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VARIABLE DISPLACEMENT OIL PUMP IMPROVES TRACKED VEHICLE TRANSMISSION EFFICIENCY

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ABSTRACT

Variable displacement pumps have been used in automotive transmissions for decades. L3T had high confidence that a Variable Displacement Oil (VDO) pump would increase overall transmission efficiency. An off-the-shelf (OTS) or OTS modified pump in this pressure and flow range was not found. Therefore, a VDO pump is being developed with the known risk of replacing a highly reliable pump with a new better performing pump of unknown reliability. In this document the development of this VDO pump is discussed.

Initial testing of the VDO pump demonstrated an average 25HP savings in pumping losses throughout the transmission operating ranges. At this point, durability testing has not been performed.

INTRODUCTION

L3 Technologies (L3T) manufactures the Hydromechanical Power Train (HMPT) transmission used in several tracked vehicles, most notably the Bradley Fighting Vehicle. The HMPT transmission has been in use for four decades. It has the advantages of a lightweight, high power density, modular design with an infinitely variable ratio allowing for optimum engine speed and torque at all conditions.

L3 Technologies HMPT Transmission

The transmission has three speed ranges. First range is fully hydraulic with a pump and motor pair, for each track, together called a hydraulic unit. Second and third range operate by sharing the power transmission between the hydraulic units and the mechanical gear drive.

These hydraulic units are of a radial ball piston arrangement, shown in an exploded view in Figure 1, along with an assembled hydraulic unit. There are two hydraulic units per transmission. The hydraulic units allow true pivot turns to be performed, where the tracks on opposite sides of the vehicle can move in opposite directions at the same time. The hydraulic unit is what gives the transmission its infinitely variable ratio capability.

