Defining the General Motors 2-Mode Hybrid Transmission

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General Motors

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ABSTRACT

The new General Motors 2-Mode Hybrid transmission for full-size, full-utility SUVs integrates two electro-mechanical power-split operating modes with four fixed gear ratios and provides fuel savings from electric assist, regenerative braking and low-speed electric vehicle operation. A combination of two power-split modes reduces the amount of mechanical power that must be converted to electricity for continuously variable transmission operation. Four fixed gear ratios further improve power transmission capacity and efficiency for especially demanding maneuvers such as full acceleration, hill climbing, and towing. This paper explains the basics of electro-mechanical power-split transmissions, input-split and compound-split modes, and the addition of fixed gear ratios to these modes to create the 2-Mode Hybrid transmission for SUVs.

INTRODUCTION

The 2-Mode Hybrid transmission for SUVs is an electrically variable transmission, which uses electric motors to operate at nearly any speed ratio through the transmission. The electric motors in the transmission also allow hybrid functions: electric vehicle operation, electric boost, and regenerative braking, as well as engine starting. The 2-Mode Hybrid transmission is also an automatic transmission, without a torque converter but with conventional hydraulically-applied wet-plate clutches to allow automatic shifting among two continuously variable modes and four fixed gears, a total of six mechanical configurations: EVT mode 1, EVT mode 2, and fixed gears 1 through 4. This combination is fully integrated into a package very much like a conventional automatic transmission, with added wires leading to electronic controls and a high-voltage battery.

DEVELOPMENT OF THE 2-MODE HYBRID

An electrically variable transmission or EVT uses electric motors to control its speed ratio, giving it a continuous choice of ratios. The input, output, and electric motors are connected to planetary gearing. In a set of planetary gears, the speed of a planet carrier is the weighted average of the speeds of its sun gear and its ring gear. In a given EVT mode, the speed of the transmission output is a weighted average of the speeds of the engine and the electric motors, as combined by the planetary gearing. So, a vehicle equipped with an EVT can be driven by the electric motor with the engine standing still (transmission ratio of zero), or the engine can be running while connected to the output with the vehicle standing still (transmission ratio of infinity), or the EVT can operate anywhere in between.

The 1-mode EVT was constructed and tested in several types of vehicles in the United States in the 1930's, with GM supplying electric motors for at least one version [1]. That work was stopped in 1941, but the design for a hybrid 1-mode EVT was developed with electronic controls in the 1960's [2], and developed further from the 1980's to the present. For road vehicles, the 1-mode EVT is an improvement over a simple series drive (a generator on the engine and a motor on the wheels) but the 1-mode EVT still requires powerful electric motors to operate through a wide range of speed ratios.

Several kinds of 2-mode EVTs were invented by GM transmission engineers [3, 4, 5, 6], which reduce the requirements for electric motors by using clutches to shift seamlessly between two different continuously-variable EVT modes. Production of a 2-mode EVT with both an input-split EVT mode and a compound-split EVT mode began at GM for transit buses in 2003. Over 600 buses have been driven more than 20 million fleet-miles in 50 locations around the world. The 2-mode EVT was also built and tested by GM for several other vehicles, including full-size SUVs.

The 2-Mode Hybrid with two continuously variable EVT modes and four fixed gear ratios has been developed from the 2-mode EVT to meet the greater demands for acceleration, speed and towing for full-size, full-utility SUVs including the GMC Yukon and Chevrolet Tahoe [7]. This development allows fuel economy and emissions benefits of a full-function hybrid system to be delivered to customers in full-size vehicles without compromising performance or utility, including towing.

1-MODE EVT

The simplest and most common form of EVT operates in a single mechanical configuration or “mode”. It has a single set of planetary gears, which includes a sun gear, a carrier for planet gears, and a ring gear with internal...
teeth surrounding the planet gears. Figure 1 shows the essential rotating parts or core of an example 1-Mode EVT, including a single set of planetary gears, two cutaway electric motors, and the connecting shafts. The input shaft is on the far left, and is connected to the ring gear. The smaller of the two motors is connected with a sleeve shaft to the sun gear. The planets are on a carrier which is connected to the long output shaft. The output shaft extends from the carrier through the hollow sun gear and sleeve shaft to the far right, and the output shaft holds the larger of the two motors.

