of this study, at this level of analysis all powerflows are assumed to have the same penalty and only the positive mechanisms are studied.

**Engine Stop-Start**

Shutting the engine off at rest eliminates idle fuel consumption. In general, all three hybrid configurations are capable braking the engine to a stop or restarting it. The output split configuration has an advantage in that one of the motors is connected directly to the engine providing improved control as well as reduced losses. In the other configurations, both of the motors must be controlled simultaneously in order to prevent the engine starting torque from being transmitted to the output. Starting the engine in the compound mode requires reverse power flow until the first mechanical point is reached.

**Electric Launch**

Electric launch allows the engine to remain off until the vehicle power demand is high enough to efficiently load the engine. The input split configuration is ideal for battery only creep and electric launch, due to the fact that one motor is geared directly to the output. Both of the other configurations also are capable of electric only operation, but both of the motors must be controlled simultaneously to prevent the engine from spinning. Efficient electric launch will be obtained by maximizing the ratio of the output motor to the transmission output.

**Infinitely Variable Ratio Operation**

Infinitely variable ratio allows the engine operating point to be optimized in order to maximize fuel efficiency. In general, this means that the engine is operated along a lower speed constraint line at low powers, then along a torque constraint line passing through the best BSFC points at higher powers. The reduction in engine losses must be traded off against the holding torque and spin losses of the electric machines. In practice, this generally means that the best system efficiency point lies at somewhat lower torques and higher speeds than the optimum engine efficiency trajectory. Full range input split systems tend to have high motor spin losses since one of the motors is geared to the output, and also must be capable of supplying the full launch torque. Torque losses under this condition can be made very
low. Output split systems can be made with very low spin and torque loss under overdrive conditions since one motor can be near zero speed while the other is connected to the engine. Compound split systems will have spin losses in between the input and output split systems, but will have low torque losses as well.

It is possible to design an input split, output split, and compound split system where the three systems have identical torque and speed requirements at the mechanical point. This allows the system losses to easily be compared for the highway cruise operating condition. For this comparison, the systems were all designed with a mechanical point of 0.75, which corresponds to a typical overdrive ratio. The design parameters are given in Table 2. The component speeds are plotted in Figure 11, and the torques in Figure 12.

Table 2: Design Parameters for Matched Systems

<table>
<thead>
<tr>
<th>Type</th>
<th>Unit A</th>
<th>Unit B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Split</td>
<td>$\alpha = 4, R_{oa} = 1, R_{oa} = 1$</td>
<td>$\beta = 0, R_{lb} = 1, R_{lb} = 1.5$</td>
</tr>
<tr>
<td>Output Split</td>
<td>$\alpha = 1, R_{ia} = 0.5, R_{oa} = 1$</td>
<td>$\beta = 4, R_{ib} = 1, R_{ib} = 1$</td>
</tr>
<tr>
<td>Compound Split</td>
<td>$\alpha = 4, R_{ia} = 1, R_{oa} = 1$</td>
<td>$\beta = -2, R_{ib} = 1, R_{ob} = 1$</td>
</tr>
</tbody>
</table>

Figures 13, 14, and 15 plot the electrical path losses as a function of transmission ratio for the three designs using three different motor types. Note that the losses for all designs are the same at the mechanical point, and that for the input split and output split the mechanical point is the point of minimum loss. For the compound split the point of minimum loss actually occurs between the two mechanical points. The compound split has a
wider range of ratios where losses are low. Figure 16 shows the result of optimizing the output ratio parameters $R_{oa}$ and $R_{ob}$ to center the three designs at a ratio of 0.8, to simulate a final drive optimized for fuel economy. From this plot, it can be seen that the compound split design has the lowest losses in the region surrounding the target ratio.

![Figure 16: Losses After Axle Ratio Optimization](image)

In order to provide good drivability, it is necessary to maintain an adequate torque reserve in order to allow for grade changes, headwinds, or changes in driver demand. All of the hybrid configurations have the capability to meet sudden torque demands with battery power, which allows the engine to be operated at lower speed than would be possible with a conventional transmission.

**Improved Power Generating Efficiency**

After all available regenerative braking energy is consumed over the course of a schedule, any additional electrical energy used for accessory loads or for vehicle propulsion must be generated from the engine, due to the charge sustaining nature of the hybrid. It is desirable to generate this energy during points where the engine is lightly loaded in order to boost its operating efficiency. The schedule average efficiency of a typical alternator is in the range of 50 to 60%. In contrast, EVT systems may provide incremental efficiency greater than 100% for power generation from the engine to the high voltage battery under some conditions. The efficiency of a typical DC-DC converter is 85% yielding much improved overall efficiency. This is due to the fact that the electric power may consume some or all of the series path power provided by the generator, eliminating the need to convert power with the motor. Table 3 summarizes the relative efficiency of accessory power generation for different modes and operating points. Both the input split and compound split configurations have high generating efficiency when operating in the normal forward power flow region.