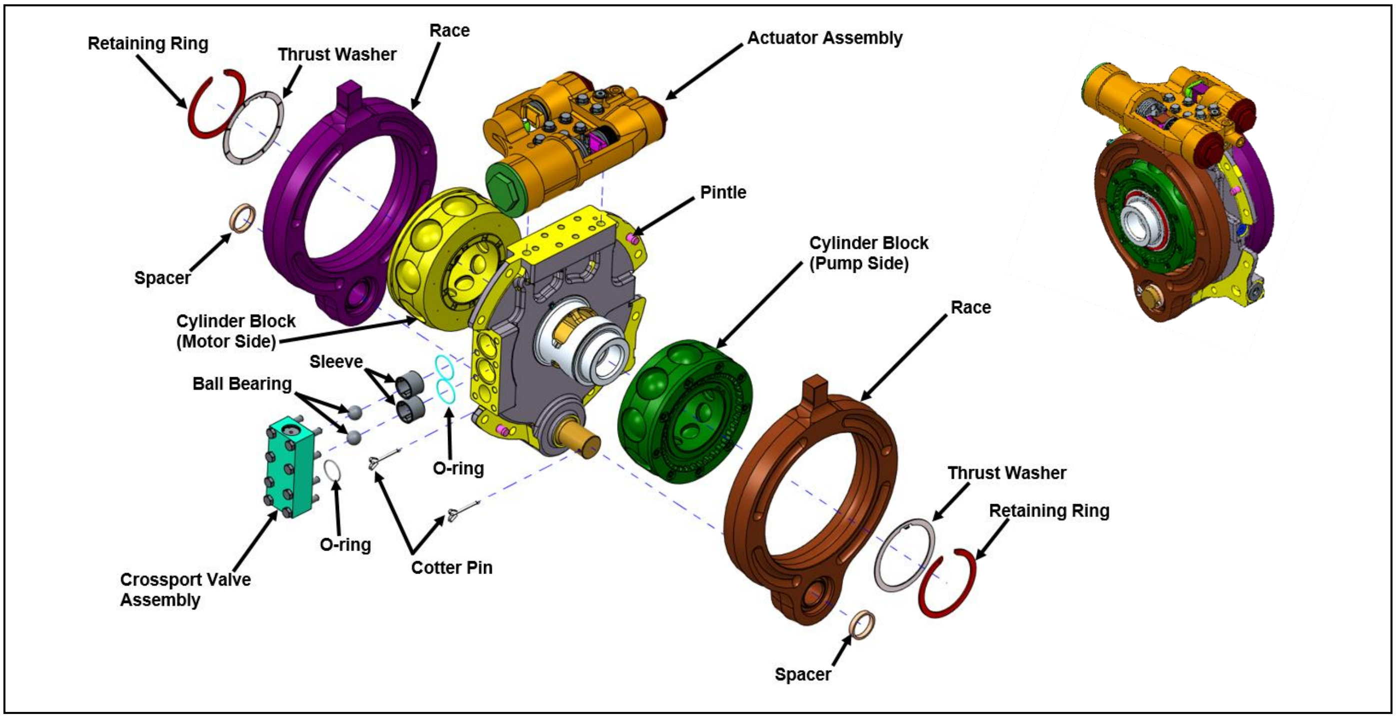

Figure 1: Hydraulic Unit (exploded view and assembled) includes one pump and one motor

The radial ball piston type hydraulic assemblies have several advantages including transmitting a great amount of power in a small package, but at high output torque operating points, the hydraulic units have the drawback of requiring a significant amount of oil to be supplied to them to make up for leakage. This oil is provided by what is referred to as the makeup pump system. The required flow rate of the makeup pump system is determined by the oil flow required at these high torque points. The pumps in the current makeup pump system are two fixed displacement gear pumps in one housing, see Figure 2, that provide oil at a flow rate that is proportional to the engine RPM.

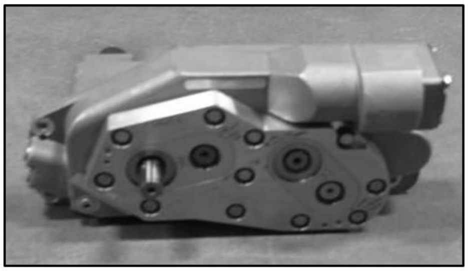

Figure 2: Current gear type makeup pump with two gear pumps in one housing

The full oil flow rate of the makeup pump system is seldom needed, the unneeded oil flow is dumped back into the transmission oil sump through regulator valves. There is a significant amount of wasted power going into pumping and dumping this unneeded oil. This waste can be avoided by replacing the current gear type makeup pump system with a variable displacement pump that only produces the oil flow that is demanded from the transmission for any given operating point. For this reason L3T is in the process of developing a Variable Displacement Oil (VDO) pump.

DEVELOPMENT OF A VARIABLE DISPLACEMENT PUMP

Requirements

A successful VDO pump development program will result in a VDO makeup pump that will be used in all new transmission products, as well as, in the transmissions that are returned from the field for remanufacture. Since there are thousands of L3T HMPT transmissions in the field, the VDO pump solution must be a "drop in" solution with little to no modification to the transmission. The VDO pump must meet the same durability, temperature, and pressure requirements as the gear pump, while only producing the flow rate the transmission requires.

An off-the-shelf (OTS) or OTS modified pump in this pressure and flow range was not found. Therefore the VDO pump system was a "clean-sheet" design. Several system configurations were considered, such as: one fixed pump in parallel with one variable pump, two variable displacement pumps in parallel, and one variable displacement pump. One variable pump was chosen due to the lowest part count, lowest cost, and highest efficiency.

A VDO pump had to be pursued with the known risk of replacing a highly reliable and durable pump with a pump of unknown reliability. Durability testing will be performed to ensure the new VDO pump system meets reliability and durability requirements for the transmission duty cycle.

A variable pump system was specified for this project since it will only produce the oil flow/pressure required. This makes the VDO pump system unique in that it will adjust to future transmission efficiency improvements and compound the power savings. For example, if the hydraulic unit leakage rate were to be reduced, the transmission oil demand would decrease and the VDO pump would reduce its output flow. This results in a power savings at the hydro units and at the VDO pump without revisiting the VDO pump design.

