Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Reduction of oil pump losses in automatic transmissions

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan vid Linköpings universitet
av

Camilla Larsson

LiTH-ISY-EX--14/4804--SE

Linköping 2014

Linköpings universitet
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Linköping, 5 november 2014

Avdelning, Institution
Division, Department

Division of Vehicle Systems
Department of Electrical Engineering
SE-581 83 Linköping

Datum
Date

2014-11-05

Språk
Language

☐ Svenska/Swedish
☒ Engelska/English
☐ ____________

Rapporttyp
Report category

☐ Licentiatavhandling
☒ Examensarbete
☐ C-uppsats
☐ D-uppsats
☐ Övrig rapport
☐ ____________

ISBN
—

ISRN
LiTH-ISY-EX--14/4804--SE

Serietitel och serienummer
Title of series, numbering

ISSN
—

URL för elektronisk version

http://www.ep.liu.se

Titel
Title

Reducering av oljepumpsförluster i automatiska växellådor
Reduction of oil pump losses in automatic transmissions

Författare
Author

Camilla Larsson

Sammanfattning
Abstract

In the vehicle industry it is of great interest to reduce the emissions and lower the fuel consumption. Up to now a lot of effort has been put into increasing the efficiency of the engine, but it starts to get expensive to keep improving the engine. In this master thesis the transmission and especially the oil supply to the transmission is investigated.

An example of how the requirements of an oil pump can be decided is described. Knowing the requirements different pumps may be adapted to meet the demands. The gear pump used today is compared with a variable displacement pump and an electric pump. The gear pump is not possible to control, but the other two are. A few simple control strategies are introduced. The strategies are implemented and the three pumps are used in the same drive cycle. It is shown that it is possible to reduce the energy that the pump requires if it is replaced by a variable vane pump or an electric pump.

Nyckelord
Keywords

oil pump, vane pump, gear pump, electric pump, variable displacement, automatic transmission, pump, oil, control

Abstract

In the vehicle industry it is of great interest to reduce the emissions and lower the fuel consumption. Up to now a lot of effort has been put into increasing the efficiency of the engine, but it starts to get expensive to keep improving the engine. In this master thesis the transmission and especially the oil supply to the transmission is investigated.

An example of how the requirements of an oil pump can be decided is described. Knowing the requirements different pumps may be adapted to meet the demands. The gear pump used today is compared with a variable displacement pump and an electric pump. The gear pump is not possible to control, but the other two are. A few simple control strategies are introduced. The strategies are implemented and the three pumps are used in the same drive cycle. It is shown that it is possible to reduce the energy that the pump requires if it is replaced by a variable vane pump or an electric pump.

Acknowledgments

I would like to start by thanking AVL for the opportunity to do my master thesis there and the possibility to learn new things. A special thanks to Martin, the other thesis worker at AVL, that was a good listener and made the days a lot more fun. Of course, I would also like to show my appreciation to Lars Eriksson and Andreas Myklebust at Linköping University for being there whenever needed.

My family deserves a great thank as well. They have always been supportive and encouraged me to do what I want. I also want to thank my grandparents for being proud of me.

The greatest thank I would like to send to all my friends that I have come to know during these five years at the University. Without you I would not be here today and finally be able to receive my degree.

Stockholm, August 2014
Camilla Larsson

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Notation

Notation for transmission elements and gears

Notation	Meaning
α	Scaling factor
$\Delta\omega$	Differential speed of two shafts
ω	Angular velocity
A	Area of piston
$B1$	Brake B1
$B2$	Brake B2
$B3$	Brake B3
$B4$	Brake B4
$B5$	Brake B5
F_s	Return spring force
h	Axial clearance between plates
$K1$	Clutch K1
$K2$	Clutch K2
$K3$	Clutch K3
N	Number of friction surfaces
r	Radius of piston
r_1	Inner radius of plate
r_2	Outer radius of plate
$R1$	Reverse gear 1
$R2$	Reverse gear 2
$R3$	Reverse gear 3

Notation for oil pumps

Notation	Meaning
ϵ	Displacement setting
η_{vol}	Volumetric efficiency
μ	Friction coefficient
D_p	Pump displacement
E	Energy
n_p	Pump speed
P	Power
p	Pressure
p_r	Required pressure
q_p	Pump flow
q_r	Required flow
t	Time
T_c	Clutch torque
t_d	Time demand

