

High Efficiency, Hydro-Mechanical Passenger Vehicle Transmission using Fixed Displacement Pump/Motors and Digital Hydraulics

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ABSTRACT

It is widely accepted that the plug-in hybrid vehicle is the most economically viable near-term solution to the petroleum and CO₂ problems associated with passenger vehicles. The battery and electric costs of gas/electric plug-in hybrid vehicles can be significantly reduced with the use of a hydraulic transmission and the implementation of hydraulic regenerative braking. This has not been done to date due to the unavailability of a low cost, reliable, compact, and efficient hydraulic transmission. This paper describes a conceptual design of such a transmission and evaluates its performance using the attributes of existing components.

The main causes of the lack of past success with hydraulic transmissions are the many drawbacks of variable-displacement hydraulic pumps and motors. This transmission is based on fixed displacement pumps and motors to avoid these drawbacks. The efficiency of the transmission is evaluated under various driving conditions and is equal to or better than present day automatic transmissions due in part to the use of an all-mechanical bypass when cruising. The transmission is configured to allow a continuously variable level of braking torque. The design, construction and performance of this digital hydraulic transmission are detailed. The use of internal gear type pump/motors results in a small size that will allow the transmission to fit within the outline of a typical SUV transmission, offering a low cost way to convert existing vehicles to hybrids. The required accumulator size is discussed.

The design eliminates the need for either a friction clutch or torque converter and is scalable such that it is applicable from compact cars to large trucks and buses. A variation is described that is suitable for adding hydraulic regenerative braking to an all-electric vehicle.

The technical trend in hydraulic pumps and motors is to higher operating pressures and speeds. Both these trends result in proportional reductions in the size and cost of this style of transmission and increased power handling capability.

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INTRODUCTION AND BACKGROUND

HYDRAULIC HYBRID VEHICLES

The use of hydraulics to generate and transmit power has some basic advantages compared to electric motor/generators and mechanical transmissions [1]. These are:

- Higher power to weight ratio
- Self-lubricating
- Higher force to mass ratio. High torque to inertia ratio (results in high acceleration and rapid response)
- No saturation phenomenon

- Simple overload protection
- Low cost, high power and highly efficient energy storage capability
- No explosion hazard

These characteristics make hydraulics a very attractive candidate for vehicle transmissions and regenerative braking.

The Environmental Protection Agency of the US government (EPA), in conjunction with various companies in the industry, has been developing hydraulic hybrid technology systems and components for various size road vehicles based on variable displacement pumps and motors for over 17 years [2,3]. Their initial focus was on "parallel" systems for heavy, start/stop intensive applications such as UPS trucks and refuse collection. These applications require



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the maximum benefits from the hydraulic regenerative braking (HRB) and so can accept the lower efficiencies and high costs associated with the variable displacement pumps and motors used. There are presently vehicles in fleet testing using much of the EPA technology. They have now shifted their focus to “series”** systems for passenger vehicles wherein the standard transmission is replaced with a hydraulic transmission. The latest available information suggests that the transmissions used are still based on variable displacement pumps and motors. Their most recent progress report dated Jan 2004 [4] details their projected results for a 1999 Ford Taurus with the 3.0 liter engine. These data provide a cost and mass bench mark for variable displacement based hydraulic transmissions in road vehicles. Overall efficiency and mpg data achievable with this series design have not yet been made available from the EPA. Eaton Corp. builds a parallel kit for refuse and other trucks, while Parker Hannifin build a series kit which includes a hydraulic transmission based on variable displacement pump/motors.

The focus of the transmission proposed in this paper is to eliminate the use of variable displacement devices for reasons of cost, efficiency and reliability and to provide for a mechanical bypass of the hydraulic portion of the transmission during vehicle cruising in order to achieve the high efficiency and reliability required for passenger vehicles. All present development for hydraulic passenger vehicles are based on variable displacement pumps and motors [5,6,7,8].