Predicting Power Savings of a VDO pump vs. Current Pump

Figure 3 shows a simplified graph of how the VDO pump saves power at each point of operation with the engine at full power. The x-axis is the torque output of the transmission, as the torque increases the road speed decreases. The blue line represents the power draw of the current binary gear pump system. The orange line shows the VDO pump power draw, which is reduced since the variable pump only produces the oil flow rate to meet transmission demand. The result of subtracting the VDO pump power from the gear pump power is the green line which shows significant power savings.

As expected the VDO pump is more efficient at all operating points. The required pump horsepower for each of the pump types is nearly the same at the highest torque points. This is due to the fact that both pumps are required to run at full displacement so the variable displacement pump loses its advantage here. An important take away from this graph is that a typical transmission is estimated to operate above a torque of 2600 ft-lb less than 5% of its life. For operation below 2600 ft-lb, the average power savings is 25HP. This initial analysis supported the case for a variable displacement pump development program that would be a worthwhile investment of resources for improving overall transmission efficiency.

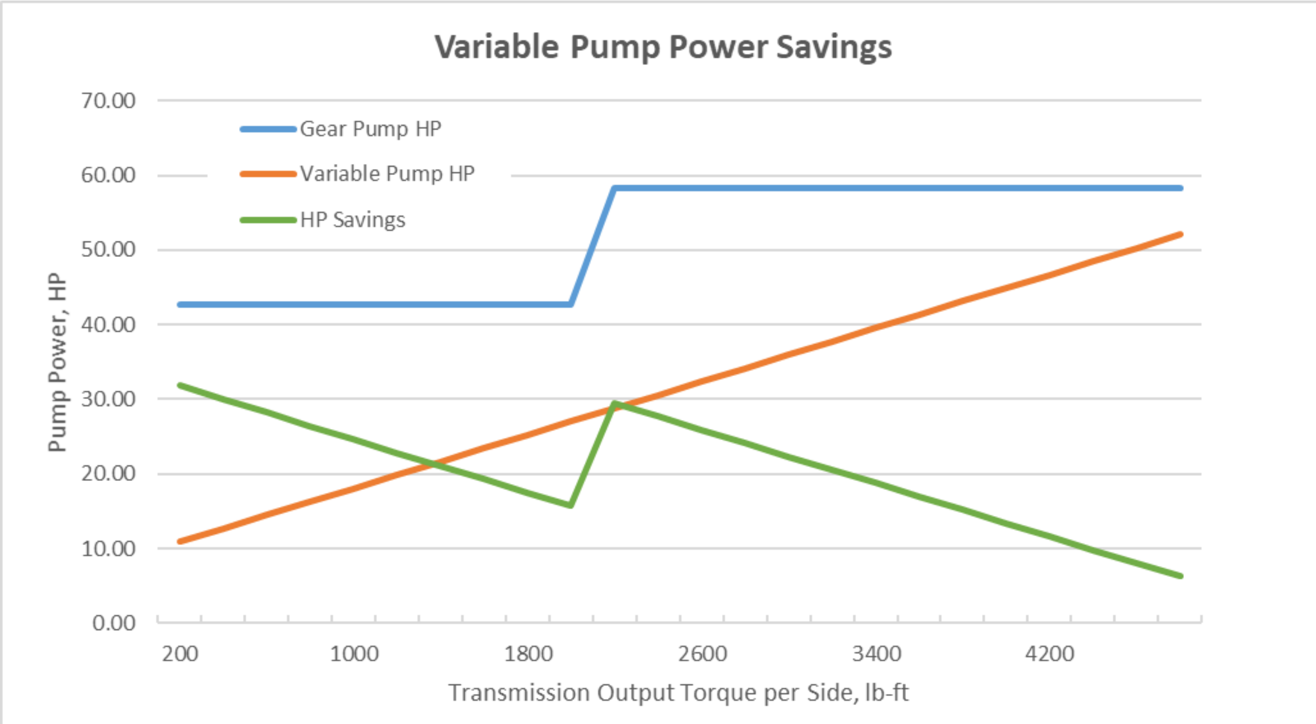

Figure 3: Simplified analysis to predict the potential power savings of changing to a variable displacement pump