Notation for energy demand

Notation	Meaning
ΔE_{ho}	Energy during handover phase
$\omega_{c,f}$	Speed after torque handover
$\omega_{c,i}$	Speed in beginning of handover torque
ρ	Oil density
A	Piston area
E_f	Energy during filling phase
$E_{p,r}$	Energy during pressure rise phase
E_d	Energy demand
F_s	Return spring force
h	Clearance between plates
J	Inertia for engine and moment
p_f	Pressure after filling phase
p_{ho}	Pressure after handover phase
p_{max}	Maximum pressure
V	Volume

1 Introduction

1.1 Background

Lowering the fuel consumption from vehicles is one of the main goals in the vehicle industry. To lower the fuel consumption work has to be done to increase the efficiency of all parts in the vehicle.

Up to now a lot of effort has been done to improve the engine efficiency. It would be very expensive to keep improving the engine. Therefore the focus is now moved to the driveline efficiency and especially the transmission. Here hydraulic automatic transmissions (AT) are studied. There are two main losses in an AT; the oil pump and open clutches. The oil pump stands for up to 56 % of the losses in the AT and the open clutches for about 32 % [Martin, 2013].

The torque converter also is a source to losses. By using a lock-up clutch that locks the pump to the turbine of the torque converter when the converter is not needed, the losses are decreased. This report however will not investigate the effect from the torque converter but instead focus on the gear shifting.

1.2 Purpose and goal

The purpose with the thesis work is to provide suggestions on how to improve the efficiency of the automatic transmission in a heavy duty vehicle. This thesis work is directed against the oil pump that provides the transmission with hydraulic pressure.

The goal is to propose a solution that reduce the losses in automatic transmissions coming from the oil pump. This is done by finding criteria for selecting pressure and flow from the oil pump and investigating different oil pumps. Another part is also to suggest strategies to control and operate the pumps.

1.3 Previous work

Investigations concerning the losses in automatic transmissions in heavy duty vehicles is not very common. Some investigations has been done for smaller transmissions. In [Park et al., 1996] an investigation was conducted on a four speed transmission, losses in each part of the transmission was calculated based on mathematical equations. It was found that there is a lot of design variables that affect the losses and by tuning those it is possible to decrease the losses when a new transmission is developed.

It is only recently that the losses in transmissions has been more and more studied. Earlier the focus has been on reducing the losses in the engine but now it has come to a point where it would be too expensive to improve the engine. During improvements of the engine investigations has been conducted on different oil pumps used for lubrication. The common pumps used in engines has been mechanical driven gear pumps, just as in transmissions.

A variable displacement pump is investigated in [Staley et al., 2007] and a validated model is analysed in [Truong et al., 2013]. The focus is on lubrication in engines. Different models of pumps are used in the studies but both models are shown to be fitted to use for lubrication as it is possible to change the displacement of the pumps. Using a variable displacement pump may improve the fuel economy.

Electric oil pumps in heavy duty engines are investigated in [Lasecki and Cousineau, 2003]. In the paper two approaches are studied, a single pump and a dual pump system. Losses may be reduced especially during conditions with high engine speed but it would add extra cost and not have the same safety as a mechanical pump. Electric pumps has also been investigated in [Ribeiro et al., 2005] where it is pointed out that an electric pump only supply the needed amount of fluid to the engine which lower the used power. In the same paper the benefits with an electric pump in hybrid vehicles is mentioned.

In [Neukirchner et al., 2002] an oil pump is developed that is similar to a variable vane pump. Benefits with a controlled pump in passenger car engines are listed as well as a comparison with the common gear pump. The authors have regulated the pump for various operating conditions and came to the conclusion that the fuel consumption is reduced and that the shear engine oil stress is decreased using the developed pump.

As mentioned the automatic transmissions in heavy duty vehicles has not been investigated much, as the focus has been on passenger cars. In this report pumps which are used in bigger transmissions in heavy duty vehicles are analysed. The focus of this report is on the pump used to supply the hydraulic system with oil, especially the part of the system that has the responsibility to shift between gears. When the more common pumps in vehicles are investigated, the focus is usually on the lubrication and not on the oil supply, which affects the shifting quality. Previous advantages and disadvantages with different pumps have been investigated when used for lubrication. Even though the focus in this report is not on lubrication, results and conclusions from previous work have been taken into consideration also in this report.