Figure 1: Core of a 1-Mode EVT

Figure 2 is a schematic cross section of this 1-mode EVT arrangement. In this example, the smaller motor on the left, "motor A", controls the speed ratio through the transmission using the sun gear and typically generates electricity. The larger motor on the right, "motor B", is connected directly to the output shaft and does not affect the speed ratio.

Figure 2: Schematic Cross Section of a 1-Mode EVT

The kinematics of the 1-Mode EVT are simple and unchanging. For the planetary gear set, the speed of the carrier is the weighted average of the speed of the ring and the speed of the sun. So, for this particular EVT arrangement, which maximizes output torque, the speed of the output is the weighted average of the speed of the input and the speed of motor A. In this arrangement, motor B has the same speed as the output.

Some simple examples of operation are shown in Table 1, with the gear ratio between the ring and the sun of 2:1. For instance, during light acceleration, twice the 2000 rpm input speed plus the -1000 rpm generator speed, divided by three, equals the 1000 rpm speed of the output (and motor B). These examples demonstrate that the speed ratio of the 1-mode EVT is variable, even though the gearing among the parts of the 1-mode EVT does not change.

Motor B, which is coupled to the output, typically uses electric power generated by motor A, balancing the electric power in the transmission, so that the net effect is to simply send all of the input power through the transmission to the output, without using the battery. As part of a hybrid system, motor B also allows power to be drawn from the battery and used to drive the vehicle directly, and motor B allows power generated from slowing the vehicle to be sent back to the battery, that is, regenerative braking.

This 1-mode EVT arrangement is known as an input-split EVT, because the input is connected by itself to the planetary gearing, and the power flow through the transmission is effectively split by the gearing at the input. Typically, some of the input power flows to motor A, which acts as a generator and turns that power into electricity. The rest of the input power flows along the output shaft. Output shaft power is added from motor B, which turns the electrical power from motor A back into mechanical power, except for the fraction lost in these conversions. Thus, there are two power paths through the transmission from input to output: an entirely mechanical path from input to gears to output, and an electrical or electro-mechanical path from input to gears to generator (A) to motor (B) to output.

From the speed examples in Table 1, note one particular example: cruising, with the engine turning 1500 rpm, motor A stationary, and the output turning 1000 rpm. This condition of operation, where the transmission is turning but the motor that controls the speed ratio is stationary, is a particular speed ratio and is called the "mechanical point", because the power flowing through the transmission from input to output all stays in mechanical form. This mechanical point tends to be the most efficient ratio for mechanical power flow through the transmission, since none of the transmitted power is converted into electricity and back again. The input-split, 1-mode EVT has one mechanical point, where motor A is stationary.

<table>
<thead>
<tr>
<th>Input</th>
<th>Motor A</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>1000 rpm</td>
<td>-2000 rpm</td>
</tr>
<tr>
<td>Light acceleration</td>
<td>2000 rpm</td>
<td>-1000 rpm</td>
</tr>
<tr>
<td>Cruising</td>
<td>1500 rpm</td>
<td>0 rpm</td>
</tr>
<tr>
<td>Electric driving</td>
<td>0 rpm</td>
<td>1500 rpm</td>
</tr>
</tbody>
</table>

Table 1: Examples of 1-Mode EVT Operation
Figure 3 demonstrates mechanical power transmission through this input-split 1-mode EVT, in a simplified example at a light load similar to cruising, with constant input speed, varying output speed and no battery power. The power flow through the electrical path is characterized by the powers of the motors. The mechanical power of the generator reaches zero, then it becomes a motor, as it changes directions at the mechanical point. The mechanical point is reached at a moderate speed, but at higher speeds the amount of power converted begins to rise again sharply.

Figure 3: 1-Mode EVT Light Power Chart

Figure 4 demonstrates maximum mechanical power flow through the transmission without battery assistance. Motor power reaches a very large magnitude for 1-mode EVT, even without battery power. This power is required to vary the speed ratio of the transmission and to transmit power through the transmission, not for the fundamental hybrid requirement to deliver the battery power. The mechanical point is always at the same transmission ratio, so increased engine speed pushes the mechanical point out beyond a useful output speed.