Phase 1 VDO pump

In order to incorporate the VDO pump into the existing transmission with minimal changes, the Phase 1 VDO pump used the same gear ratio as the legacy gear pumps. This is a ratio of 1:1.6 between the engine output speed and the pump shaft speed. At this speed, the pump displacement was sized to provide a flow rate equivalent to the previous gear pump system. A CAD model of the selected vane type variable displacement pump configuration is shown in Figure 4.

Computational Fluid Dynamics (CFD) software showed that this speed ratio had the negative effect of increasing the vane tip speed to the point of causing cavitation at the intake side of the pump before the required flow rate could be achieved.

Figure 4: CAD Model of Pump Showing Internal Components

The vane pump model was modified to include a center fill inlet to the pump, in addition to the side inlets. The CFD model was run again with the addition of the center fill port. The CFD results showed that this new geometry increased the pump flow rate on the order of 10 GPM. Figure 5 shows screen shots from the CFD run.

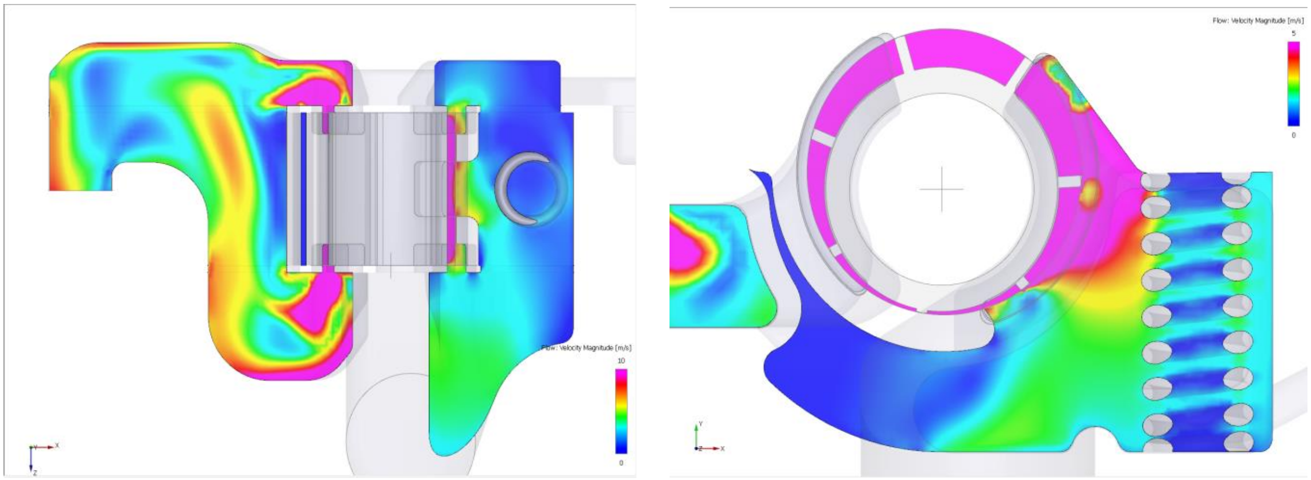

Figure 5. Top and side views of the CFD output showing fluid velocity with center fill geometry on intake side of pump

The gear pump output flow has a nearly linear relationship with engine RPM, shown with the orange data line in Figure 7. The blue data line shows that the output flow of the Phase 1 VDO pump is not linear and begins to level off at an engine speed around 2000 RPM. This leveling off is due to pump cavitation. While the CFD predicted cavitation, the test results demonstrate that it happens earlier than expected. The result was a VDO pump that did not produce the required peak flow at high engine RPM. Additionally, the Phase 1 VDO pump was capable of unnecessarily producing more flow than required at low RPMs.