1.4 Outline

The outline of this thesis is as follows:

- **Chapter 2** introduces different parts of an automatic transmission as well as the different stages of a gear shift. This is a good chapter to read in order to understand all the technical terms and references in the rest of the report.
- **Chapter 3** describes how requirements for a pump can be decided. Examples of flow demand and pressure demand are showed. Other possible requirements of pumps are also discussed.
- In **Chapter 4** three different pumps and a combination of pumps are introduced and the requirements of the pumps to make the flow demands are investigated.
- **Chapter 5** presents a few simple control strategies for the controllable pumps as well as some development of the strategies.
- In **Chapter 6** the different pumps are compared during the same drive cycle.
- **Chapter 7** contains the conclusions, reflections and future work.

2

Background

Automotive vehicles have a transmission that transfer the power from the engine to the wheels. The transmission is necessary for the vehicle, without a transmission the vehicle would move synchronously with the engine speed all the time. It would not be possible to reverse the vehicle or stop it without stopping the engine.

Transmissions can be divided into two groups: manual and automatic. There are plenty of different types of manual and automatic transmissions, the one considered in this work is a stepped automatic transmission with planetary gear sets.

2.1 Automatic transmission

The automatic transmissions consists of the following main parts listed below. The main parts that will be discussed in this section are:

- Torque converter
- Planetary gear set
- Clutches and brakes
- Oil pump
- Hydraulic system

2.1.1 Torque converter

The torque converter makes it possible for the engine to run even when the wheels and gears do not move. It is located between the engine and the transmission. The pump of the converter turns at the same speed as the engine since the housing of the torque converter is bolted to the flywheel of the engine.

2.1.2 Planetary gear set

A planetary gear set consists of three main parts: an outer ring gear, three or more planet gears and a sun gear, see Figure 2.1 [Rosander, 2013]. The planet carrier holds the parts together.

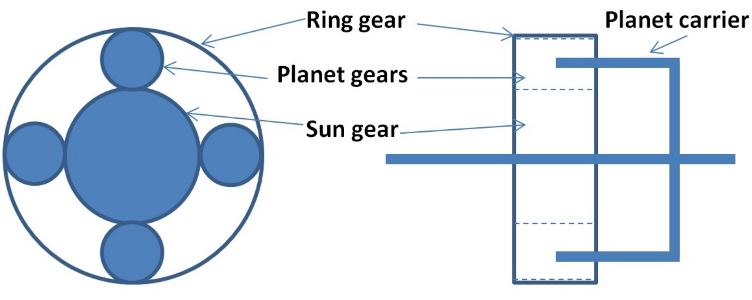

Figure 2.1: *Planetary gear set*

Each of the three parts can be output, input or held stationary. By holding and driving different parts the power from the engine is transferred to the wheels. Different gear ratios are achieved depending on which part that is given which configuration. In transmissions several gear sets are connected to each other to give various gear ratios.

In the transmission under consideration five gear sets are connected to each other. The powerflow for the transmission can be seen in Figure 2.2 [Volvo, 2013b]. The figure also show which parts of each gear set that can be held stationary, as well as which parts that are input and output on each gear set. The red block is the sun gear, the green is the planet carrier and the brown the ring gear.

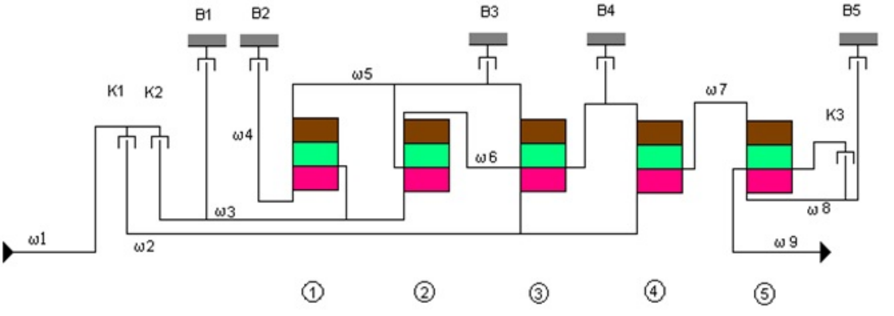

Figure 2.2: *Powerflow for the transmission. Show which parts of each gear set that can be held stationary as well as which are input and output of the sun gear (red), the planet carrier (green) and the ring gear (brown). The brakes, B, clutches, K, and the speed, ω, between the gear sets are shown.*

2.1.3 Clutches and brakes

Clutches and brakes are used to rotate respectively lock the different parts of the planetary gear sets. As seen in Figure 2.2 this transmission has three clutches, K1-K3, and five brakes, B1-B5. The clutches and brakes are soaked in oil to decrease the friction when the clutches and brakes are released. The oil also contributes to lower the temperature in the transmission.