![Table 3: Relative Accessory Power Generation Efficiency](image)

**Regenerative Braking and Deceleration**

Potentially recoverable vehicle kinetic energy that is dissipated in vehicle brakes accounts for roughly 20% of typical vehicle energy as measured at the engine output on the urban drive schedule. Additionally, a hybrid vehicle enables greater opportunity to turn engine fuel off and/or stop engine rotation during deceleration that results in the potential for additional fuel savings. Figure 17 shows calculated electrical conversion efficiency for the various design types with the engine stopped, assuming loss characteristics typical of a weak permanent magnet motor. The electrical conversion efficiency includes the spin and torque related losses of both electric motors to produce the desired transmission output torque, but does not include other transmission or engine dragging losses and thus represents an upper bound on system efficiency.

![Figure 17: Regenerative Braking Efficiencies, Engine Off](image)

The compound split has poor efficiency at high speed when the engine is off, due to the high circulating power...
required. The full range input and low range output split systems show generally good efficiency across the speed range. Below 40 kph, the efficiency of all designs except the high range input split fall rapidly due to the low motor speeds. The efficiency of the high range input split decreases at high vehicle speeds due to excessive motor speeds.

Figure 18 shows calculated electrical conversion efficiency for the various designs with the engine dragging. The efficiency of the compound split is greatly improved under this condition since the need to circulate power through the electrical path is reduced. The input and output split systems also show improvement at high speeds if the engine remains on, although in practice the improvement in electrical efficiency will need to be balanced against the power consumed by dragging the engine.

VEHICLE PERFORMANCE

A separate set of mechanisms allows the hybrid system to improve vehicle acceleration performance. Again, a hybrid system starts out at a performance deficit due to the increased mass of the system and must be able to offset this before a net gain is realized.

Increased Effective Low End Ratio

EVT designs may be capable of increased ratio coverage as compared to automatic transmissions. However, this is a potential area for EVT weakness as well, since the conventional automatic transmission gains torque multiplication from the torque converter that is not present in an EVT. A typical engine outputs maximum torque in the mid speed range. At zero speed, all of the engine output power must be dissipated or absorbed by the battery. Since the EVT has limited power dissipation capability, the battery charge acceptance constrains engine speed and may prevent the engine from being run at its maximum torque point.

For an input split mode, launch torque is given by the following equation:

\[
T_o = T_p R_{ob} + \frac{\alpha - 1}{\alpha} R_{oa} \text{MIN} \left( T_i, \frac{T_a}{\alpha} \right) \quad (12)
\]

Assuming that engine speed is constrained by battery power for all system, and that Unit A torque is sufficient, this points to two ways to increasing launch torque: increase the ratio of Unit B to output, or increase the mechanical point of the input split. Increasing the mechanical fraction of torque on the input split, or increasing the ratio of the mechanical path to output may accomplish the latter. For a low torque engine, more advantage may be gained by increasing motor B ratio; for a high torque engine, the mechanical path becomes more important.

For an output split mode, launch torque is given by the following equation:

\[
T_o = R_{ob} \text{MIN} \left[ \frac{\beta - 1}{\beta} \left( \frac{T_a}{R_{oa}} + T_i \right), (1 - \beta)T_p \right] \quad (13)
\]

Since an output split has reverse power flow at high ratio, \( T_s \) will be positive and will add to the output. Again assuming that engine speed is constrained for all systems and that unit B torque is sufficient, launch torque may be increased by increasing the mechanical point or by using a step-up ratio between unit A and the engine.

The effective ratio of a compound split is limited by the fact that the electrical path power flow reverses when the ratio exceeds the higher of the two mechanical points. Since unit B is negative speed, it will generate power that must be supplied to the battery or to unit A. Positive torque on unit A must be balanced by an increase in torque on unit B and also causes a decrease in output torque, due to this effect it is less practical to use motor A to boost output torque than with the output split mode. Due to this limitation, compound splits are generally used for high range operation.

Elimination of Ratio Steps

Assuming that the EVT is designed to transmit peak engine torque over the full range of operation, the continuously variable nature of the EVT provides a significant performance advantage relative to a conventional step gear transmission. In order to provide WOT performance comparable to a conventional step ratio transmission, a range of ratio coverage capable of transmitting full engine power is is needed. The upper bound of the ratio range should match the effective ratio of an automatic transmission with torque converter unlocked in order to give comparable performance. The lower bound of the ratio range is determined either by the required top speed of the vehicle (if less than the theoretical maximum) or the road load curve. In the example shown in Figure 19, ratio coverage of 3.25 to 1.53 is required based on the design top speed of 160
kph. At ratios below 1.53, the maximum engine speed will not be reached.