As mentioned previously, this peak flow, while necessary, is rarely required. Therefore the Phase 1 VDO Pump performed well in the transmission. The VDO pump did an excellent job of self-regulating its flow to the demands of the transmission, in fact, the overall efficiency curve was smoothed since the regulator valves were not opening and closing between the test points as with the gear pump.

Phase 2 VDO pump

To improve the next iteration of VDO pump two significant changes were proposed. The first was to slow the pump shaft rotational speed by reducing the ratio of the engine speed to pump shaft speed from 1:1.6 to 1:1.2. A prototype Phase 2 VDO pump is shown in Figure 6. The speed reduction moved the predicted point where cavitation occurs from 2000 RPM out past the normal engine operating range of 2800 RPM. At the same time, the displacement of the pump was increased by 10% to meet the flow requirements at the high engine speeds. The green data line of Figure 7 shows the projected flow rate of two changes. The flow was expected to be very close to the gear pump flow rate.

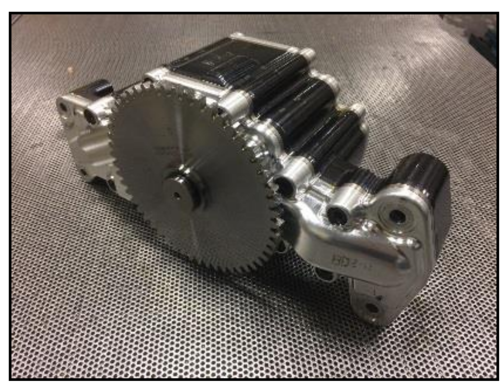

Figure 6: Phase 2 Variable Displacement Oil Pump

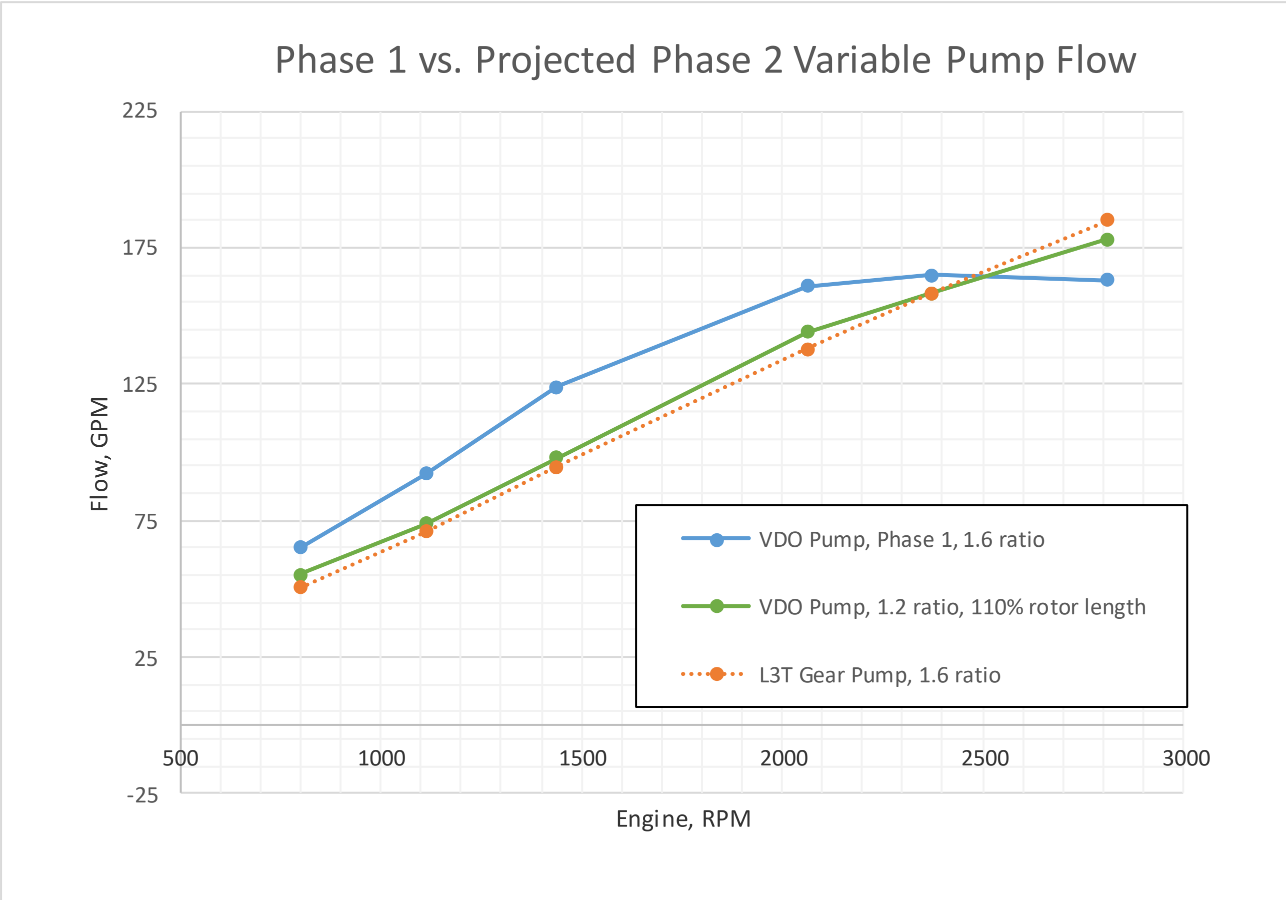

Figure 7: Phase 2 VDO pump projected flow rate improvement

Reducing the gear ratio and therefore the rotation shaft speed of the Phase 2 pump improved its efficiency over the Phase 1 VDO Pump primarily due to the reduction in cavitation, but also because the mechanical losses are reduced. Figure 8 compares the efficiency of the baseline gear pump to the Phase 1 and Phase 2 VDO pumps. The efficiency of the gear pump is the most consistent throughout the engine speeds, but is poor. The efficiency of both VDO pumps tail off at the higher shaft speeds, but slowing the Phase 2 shaft speed significantly helped the Phase 2 pump maintain efficiency

A surprising result of this program is how much better the overall efficiency of both the Phase 1 and Phase 2 VDO pumps are at full displacement when compared to the current gear pump. The power savings was expected to come from optimizing the pump displacement, but as can be seen from Figure 8, at each RPM the VDO pumps are superior.

It should be noted that the gear pump data and VDO pump data came from separate test stands at separate facilities, therefore the results likely have some testing variation due to test hardware and method with oil aeration likely the largest contributor to the variation. To compound the difficulty of comparing the pumps, when they are run in the transmission, at high flow rates, the aeration measures in the 20-25% range, while in the test stand the values are estimated to be in the 4-8% range. With that said, the improvement trends have been reliable predictors of transmission level improvements.