Each element, clutch or brake, consists of packages of plates. Every second plate in the package are called separate plate and are made of steel. The others are called friction plates and are covered with friction material. Figure 2.3 [Kumar Kodaganti Venu, 2013] shows a disengaged clutch with the axial clearnace, h, the difference in angular velocity, ω, and the inner and outer radius of the plates, r_1 and r_2.

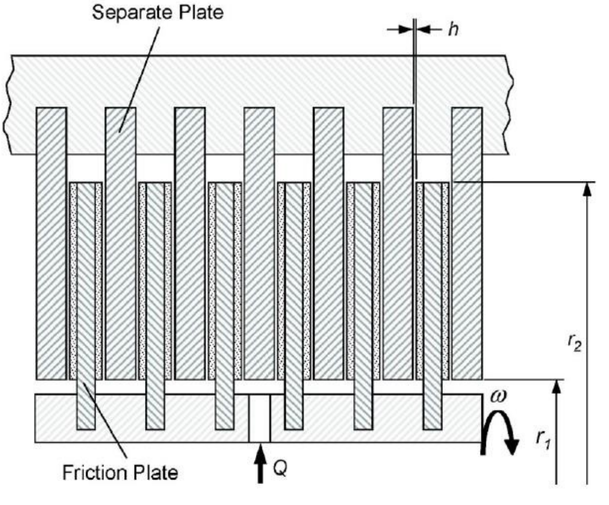

Figure 2.3: *Schematic of a disengaged clutch*

A hydraulic piston compresses the plate package and the two shafts of the clutch gets coupled through friction. The brakes are activated in the same way but instead of connecting to a shaft the brakes connect to the housing of the gearbox which makes the sun gear, planet carrier or ring gear stop rotating.

For each gear three elements are activated to give various gear ratios and transfer the power from the engine to the wheels. At least one of the elements is a clutch in every gear and the rest of the elements are brakes. Table 2.1 [Volvo, 2013b] shows the combination of elements for each gear.

Gear	Clutch			Brake				
	K1	K2	K3	B1	B2	B3	B4	B5
Reverse 3		X				X		X
2		X	X				X	
1		X					X	X
Forward 1	X						X	X
2	X		X				X	
3	X					X		X
4	X		X			X		
5	X		X	X				
6	X		X		X			
7	X	X	X					
8		X			X			X
9		X	X		X			

Table 2.1: *Activated elements for each gear*

2.1.4 Oil pump

The oil pump provides transmission fluid, oil, to the torque converter and the hydraulic system. The oil from the pump also is used for lubrication of all parts in the transmission as well as lowering the temperature.

2.1.5 Hydraulic system

The hydraulic system in the transmission under consideration consists of two circuits called main circuit and torque converter circuit. The main circuit controls gear shifting and the torque converter circuit supplies the torque converter with oil and is responsible for the lubrication of the transmission. Figure 2.4 [Volvo, 2013a] shows the hydraulic circuit in the considered transmission, the upper part of the circuit is the main circuit and the lower is the torque converter circuit. Each part has an oil pump that supplies the circuit with flow and pressure. The oil used in the hydraulic system is taken from an oil sump underneath the transmission.