Figure 19: Effective Ratio Coverage Required

It is difficult to achieve the required level of ratio coverage with a single mode system. Assuming that the low end mechanical point for a single-mode input split or output split needs to be in the range of 0.75 to 1.0 in order to provide good fuel economy during highway cruising, an upper bound ratio of 1.1 to 1.5 is achievable with an output split design limiting circulating power to 50% of engine power. An input split is capable of providing the desired ratio coverage at the expense of transmitting a high percentage (>75%) of the engine power through the electrical path, per Figure 20.

Figure 20: Percent of Engine Power Transmitted Through Electrical Path vs. Transmission Ratio

With a 2 mode system, full ratio coverage may be obtained with electrical path power kept below 50% of engine power. This is demonstrated by simulation of the full size truck application. Figures 21 and 22 show the powers and speeds of the components during a simulated WOT acceleration. The system shifts from the 1st to 2nd mode at 140 kph. Note that the engine is operated at the power peak throughout the speed range, the battery supplies power to boost acceleration at speeds above 20 kph, and the electrical path power peaks at 44% of the engine power. Also, the motor speeds are less than 2X engine speed, and motor torques are less than 50% of engine torque.

Figure 21: Two Mode EVT Component Powers During WOT Accel

Figure 22: Two Mode EVT Component Speeds During WOT Accel

Acceleration Boost

The battery pack is available to provide additional power during peak acceleration. This advantage may be offset due to decreased power transmission losses due to the inefficiency of the series path. For the input split configuration operating above the mechanical point, the additional battery power directly increases the power requirement of the output motor since both motors are fully utilized during the WOT acceleration condition. Below the mechanical point the effect of battery power is beneficial since it delays the onset of reverse power flow. The output split configuration is able to make use of battery power without requiring an increase in motor size since the battery power displaces power generated by the input motor, allowing more of the engine torque to be sent to the output. The compound split design is also able to make use of battery power except in the range near the second mechanical point. With the output (motoring) motor near zero speed, the input (generating) motor must switch over and become a motor, increasing
the torque (but not power) requirement of the output motor.

OTHER DESIGN POINTS

Trailer Towing

If a hybrid system is applied to heavy-duty vehicles, the additional duty cycles of trailer towing must be considered. Trailer towing increases vehicle load in two areas: increased steady state cruising loads and increased grade loads. Steady state road loads increase due to mass increases and increased aerodynamic drag. In addition, grade load will increase due to the mass, and accelerations will lengthen in duration, raising the percentage of time spent at high torques. Typically, the increased road load would force a conventional transmission to operate near a 1:1 ratio condition for highway cruise. As was shown above, the compound split can be designed to have minimum loss near this operating point, and so is ideal for trailer towing.

Reverse Grade

Another design point is the reverse grade condition. The steepest on-road grades are typically on the order of 30%. Unless an EVT has a separate mechanical reverse gear, the reverse grade condition must be met using motor torque alone. Additionally, depending on the powerflow, the reverse speed condition may result in power circulation that limits the vehicle speed and/or achievable torque. The compound mode has unacceptable performance in reverse mode due to power circulation.

CONCLUSION

A generalized model for EVT powerflows was developed which allows analysis of EVT modes and their combinations. This model has proved useful in evaluating EVT concepts with regard to fuel economy and performance. The choice of EVT powerflow and gear ratio has a large effect on the efficiency of the electric drive and the maximum output capability of the system.

In general, only the input split configuration is feasible as a full-range single mode hybrid system. While feasible, single mode input split systems require high power (~75% of engine peak power), high output motor torque capability, and high input motor speed capability. Output split systems are not feasible as single mode systems due to limits on achievable ratio coverage; however, they are useful as a submode, especially at low numerical gear ratios.

The compound split mode is useful as a high range but not for launching due to poor efficiency and power circulation issues. The input split with high mechanical point is useful for launch, and is capable of providing high launch torque without large output motor torque requirements.

The combination of input split and compound split is capable of providing full ratio coverage with moderate component speeds and torques, and electrical path power < 50% of the engine peak. The compound split mode provides comparatively low electrical path losses during cruise conditions. This combination of EVT transmission modes allows a system to be designed that is capable of matching an automatic transmission in performance while also enabling all modes by which hybridization increases fuel economy.

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REFERENCES


DEFINITIONS, ACRONYMS, ABBREVIATIONS

BSFC: Brake Specific Fuel Consumption
CVT: Continuously Variable Transmission
DOF: Degree of Freedom
EVT: Electrically Variable Transmission
PM: Permanent Magnet
WOT: Wide Open Throttle