Ford Motor has a common development program with CCEFP [9] and Folsom Technologies International (hydro mechanical transmission mfg.) to build a parallel hydraulic version of the F150 pick up. The transmission is a power splitting design as in Figure 3. No information is available yet on the efficiency of the transmission over the driving cycle. Simulation indicates a 50% improvement in fuel economy relative to a conventional drive train due primarily to the addition of HRB. In Jan, 2011, Chrysler announced a joint program with the EPA to build prototype series hydraulic hybrid version of the Town and Country Minivan. BMW has cooperated with Artemis Intelligent Power [10] to produce a hydraulic hybrid prototype of their Model 530i. This series design uses one of their digital pumps (see below) and two digital motors—one for each back wheel. They claim a doubling of mpg in city driving. INNAS BV, a Dutch engineering company, built a prototype hydraulic hybrid based on the Volkswagen Passat. Their series design used fixed displacement pumps and motors interconnected with their proprietary variable displacement “hydraulic transformer” [11]. They haven't released the power train efficiency independent of the benefit of HRB.

As of the date of this paper, no one has announced the intention to build a hydraulic hybrid passenger vehicle though many designs are in the simulation stage.

The Hydraulic Plug-In

A target application of this transmission is for use in a combination gas, electric, hydraulic plug-in series hybrid vehicle. It has been shown that there are unexpected additional benefits to be obtained when hydraulic regenerative braking is added to gas/electric plug-in hybrids [12]. Figure 1 illustrates the basic architecture of the hydraulic plug-in hybrid. The transmission allows HRB to be added to a gas/electric plug-in at a net cost reduction [12]. The hydraulic system will reduce the electrical stress on the electric motor/generator, batteries and associated electronics resulting in significant size and cost reductions and reliability improvements. The result is a very high performance, fuel efficient vehicle that can be powered by the internal combustion engine, the electric motor and the hydraulic accumulator separately or simultaneously.

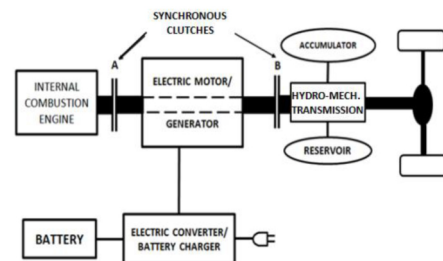


Figure 1. The hydraulic plug-in

HYDRAULIC TRANSMISSIONS

Hydrostatic and hydro-mechanical power transmission systems are widely used on excavators, lawn tractors, forklifts, winch drive systems, heavy lift equipment, agricultural machinery, etc.

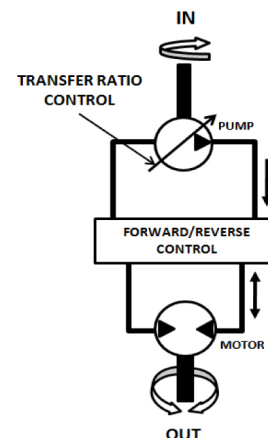


Figure 2. Basic hydrostatic transmission

Figure 2 illustrates a basic hydrostatic transmission using a variable displacement pump driving a fixed displacement

*The parallel design in most cases involves attaching a hydraulic pump/motor to the existing mechanical power train so that the hydraulic device operates in “parallel” with the internal combustion engine and the mechanical power train.

**In a “series” design all power passes through the hydraulic transmission (Figure 1).

motor. The output direction is changed by reversing the flow in the motor. A larger speed ratio range can be realized if both devices are variable displacement. As will be discussed, this arrangement suffers from low efficiency and high cost.

Most hydro-mechanical transmissions are implemented as power-splitting or differential transmissions in order to improve their efficiency. These involve both a hydraulic and a mechanical path from input to output. The mechanical path by its nature can transmit power at high efficiency. [Figure 3](#) illustrates such a transmission consisting of a variable displacement pump and a variable displacement motor combined with a planetary gear set to create a power-splitting hydro-mechanical transmission. The power is split between the mechanical path and the hydraulic path and their outputs are combined by the planetary gear to form a single output. The differential sums the speeds of the hydraulic path and the mechanical path.