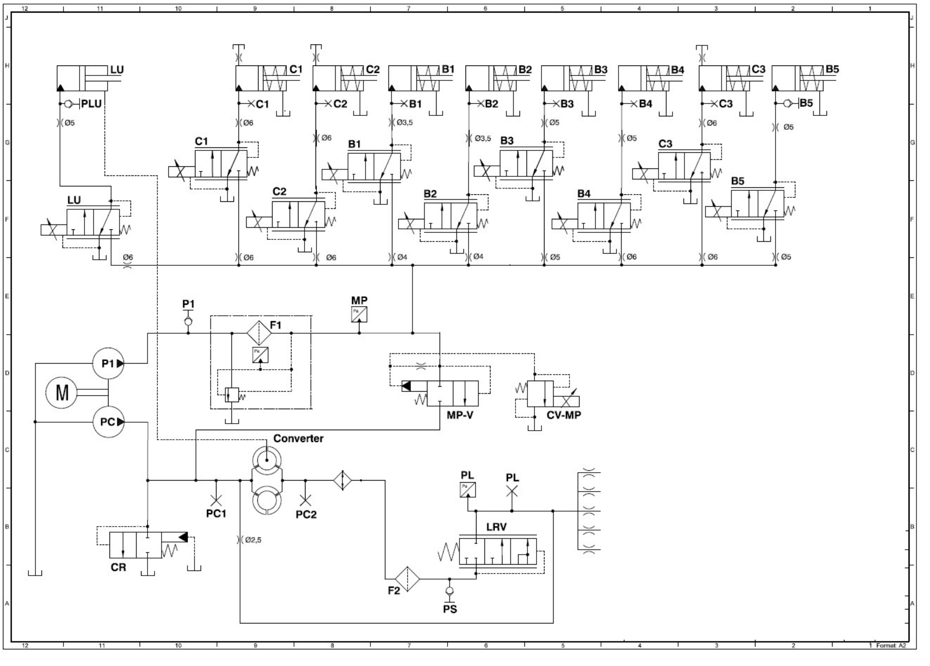

Figure 2.4: Hydraulic circuit of the transmission. In the upper part the pistons and valves connected to the gear sets are shown. In the lower part is the converter and the valves used for lubrication of the transmission.

Clutches and brakes are activated with a pressure on the piston. As mentioned three clutches and/or brakes are applied for each gear. Which clutches and brakes that should be activated are controlled with the PWM valves in connection with every element. The return of the piston occurs through spring force and hence the clutch or brake will be deactivated. Before and after each PWM valve are defined orifices. The orifice before the valve prevents the main pressure to drop too fast during the filling of an oncoming element. If the main pressure drops to fast the offgoing element may start slipping too early. The orifice after the valve helps making smoother transitions from the filling phase to the control phase of the element.

2.2 Gear shift

A gear shift consists of four phases:

1. Filling phase
2. Torque handover phase
3. Inertia phase
4. Safety phase

Figure 2.5 [Karlsson, 2013] shows the theoretical shift concerning pressure between two elements.

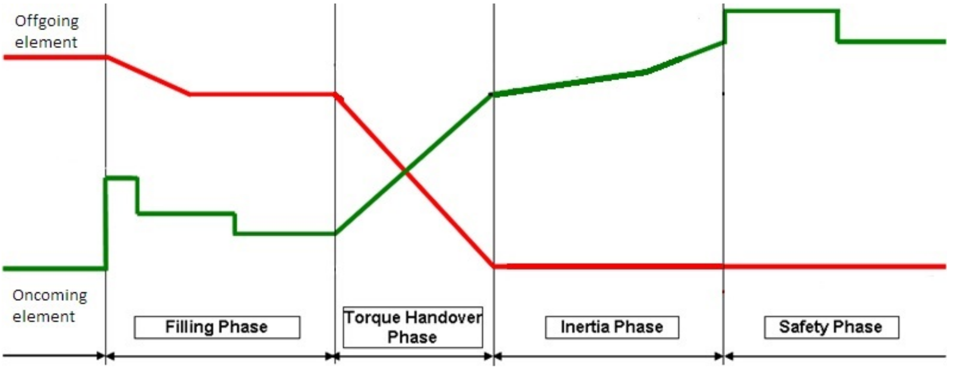

Figure 2.5: *Theoretical element shift that shows pressure for oncoming and offgoing element*

2.2.1 Filling phase

During the first phase the oncoming element is filled with oil and level at landing pressure while the offgoing element ramps down to the pressure where the element starts to slip. The pressure in the oncoming element must overcome the spring force that return the piston and the volume behind the piston must be filled with oil. When the pressure in the offgoing element is decreased the oil volume is also decreased and the oil returns to the oil sump.

2.2.2 Torque handover phase

The second phase is where the torque is handed over from the offgoing elemenet to the oncoming. In this phase both elements transmit torque. Though the offgoing element has begun to slip and the oncoming element slips as well.