Figure 4: 1-Mode EVT Maximum Power Chart

Together, Figure 3 and Figure 4 show the critical limitation of the 1-Mode EVT. The choice of the ratio for the only mechanical point must be a compromise between efficiency, as shown by Figure 3, and electric motor capacity, as shown by Figure 4. If the mechanical point is chosen for low engine speeds, it will restrain continuous motor power during cruising, leading to high highway fuel economy. If the mechanical point is chosen for high engine speeds, it will restrain peak motor power during acceleration, leading to relatively low mass and cost for the motors and their electronic power supply. Alas, the 1-Mode EVT cannot have both; it must compromise between fuel economy and power. So, it was not selected by GM for full-size vehicles.

2-MODE EVT

The need for the highest highway fuel economy and for high power output, along with moderate size, weight and cost for the electric motors led to further mechanical development of the EVT. A second mechanical point provides the ability to restrain both continuous motor power during cruising and peak motor power during acceleration. A 2-mode EVT with both an input-split mode, with one mechanical point, and a compound-split mode, with two additional mechanical points, fundamentally lowered the requirement for motor power, allowing the EVT to be selected as a sound basis for GM’s heavy-duty bus hybrids.

Figure 5 is a schematic cross section of the 2-mode EVT used in buses, which is the direct ancestor of and basis for the 2-Mode Hybrid for full-size vehicles. The 2-mode EVT contains three planetary gear sets. Two planetary gear sets are required for a compound power split. In the 2-mode EVT they are used for both the input split and compound split, depending on which of the two clutches in the transmission are activated. The third planetary gear set multiplies the torque from the input and both of the electric motors during input-split operation, much like a planetary gear set in a typical automatic transmission.

Figure 5: Schematic Cross Section of 2-mode EVT

The two clutches in the transmission are both hydraulically-actuated, wet-plate clutches similar to those in conventional automatic transmissions, driven by an oil pump and controlled with valves and other hardware. The first clutch "C1" is a stationary clutch or brake which activates the input-split mode and low-speed torque multiplication by holding the ring gear of the third planetary gear set. The second clutch "C2" is a rotating clutch which activates the compound-split mode by connecting the main shaft from the carriers of the first and second planetary gear sets to the output shaft.
Figure 6 demonstrates mechanical power transmission through this 2-mode EVT, in a simplified example at light load similar to cruising with constant input speed, varying output speed, and no battery power. The mechanical power of the generator reaches zero, then it becomes a motor as it changes directions at the first mechanical point. The shift ratio is slightly beyond the first mechanical point, with motor A spinning slowly. A second mechanical point is reached as motor A stops again at a slightly higher speed, and at increasing speeds the magnitude of power converted rises some but then falls though zero at the third mechanical point where motor B stops. The power flow through the electrical path is characterized by a series of three small curves, rather than one large curve.

SYNCHRONOUS SHIFTS BETWEEN EVT MODES

Changing modes can be smooth in this 2-mode EVT, because the shift can be synchronous in speeds and is merely a hand-off of torque from one clutch to another. That is, the relative speeds of the on-coming and off-going clutches can be held at zero during the shift or even indefinitely, because the state of the transmission during the shift is simply a fixed transmission ratio.

In a fixed ratio, a conventional transmission has only one degree of freedom. The speeds of the input and the output can vary, but only in proportion to each other. If two stepped ratios are selected at the same time, the transmission loses its one degree of freedom. In other words, two proportional speed relationships can be satisfied at only one input and output speed, zero, so the transmission is locked.

In a continuously variable mode, an EVT has two degrees of mechanical freedom: speed and ratio. The EVT can be designed so that if two modes are selected at the same time, the transmission loses one degree of freedom, ratio, and is therefore locked into a fixed gear ratio. The two linear combinations of speeds describing the two EVT modes can be satisfied at the same time at only one speed ratio, the “synchronous shift ratio”.

This can be described operationally. If the transmission is in input-split mode and a synchronous shift to compound-split mode is wanted, then the electric motor controlling the speed of the transmission in input-split mode varies the ratio through the transmission until the clutch for the compound-split mode has zero relative speed. Then the shift, which is simply a torque transfer from one clutch to another, can proceed synchronously, leaving the transmission in compound-split mode at the particular speed ratio where the clutch for the input-split mode has zero speed.