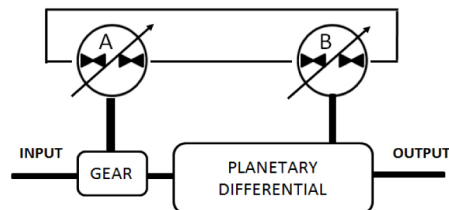


Figure 3. Power-splitting hydro-mechanical Transmission

Power-splitting hydro-mechanical transmissions transfer power in three different modes. At a low speeds, most of the power is transferred hydraulically and at a high speeds, power is transferred primarily mechanically. As will be discussed, the efficiency of the hydraulic path will be relatively low if it is based on variable displacement pumps and motors. Since the hydraulic path is involved to some degree at all speeds, the average efficiency is low. The various structures for this style of transmission are evaluated in detail in reference [13](#). Power-splitting hydro-mechanical transmissions are well suited for slow moving, heavy-duty applications, (where high efficiency, and low cost are not crucial) which is why they are common in agricultural and construction equipment. Bosch Rexroth Hydro-mechanical Variable Transmission (HVT) is configured as in [Fig. 3](#). Pump A is a fixed displacement unit rather than variable displacement. It is intended as a transmission for earth moving equipment. Fendt “Vario” from AGCO Corporation builds a transmission for tractors that is also configured as in [Fig. 2](#) but has two speed ranges in the mechanical path and both the hydraulic pump and the motor are variable displacement.

Neither hydro-mechanical nor hydrostatic transmissions have been employed on road vehicles except where they are part of a hydraulic regenerative braking (HRB) system applied to large vehicles that require a lot of stopping and starting and do little sustained high-speed driving (refuse trucks for example). In some cases, the benefits of the regenerative braking can justify the higher costs and lower

efficiencies of these transmissions and are now being adopted more widely. They have not been applied to passenger vehicles successfully due to the transmissions large size and cost, low efficiency, high noise and low reliability (by passenger vehicle standards).

FIXED VS. VARIABLE DISPLACEMENT HYDRAULIC PUMP/MOTORS

Major drawbacks to past designs are cost, weight, reliability, efficiency (at low displacement settings) and size of variable displacement hydraulic pumps and motors. [Figure 4](#) illustrates a typical variable displacement pump or motor. This “bent axis” design is often used in mobile applications because of its relatively high efficiency. The stroke of the pistons is reduced as the angle of the “bent axis” is increased thereby reducing the displacement. [Figure 5](#) illustrates the relative simplicity of a fixed displacement hydraulic pump or motor. This “internal gear” design is commonly used in mobile applications such as forklifts and golf course mowers because of its high efficiency, low noise and light weight.

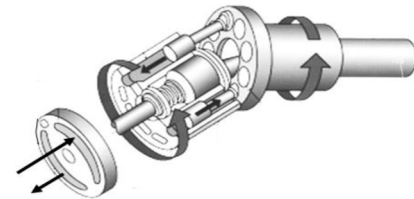


Figure 4. “Bent Axis” variable displacement hydraulic pump or motor

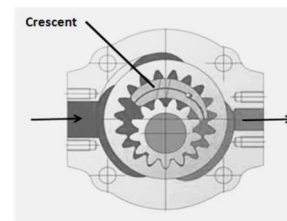


Figure 5. Crescent style “Internal Gear” fixed displacement hydraulic pump or motor. Eckerle series EIPS-2

[Figure A1](#) & [A2](#) in [Appendix 1](#) give the outline dimensions of a Rexroth model A6VM-28 bent axis variable displacement motor and the Eckerle model EIPS 2-025 fixed displacement pump with the following attributes:

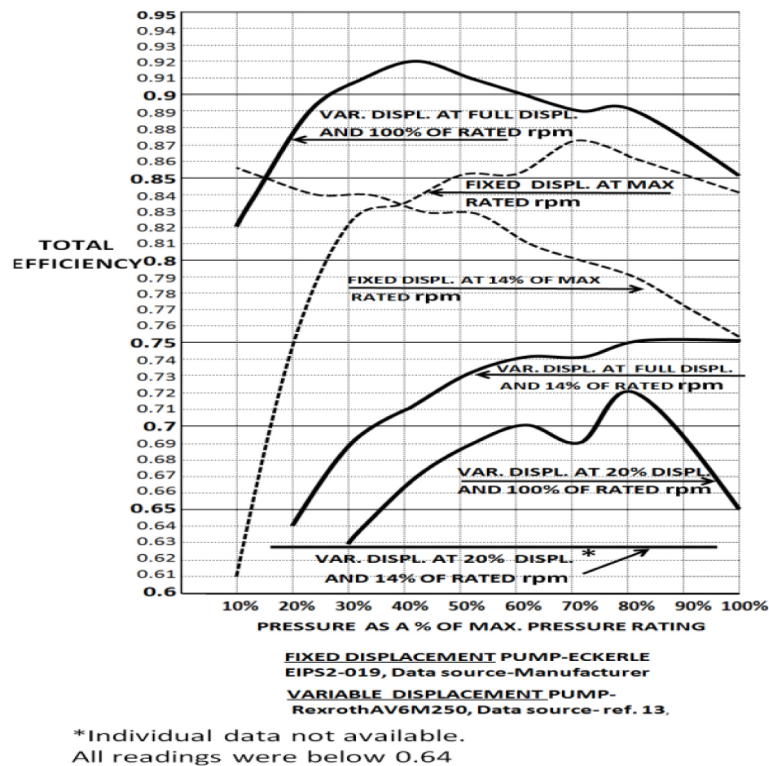


Figure 6. Efficiency of fixed vs. variable displacement hydraulic pumps

	Variable- Displacement Pump	Fixed- Displacement Pump
Model	Rexroth A6VM-28	Eckerle EIP5 2-025
Displacement:	28 cm ³ /rev.(max.)	25cm ³ /rev.
Mass:	16 kg	4.2kg
Occupied volume:	6,700 cm ³	1,345 cm ³
Efficiency*		
@ max. rpm & max. Displacement.	89%	87%
@14% of max rpm & 20% of max. Displ.	63%	80%

*@ 70% of rated pressure

Note the advantage in mass, volume, efficiency, and mechanical complexity for the fixed displacement device. The mechanical complexity of the variable displacement devices also results in higher cost, lower reliability and greater noise. It is primarily for these reasons that this paper proposes a hydraulic transmission based on fixed displacement pump/motors.

It is a characteristic of most variable displacement pumps and motors that the efficiency drops off dramatically at lower displacement settings, pressures and rpm*. The curves of figure 6 illustrate the different in efficiency between a common fixed and variable displacement hydraulic pump.

Figure 3A in Appendix I illustrates the efficiency curves for a typical variable displacement pump as a function of displacement and angular velocity and further illustrates the efficiency problem.

Reference 14 describes a computer simulation of a passenger vehicle design based on a power-splitting, hydro-mechanical transmission using variable displacement hydraulic pumps and motors. They found from simulating the vehicle through the EPA Urban Dynamometer Driving Schedule that the average displacement of the pumps and motors was 20% of maximum. They also show that at 20% displacement, the efficiency of a typical variable displacement pump/motor was 50% to 55%, and that roughly 40% of the time the pump or motor was operating at an efficiency of 10% to 15%. If both the pump and the motor are variable displacement- as was the case in this study- the efficiency of the hydraulic path would be roughly 5% to 8%, 40% of the time [14].

A new variable displacement pump and motor design has been introduced by Artemus [10] that addresses the efficiency problems mention above (with the exception of low efficiency at low rpm). The product is a circular array of pistons that can be individually enabled and disabled electrically on a pulse width modulation basis. They claim an efficiency of over 80% for displacements down to 10% of maximum and over 90% over most of the operating range.

*This follows from the fact that some of the losses are independent of the displacement setting (e.g. fluid leakage and most of the friction components). Since the total power is proportion to total fluid flow it is inherent in the design that the efficiency will drop off with lower fluid flow.

Though relatively large, complex and expensive, this innovative product is a major advance in improving the efficiency of variable displacement pumps and motors.

As will be seen, the gear type fixed displacement pump/motor is particularly compatible with the construction of a very compact transmission.