2.2.3 Inertia phase

In the inertia phase, the offgoing element does not transfer any torque and the pressure increases in the oncoming element. The pressure is increased to ensure the speed change into the new gear and the torque transfer of the oncoming element.

2.2.4 Safety phase

In the last phase the pressure is further increased to ensure that the clutch or brake does not slip. It is only in the first phase that significant movement of the piston occur. In phase 2-4 it is mostly increase in pressure that occur and the movement of the piston can be neglected.

2.3 Problem definition

Since the oil pump is the greatest contributor to the losses in the transmission it is of great interest to find other solutions than the one that exist today. Since pressure and flow is what defines a pump the pressure and flow requirements have to be decided before the choice of pump is made. Different pumps need to be investigated to learn their respective characteristics and behaviours. Also, control strategies for lowering the pumps energy needs to be suggested.

3

Requirements for pump

The oil pump must supply enough flow and pressure to the hydraulic system during all driving conditions in order to be able to drive the vehicle. The pump supplies flow and when the flow travels through channels pressure is created. A high rise in pressure does not require a great change in flow.

The hydraulic system has losses of leakage and friction. This means that even when there is no shift between gears the pump has to supply flow to maintain the pressure at the elements.

The driving experience is of great interest. Gear shifting is supposed to occur fast, the driver does not want to wait during an up or down shift. To have a good driving experience it is necessary to have high flow and pressure to activate or change gears.

3.1 Method

Looking back at the gear shifting in Section 2.2, a gear shift has four different phases. In the first filling phase, the flow demand is very important. In the following three phases the pressure rise is the most important.

The flow requirements are decided during the filling phase. To achieve the shift quality that is wanted the required flow, q_r needs to be decided. The required flow depends on the time demand, t_d, which is a demand from the developer. Simulations of a transmission, including the hydraulic system, can be done to see how large the displacement volume has to be in order to meet the demands of time, t_d. The model used for simulation should contain all elements and losses that may occur. In this report no model is available, only a few examples of the required pressure and flow demand.

By simulating the transmission and especially gear shifts at different engine speeds the flow demand for different engine speeds is achieved. Simulations may be done with different constant flow pumps. When the requested time is reached the flow demanded is decided. The flow is measured in m^3/min or l/min. When a pump is driven by the engine crank shaft it is possible to get the displacement when the flow demand is decided.

In all gear shift phases except the first it is mostly pressure rise that affects the shift. The pressure depends on the layout of the hydraulic system. One way to increase the pressure is to increase the flow. Since the system is not an open system but a closed system the pressure will not decrease when the flow increases. Although different losses must be taken into consideration, for example leakage losses.

The required pressure, p_r, for an existing hydraulic system can be calculated using (3.1) [Bai et al., 2013]. Rearranging (3.1) and using (3.2) for each clutch and brake at different gears gives the pressure, p_r, that is required.

$$T_c = \mu \cdot N \cdot r\,(A \cdot p_r - F_s)\tanh\left(\Delta\omega/\alpha\right) \tag{3.1}$$

Which gives:

$$p_r = \frac{1}{A}\left(\frac{T_c}{\mu \cdot N \cdot r \cdot \tanh\left(\Delta\omega/\alpha\right)} + F_s\right) \tag{3.2}$$

With an existing transmission the clutch torque,T_c, friction coefficient, μ, number of friction surfaces, N, area, A, and radius, r, of the clutch piston, scaling factor, α, differential speed of two shafts, $\Delta\omega$ and clutch return spring force, F_s, are known for different gears.

The most important thing is to ensure that the clutch or brake does not start to slip, which may cause great damage to the transmission. To prevent this the ability to transfer torque, torque capacity, needs to be kept over 1 during all shifts which is achieved by applying a pressure. In Figure 3.1 there is an example of required pressure to maintain the torque capacity over 1 plotted against engine speed. The slope in the middle of the figure comes from limitations of elements in the transmission. If the pressure is too high the elements may break and the transmission will not work.