The 2-mode EVT is a relatively compact and cost-effective system for a hybrid with a large engine, compared to the 1-Mode EVT or series hybrids. The 2-mode EVT is successful in bus applications and is appropriate for many other heavy-duty stop-and-go applications. After developing the 2-mode EVT for buses, the logical next step in GM’s series of hybrid development programs was to investigate it for personal vehicles, starting with a full-size SUV demonstration vehicle. The 2-mode EVT demonstrated substantial improvement to the urban-cycle fuel economy in a full-size SUV, but for production, it would have required vehicle structural changes to accommodate a larger transmission, or a reduction in towing capacity as compared with a conventional fixed-ratio transmission.

2-MODE HYBRID WITH FIXED GEAR RATIOS

Full-size SUVs and other personal trucks are extremely challenging applications for hybrids, because the load that a full-size, full-utility SUV can tow is more than the weight of a fully-loaded SUV. The demands of towing,
especially for high continuous engine power, led to the addition of fixed gear ratios to the 2-mode EVT to create the 2-Mode Hybrid for SUVs. Figure 8 is a schematic cross section of the 2-Mode Hybrid, showing the additional stationary clutch or brake "C3" and the additional rotating clutch "C4". Table 2 is a clutch table for the 2-Mode Hybrid, showing which of its four clutches are required to achieve its four fixed gear ratios and its two EVT modes.

Figure 8: Schematic Cross Section for 2-Mode Hybrid with Fixed Gear Ratios

<table>
<thead>
<tr>
<th>2-Mode Hybrid Operation</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Launch</td>
<td>EVT 1</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Starting</td>
<td>EVT 1</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVT Mode / Range 1</td>
<td>EVT 1</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Fixed Gear Ratio</td>
<td>FG 1</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVT Mode / Range 1</td>
<td>EVT 1</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd Fixed Gear Ratio</td>
<td>FG 2</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVT Mode / Range 2</td>
<td>EVT 2</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Fixed Gear Ratio</td>
<td>FG 3</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EVT Mode / Range 2</td>
<td>EVT 2</td>
<td>On</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th Fixed Gear Ratio</td>
<td>FG 4</td>
<td>On</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Clutch Table for 2-Mode Hybrid

The 2-mode EVT already has a native fixed gear ratio, the synchronous shift ratio, where the action of two clutches at the same time provides a fixed ratio. For the 2-Mode Hybrid, one fixed gear was added within the ratio range of the first EVT mode, and two more fixed gears were added within the ratio range of the second EVT mode. So, for the 2-Mode Hybrid the native fixed gear between the two EVT modes is fixed gear 2 or FG2.

The top fixed gear ratio, fixed gear 4 or FG4 was added by putting stationary clutch or brake C3 on one of the motors that regulates the speed ratio through the transmission, motor B. This third clutch was added to improve the highway fuel economy by replacing electricity fed to motor B to maintain holding torque at the third mechanical point with hydraulic pressure already needed to keep clutch 2 activated.

Fixed gear 1, FG1, and fixed gear 3, FG3, were both added with rotating clutch C4. This fourth clutch locks both the first and second planetary gear sets, which together provide the input power split and compound power split through the EVT. Fixed gear 1 comes from locking up the input-split mode, so the speed, torque, and power from the engine go through the torque multiplication of the third planetary gear set. FG3 comes from locking up the compound-split mode, so the speed, torque and power from the engine are coupled directly to the output.

Fixed gear 1 and fixed gear 3 are a major departure from pure EVT operation. They are in the centers of the input-split and compound-split ranges, where motors A and B are both turning the same speed and exchanging the maximum amount of power. Activation of either of these fixed gears eliminates the motor power that would be required to transmit engine power through the transmission in at this ratio in the EVT modes.

Figure 9 demonstrates the effect in concept of fixed gear operation on the maximum mechanical power through the transmission without battery assistance, relative to the earlier figures for the 1-mode EVT and 2-mode EVT concepts. Without battery use, motor powers are reduced to essentially zero or to generating for accessories during the range where fixed gear 1 is used. During fixed gear 1 operation, if battery assistance were needed, both of the motor could be devoted to this task.

Another similar benefit from the fixed gear ratios is that the transmission can resort to fixed-gear operation whenever the motors would overheat in EVT operation. That is, the control system can exit an EVT mode and enter a fixed gear if the temperature of one of the motors is reaching a critical level. This improves the towing ability of the system over a hybrid with EVT functions.
alone, and allows the hybrid vehicle to have the same towing capacity as a conventional vehicle.