DESCRIPTION OF THE TRANSMISSION

In order for the transmission to perform all the functions to support HRB, it is necessary that it be able to:

- allow the output (vehicle wheels) to pump oil from the reservoir into the accumulator (Fig. 7) to store the braking energy in a continuously variable manner at high efficiency,
- allow the output pump to drive the input to turn the electric generator to capture braking and deceleration energy when the accumulator is charged to capacity,
- allow high pressure oil from the accumulator to drive the output (wheels) in order to recover the braking energy,
- and have the input pump oil into the accumulator to maintain a minimum pressure for predictable start-up accelerating performance.

It will be shown how all these functions can be accomplished with this design.

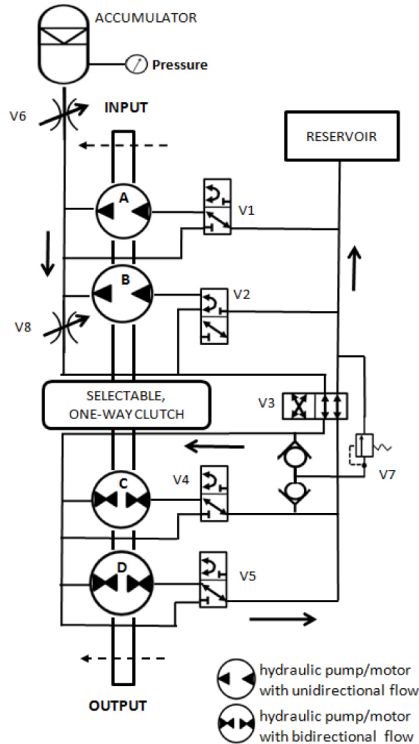


Figure 7. Proposed hydro-mechanical transmission

The proposed transmission (Figure 7) uses one or more fixed displacement hydraulic pump/motors driving one or

more hydraulic pump/motors with a total of at least three pump/motors with displacements chosen to allow a useful range of gear ratios by selectively deactivating one or more of the pump/motors by means of valves V1, V2, V4, & V5. The valves cause the fluid to re-circulate within each device thereby deactivating them. Valve V3 will reverse the flow direction in the output devices thereby switching the transmission in and out of reverse. An all mechanical by-pass is provided for the cruise condition to allow for peak efficiency in the most used driving mode. The mechanical by-pass is engaged and disengaged using a selectable one-way clutch. This allows the vehicle to go into regenerative braking mode in a seamless fashion when decelerating and braking and to be able to shift down into high-speed passing gear when higher torque is called for. As will be shown, 9 useful transmission ratios can be achieved using two pumps and two motors and 15 useful ratios can be achieved using two input pumps and three output motors. To predict the performance of this transmission we used the characteristics of off-the-shelf hydraulic pumps designated as Eckerle Model EIPS 2. An input reduction gear (Figure 8) is used to allow the use of larger displacement input pumps relative to the output pumps thereby increasing the power and torque capacity of the transmission while preserving useful transmission ratios. It can be implemented with a planetary gear and packaged in a coaxial manner as shown in Figure 10.

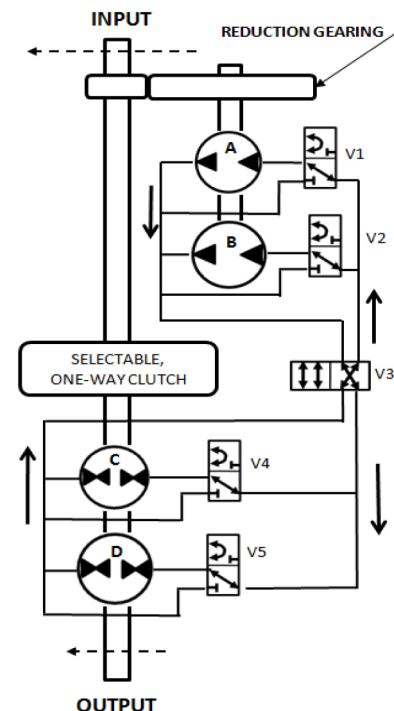


Figure 8. The transmission with an input reduction gear to allow larger displacement input pumps and still produce useable transfer ratios (Accumulator and reservoir not shown)