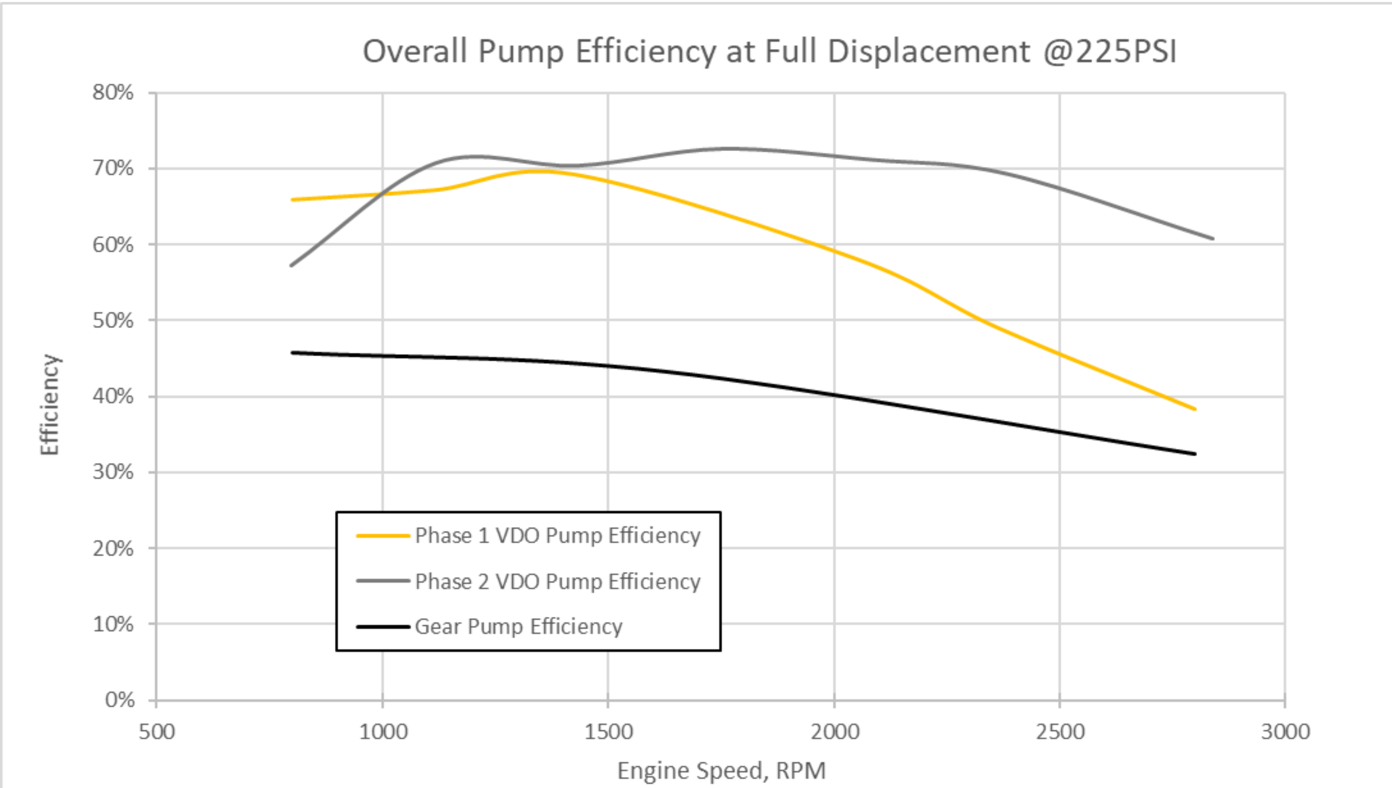

Figure 8: Pump Efficiency Comparison

VDO Pump Testing in the Transmission

The Phase 1 VDO pump performed well when installed in the transmission. The Phase 2 VDO pump was also installed in a transmission with the overall transmission efficiency results shown in Figure 9. The VDO pump clearly improves transmission efficiency in all three ranges. Note: The Figure 9 efficiency data is not from the latest L3T HMPT transmission configuration, due to asset availability at the time of test, therefore the efficiency improvement delta for the VDO pump upgrade is shown, not the overall transmission efficiency.

This power savings gives the customer the flexibility to reduce the size of the vehicle cooling system, and/or increase: vehicle acceleration, top speed, torque output, and fuel economy.

Development of the VDO pump is planned to continue. The next major milestone will be passing the various durability tests including a 440 hour transmission durability test. Success in durability testing will give confidence that the VDO pump can be integrated into the L3T HMPT transmission.