Another benefit is that operation in the fixed gear ratios can enable the motors to exchange power with the battery more efficiently. The activation of C4 for fixed gear 1 or fixed gear 3 frees the motors from the need to transmit a fraction of the engine power through the transmission, so they are fully available for using battery power or for recovering regenerative braking power to the battery. Power from the battery can be especially helpful in fixed gear 1 to add motor torque to engine torque at low speeds for acceleration, and fixed gear 4 is efficient for regenerative braking from high speeds.

The results section below describes the effects of fixed gears on performance and fuel economy in detail, based on detailed models of the X20R in a full-size GM SUV.

RESULTS

The effect of the additional clutches and fixed gears on vehicle performance and fuel economy was investigated through simulation. Motor capacities for torque and power were held constant for this study, because the space for motors is firmly limited by the uncompromised vehicle structure.

VEHICLE PERFORMANCE

A hybrid system may improve vehicle performance either by increasing the ability of the engine to operate at its power peak through transmission improvements, or through use of battery power boost to improve performance. To obtain the best vehicle performance, the control system should select the engine speed and torque at each vehicle speed to maximize the vehicle tractive effort. This section presents the results of an analysis comparing the performance of the GM 2-Mode Hybrid system with and without fixed gear 1. For each system and at each vehicle speed, the analysis determined the engine speed and torque that maximized transmission output torque.

Effect of Fixed Gears on Vehicle Performance

Figure 10 shows the tractive capability of the system with and without fixed gears, based on optimum selection of engine speed to provide the highest level of tractive output. From this graph, it can be seen that fixed gear 1 increases the vehicle tractive capability significantly in the range of 10-45 mph. To see why this is so, refer to figures 11 and 12. Figure 11 shows the power level of the engine, battery, motors, and output over the acceleration for the case using EVT modes only, while Figure 12 shows the same parameters for the case using both EVT and fixed gear modes.

The use of fixed gear 1 helps increase the vehicle performance in two ways. Without the fixed gear, the capacity of the electric machines is used for processing engine power and the battery power is not able to contribute significantly to vehicle acceleration until about 60 mph. In contrast, the use of fixed gear 1 over a large range of vehicle speeds eliminates the need to use the motors for processing engine power, freeing up capacity to boost acceleration by adding battery power while keeping the total motor power relatively low. Battery power is maintained at a high level throughout the range of acceleration.

A second reason for the performance increase is the ability of the engine to operate at higher speed and power due to the favorable 3.69 fixed gear ratio. Without the fixed gear, the engine speed is constrained by power limitations in the electric machines, as shown in Figure 13. Note also that the shape of the engine speed profile with fixed gears is a “sawtooth” shape similar to that of a conventional automatic transmission.

The acceleration performance of the transmission with fixed gear 1 is equivalent to the performance of the EVT only transmission at an 11% higher final drive ratio. This gives the system designer the option to trade the increased performance for increased fuel economy at a reduced axle ratio.
**Effect on Performance when Battery Power is Limited**

In the case where battery performance is limited due to cold temperature or low state of charge, the relative benefit of fixed and EVT operation changes. Figure 14 shows the tractive capability of the system with and without fixed gears, based on optimum selection of engine speed to provide the highest level of tractive output, with zero battery power. Figure 15 shows the engine speed profile under the same two cases.

From these plots, it can be seen that the advantage of fixed gear operation at low vehicle speed, which is dependent on electric boost, is eliminated, while the advantage at high speed, which is a function of the high mechanical gear ratio, remains. Therefore the system control strategy adapts to use EVT rather than fixed gear operation at low speed.

**Effect on Trailer Towing Performance**

When a hybrid system is applied to full size SUVs, 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. In the 2-Mode Hybrid transmission, fixed gears increase the ability of the system to operate in a trailing duty cycle without excessive electrical path losses or motor heating. The fixed gear 3 with a ratio of 1.0 provides optimum fuel economy for trailer cruise by reducing the need to process power electrically. Fixed gear 2, with a ratio of 1.7, is useful for trailering on a grade at highway speeds, and fixed gear 1, with a ratio of 3.69, provides high torque to accelerate the vehicle at low speeds.
VEHICLE FUEL ECONOMY

Vehicle fuel economy is also affected by addition of the fixed gears. The addition of clutches 3 and 4 will increase the spin and pump loss of the transmission. The use of fixed gears may cause the engine to operate further from its best efficiency point, increasing engine losses. However, the use of the fixed gears also reduces the total amount of energy transmitted through the electrical path which reduces motor losses. To determine the net effect of fixed gears on fuel economy, a simulation experiment was performed using a model of the 2-Mode Hybrid powertrain installed in a full-size SUV in a GM simulation tool.