DIGITAL HYDRAULICS

In most mobile hydraulic equipment, e.g. a back hoe, the control of hydraulic power to the various elements of the equipment is accomplished by either throttling the fluid flow to a device or diverting the flow around the device. Significant power is lost in the valves to effect this throttling or diversion and turbulence in the valves make it difficult to achieve proportionality. One way around this is switch different sized valves in and out of the circuit. If switched rapidly, the power loss in such an arrangement is very low since there are no losses in either a closed or a fully open valve. Further, with a wide choice of valves (typically binary weighted in aperture size) to select from, a high degree of control can be achieved [15]. This is an example of one of many devices in development under the heading of Digital Hydraulics. A common feature of all digital hydraulic devices is rapid on/off switching to minimize losses during the on/off transition. Other examples include; a valve that achieves different capacities by pulse width modulation [16], the Artemis digital transmission [10] discussed below, and a hydraulic cylinder with various diameter pistons on a common shaft that can be selectively activated [17]. The subject transmission can be classified as a digital hydraulic device because it relies on rapid switching of various combinations of different sized pumps and motors. The section below on "smooth shifting" illustrates how the use of the accumulator allows rapid shifting.

HYDRAULIC PUMP/MOTORS

Optimum hydraulic pump/motors for this application would have the following capabilities:

- High operating pressure - smaller pump or motor required for the same power.
- High rpm capability - also results in a smaller pump or motor for the same power.
- High efficiency at a wide range of rpm and pressure- especially important for a passenger vehicle transmission.
- Low oil pressure pulsations - for reduced noise.
- Light weight - transmission weight is an important percentage of overall vehicle weight.
- High reliability - passenger vehicles need a transmission rated for at least 300,000 miles.

An off-the-shelf pump provides a good match to the capabilities listed above. Model number EIPS-2-025 manufactured by Eckerle Industrie-Elektronik GmbH is a gap-compensated high pressure internal gear pump suitable for this application. As a pump it has the following specifications:

Displacement-	25.2 cm ³ /rev.
Peak operating pressure-	280 bar
Maximum speed-	3600 rpm
Operating temp.-	-20 to +100°C
Mass-	4.2 kg
Volumetric efficiency*-	94%
Mechanical efficiency*-	92%
Pump noise*-	60 dB (A)
Pressure pulsation-	less than 2%
Life expectancy-	3 x 10 ⁶ **

*measured at an rpm of 1450, Δp of 250 bar at temperature of 50°C

**Cycle duty test against peak operating pressure

The design is such that the hydraulic pressure causes the two pieces of the crescent (Figure 5) to separate, thereby maintaining a tight seal against both sets of teeth and accommodating manufacturing tolerances and wear; resulting in high efficiency (low leakage), long life, and high pressure and rpm ratings.

Table 1 shows a set of possible transmission ratios using 4 pump/motors with the relative displacements shown and an input reduction ratio of 2.63.

The control of the selectable one-way clutch shown in Figure 7 would be as typically done in manual transmission vehicles with overdrive; de-selected when additional power is called for and going into free-wheeling mode when the engine slows relative to the vehicle speed. The transmission would be shifted into 9th gear to ease the synchronization of input and output speeds before selecting the cruise one-way clutch. The clutch would be selected when the input is turning slightly more slowly than the output and become fully engaged when the input speeds up to match the output speed. This would require dynamic measurements of input and output rpm and that valve V6 (Figure 7) be used to trim the speed. When decelerating in the free-wheeling mode, the hydraulic transmission would be configured to capture the energy for storage in a hydraulic accumulator, eliminating the safety problem associated with lack of engine braking in a conventional transmission when free-wheeling. Besides greatly improving the efficiency of the transmission during cruising, the mechanical by-pass increases the reliability since the hydraulic portion will be operating under a no-load condition most of the time during highway driving.