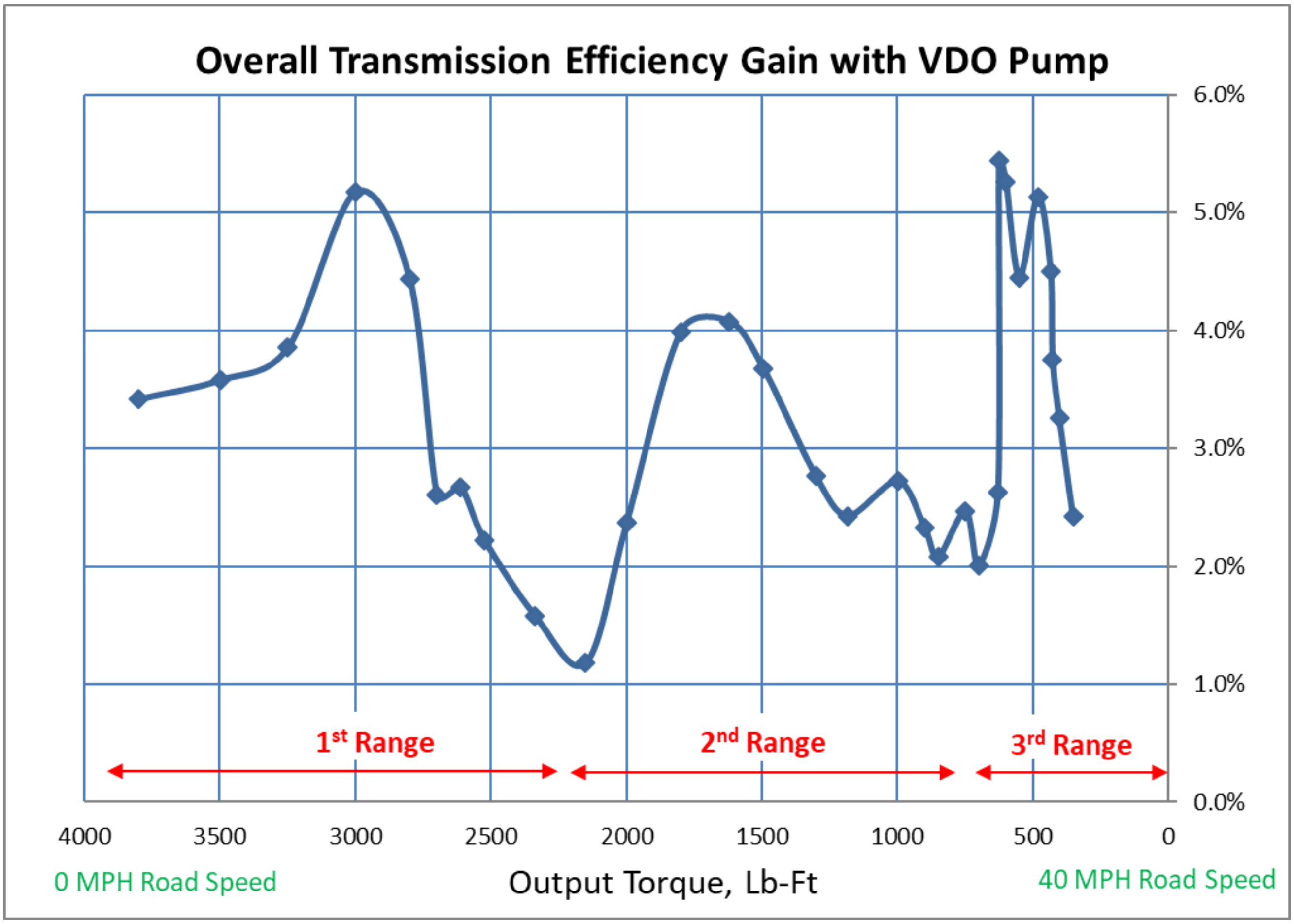

Figure 9: Overall Transmission Efficiency Gain with the VDO pump