The design of experiments study consisted of 4 cases, with a single factor change between each case, as described in Table 3. The axle ratios were selected so that the 2 clutch design with the higher final drive "FD" ratio has equivalent acceleration performance to the 4 clutch design with the lower final drive ratio. With the additional clutches, transmission pump loss was increased to account for the 4 clutch design. Case 3, with the additional clutch losses present but without the additional fixed gears, was included to separate the increase in transmission mechanical loss due to adding the clutches from the reduction in motor loss enabled by using the fixed gears.

<table>
<thead>
<tr>
<th>#</th>
<th>Case</th>
<th>Design Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Final Drive</td>
</tr>
<tr>
<td>1</td>
<td>2-mode EVT</td>
<td>3.42</td>
</tr>
<tr>
<td>2</td>
<td>Reduce axle ratio</td>
<td>3.08</td>
</tr>
<tr>
<td>3</td>
<td>Add C3 and C4 but don’t enable</td>
<td>3.08</td>
</tr>
<tr>
<td>4</td>
<td>Use FG 1,3,4 (2-Mode Hybrid)</td>
<td>3.08</td>
</tr>
</tbody>
</table>

Table 3: Fuel Economy DOE Cases

Effect on Time in Mode

The C4 clutch enables fixed gears 1 and 3, while the C3 clutch enables fixed gear 4. Only clutches C1 and C2 are required to enable fixed gear 2, so fixed gear 2 is included in all cases. Since the addition of clutches without enabling the fixed gears includes the same modes, the time in mode distribution is not substantially different and therefore this result for case 3 is not included in that part of the analysis. Figures 16, 17, and 18 show the distribution of time-in-mode over the EPA Urban schedule, Highway schedule, and US06 schedule, respectively.

On the urban schedule, the additional fixed gears 1, 3 and 4 are used about 14% of the time, which reduces the time spent in EVT modes from 68% to 54%. Since EVT mode 1 is used for all engine off operation, the transmission spends a substantial amount of the engine on time in fixed gears.

On the highway cycle, top gear operation predominates as can be seen in the total amount of time spent in EVT mode 2 and fixed gear 4. The addition of fixed gear 4 reduces the amount of time spent in EVT mode 2 by approximately 50%.

The US06 cycle contains higher speeds and more aggressive acceleration rates, which causes more use of fixed gears 1 and 3. However, fixed gear 4 has a similar effect as in the highway cycle, again reducing the amount of time spent in EVT mode 2 on the order of 50%.
Effect on Component Losses and Engine Efficiency

Fuel economy is a function of system losses, which are affected by the additional fixed gears primarily in 4 ways:

1. The addition of clutches 3 and 4 increases the spin and pump loss of the transmission.

2. The use of the fixed gears reduces the total amount of energy transmitted through the electrical path which reduces motor losses. In addition, the ability to use fixed gear 4 for regenerative braking with the engine on at high vehicle speeds eliminates inefficient electrical power circulation through motor B.

3. The use of fixed gears may cause the engine to operate further from its best efficiency point, increasing engine losses.

4. As described in the performance section, the use of fixed gears increases the tractive effort capability of the system, and output torque from the transmission. The increased output torque allows a reduced final drive ratio for reduced transmission spin losses and a more optimum engine N/V ratio in fixed gear 4.

Figure 19 shows the average engine input fuel power and the average engine output power for each of the four cases in the most demanding driving cycle, the US06. This graph demonstrates the related effects of fixed gears on engine efficiency (diagonal lines) and engine power for overall fuel consumption.

Figure 19: Engine Average Fuel Power and Load, US06 Cycle

On the urban schedule, the addition of the C3 and C4 clutches reduces motor losses by about 35%, while increasing transmission losses by about the same percentage. Between the cases representing the 2-mode EVT (2 clutches, FG2 only, 11% higher FD) and the 2-Mode Hybrid (4 clutches, FG 1, 2, 3, 4), engine operating efficiency is reduced by about 0.2% with the use of fixed gears, but average engine output power is also reduced, yielding equivalent fuel consumption.