FIVE PUMP MOTORS

Further discussion of performance of this transmission will assume two input pump/motors and three output pump/motors using the displacements of Table 2. This was selected to result in a transmission that could handle the torque and power for a Toyota Corolla sized car. (Fixed displacement pump/motors deliver more kW/kg the lower the displacement) An additional benefit of this arrangement is that the three output pump/motors allow 6 different levels of hydraulic braking torque. (See figure 9)

Table 1. Transmission parameters with four hydraulic pump/motors (see Appendix II)

DISPLACEMENT cm ³ /rev. INPUT HYDR. P/MS				RATIOS				PEAK OUTPUT DISCHARGED ACCUMULATOR					PEAK OUTPUT CHARGED ACCUMULATOR				
OUTPUT HYDR. P/MS				Input													
A	B	C	D	Gear	Gear	Gear	Gear										
23	27	19	30		Ratio	Reduct.	Ratio**	rpm	Nm	lb-ft	kW	hp	rpm	Nm	lb-ft	kW	hp
0	0	1	1		∞		∞						3600	203	275	68	93
1*	0*	1	1	1st	2.130	2.631	5.605	1690	203	275	32	44	3600	203	275	68	93
0	1	1	1	2nd	1.815	2.631	4.775	1984	203	275	38	51	3600	203	275	68	93
1	0	0	1	3rd	1.304	2.631	3.432	2760	124	169	32	44	3600	124	169	42	57
0	1	0	1	4th	1.111	2.631	2.923	3240	124	169	38	52	3600	124	169	42	57
1	1	1	1	5th	0.980	2.631	2.578	3600	203	275	68	93	3600	203	275	68	93
1	0	1	0	6th	0.826	2.631	2.173	3600	78	106	26	35	3600	78	106	26	35
0	1	1	0	7th	0.704	2.631	1.851	3600	78	106	26	35	3600	78	106	26	35
1	1	0	1	8th	0.600	2.631	1.579	3600	124	169	42	57	3600	124	169	42	57
1	1	1	0	9th	0.380	2.631	1.000	3600	78	106	42	57	3600	78	106	42	57

PASSING GEAR

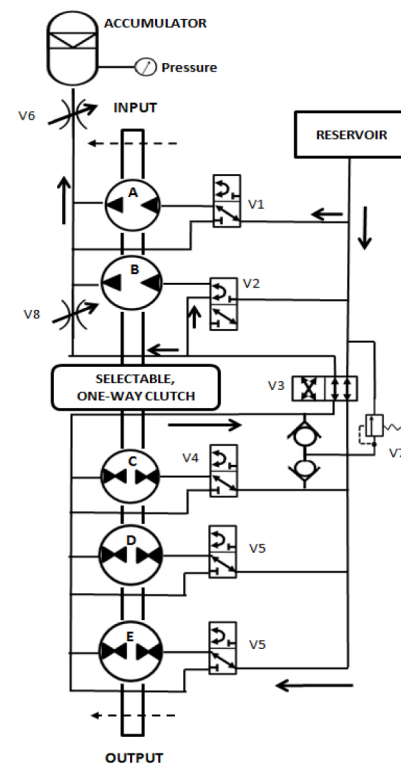
ENGAGEMENT GEAR
FOR CRUISE.

*1 = pump/motor active. *0 = pump/motor by-passed

**Resulting transmission gear ratio after introduction of input gear reduction ratio of 2.631

HYDRAULIC REGENERATIVE BREAKING

HRB is significantly more efficient than electric regenerative braking (Approx. 70% vs. 25%) [2] and is less restrictive in the range of braking energy that can be captured. Implementing hydraulic regenerative braking in a vehicle with a hydraulic transmission simply involves the addition of an accumulator, a reservoir, interconnections, and some additional controls. HRB requires that a continuous range of braking torque be available to meet the various level of braking required in normal driving. To brake, valve V3 (Figure 9) is set in the position shown so that the output motors now become pumps and pump fluid from the reservoir to the accumulator. If valve V8 is set to constrict the flow, some of the fluid will be diverted to drive pump/motor B as a motor. This will in turn drive pump/motor A as a pump to force additional fluid into the accumulator. This provides a continuous range of braking torque over and above that supplied by the selective activation of pumps C, D, & E. This then allows the braking resistance to be continuously varied to meet the need without a significant loss of efficiency.

**Figure 9. Arrangement for hydraulic regenerative braking**

The braking torque applied would be determined by the above and the pressure in the accumulator. Since the decelerating sensation to the driver will determine the pressure on the brake pedal, the variation of pressure in the accumulator will be automatically accommodated by the