On the highway schedule, the addition of C4 increases transmission spin and pump loss. Fixed gears 1 and 3 are not used much during the cycle, so the clutch is open and contributing to spin loss. The C3 clutch, due to its small size and low speed under cruising conditions, does not contribute significantly to the increased transmission spin and pump loss. The C3 clutch reduces the motor losses on the highway schedule by about 40% by enabling fixed gear 4 and improved regenerative braking efficiency. However, engine operating efficiency is reduced by about 0.9%, offsetting some of this gain. Thus, the net effect on highway fuel consumption of adding C3 and C4, using the additional fixed gears and changing the final drive ratio between the 2-mode EVT and the 2-Mode Hybrid was a 0.3% improvement.

On the US06 schedule, which is the most difficult of widely used fuel economy driving schedules, the benefit of the added fixed gears becomes apparent and highly significant. Transmission spin loss is increased by 25% while the motor losses are reduced by 45% resulting in a significant decrease in total transmission losses. Although engine efficiency is decreased by 0.4%, fuel consumption is reduced by 2% for the 2-Mode Hybrid versus the 2-mode EVT. This number appears small, but the effect is very significant, since this might mean an additional savings through the life of the vehicle of up to 500 liters of fuel, if the vehicle were used in relatively demanding driving.

Table 4 summarizes the fuel consumption impact of the additional C3 and C4 clutches enabling fixed gears 1, 3, and 4, on the various schedules, with the 11% reduction
in axle ratio from 3.42 to 3.08 enabled by the additional transmission output torque. Half of the fuel consumption effects come from the change in axle ratio, which results from the greater performance capability with fixed gears.

### Table 4: Effect of Fixed Gears 1, 3, and 4 on Schedule Fuel Consumption

<table>
<thead>
<tr>
<th>Fuel Economy Schedule</th>
<th>Improvement in Fuel Consumption, 2-Mode EVT to 2-Mode Hybrid (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPA Urban</td>
<td>+0.0</td>
</tr>
<tr>
<td>EPA Highway</td>
<td>+0.3</td>
</tr>
<tr>
<td>US06</td>
<td>+2.0</td>
</tr>
</tbody>
</table>

The increase in average transmission output torque gained with fixed ratios enables a reduction in axle ratio and the same reported fuel economy on the EPA composite cycle, while improving fuel economy further for heavier loads or more aggressive driving as represented by the US06 cycle.

This optimization for fuel economy in the design of the 2-Mode Hybrid with fixed gears may be viewed as a profitable trade between fixed transmission losses and engine losses in one hand and variable losses in the other hand. The variable losses (the electrical path motor losses) have been reduced, at the lower cost of adding additional fixed losses (the drag of the additional clutches, which is essentially fixed with load) and deviating slightly from the optimal engine operating point.

This design strategy of reducing losses that vary with load is especially good for a vehicle designed to tow a trailer, since the motor losses will increase with vehicle drag and mass, while the transmission losses will be relatively constant, and the engine efficiency will increase as its average load increases.

### CONCLUSION

The 2-Mode Hybrid transmission is an optimized combination of two continuously variable operating ranges and four fixed gear ratios for parallel hybrid operation. It is particularly appropriate for full-size SUVs, which have substantial towing capacity and large engines. The 2-Mode Hybrid has the advantage over a 1-mode EVT of greater ability to transmit power mechanically, minimizing engine power conversion to electricity and back again. The 2-Mode Hybrid also significant advantages over a 2-mode EVT, adding fixed gears for strong towing capacity and reducing or eliminating extreme continuous-duty motor requirements without sacrificing fuel economy. The addition of fixed gear ratios in the 2-Mode Hybrid allows the system to use a lower axle ratio and to select either variable modes or fixed gears for the highest fuel economy under widely varying conditions, maximizing its fuel economy improvement and best meeting the challenges of demanding SUV driving.

### REFERENCES

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### DEFINITIONS, ACRONYMS, ABBREVIATIONS

- **BSFC**: Brake Specific Fuel Consumption
- **CVT**: Continuously Variable Transmission
- **EVT**: Electrically Variable Transmission
- **FG**: Fixed Gear
- **FD**: Final Drive
- **SUV**: Sport-Utility Vehicle
- **PM**: Permanent Magnet
- **WOT**: Wide Open Throttle