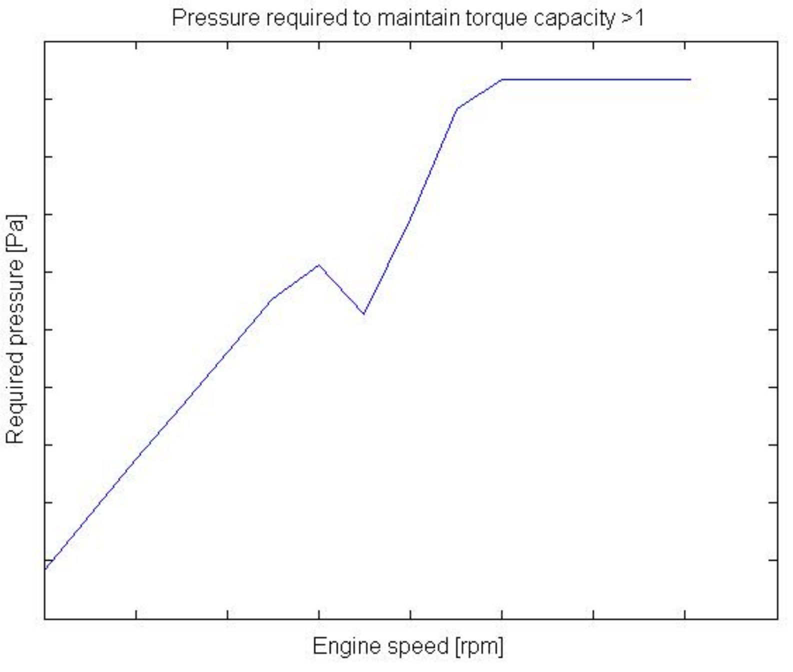

Figure 3.1: *Example of required pressure against engine speed to maintain torque capacity > 1*

3.2 Flow demands

This section is based on examples of three different shifts. One of the shifts is called double shift, since it has two oncoming elements. The other two are called single shifts, they only have one oncoming element. The double shift needs more flow since two elements needs to be filled with oil and require pressure, not only one as in the single shift. All shifts are forward shifts investigated during different engine speeds in order to see the demand for different shifts during different conditions.

In Figure 3.2 an example of the flow demand against engine speed for the three shifts are plotted.

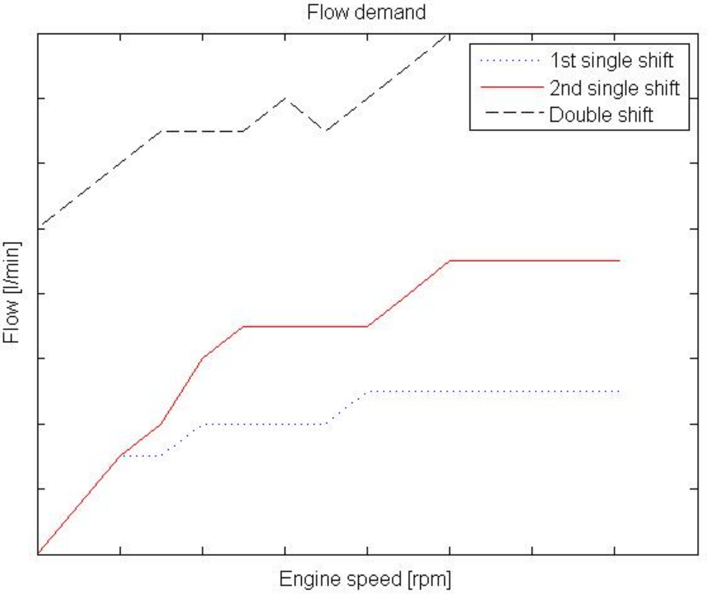

Figure 3.2: *Example of flow demand for three different shifts against engine speed*

The dimension of the pump is mostly decided by the displacement. Since the pump efficiencies varies non-linearly with the engine speed the volumetric efficiency and the displacement are seen as one value in this report. One alternative way to see it is that the volumetric efficiency always is 100 %. The product of the displacement and the volumetric efficiency, $D_p \cdot \eta_{vol}$, is calculated in 3.3 using the flow demand, q_r, during the shifts and the speed, n_p. The maximum and minimum values are shown in Table 3.1. Figure 3.3 shows all values against the engine speed. The products are calculated by dividing the flow demand with the engine speed.

$$D_p \cdot \eta_{vol} = \frac{q_r}{n_p \cdot \epsilon} \tag{3.3}$$

Displacement · pump efficiency [l/rev]					
1st single shift		2nd single shift		Double shift	
max	min	max	min	max	min
0.0433	0.0154	0.0433	0.0174	0.0600	0.0209

Table 3.1: *Estimated flow demand for the evaluated shifts*

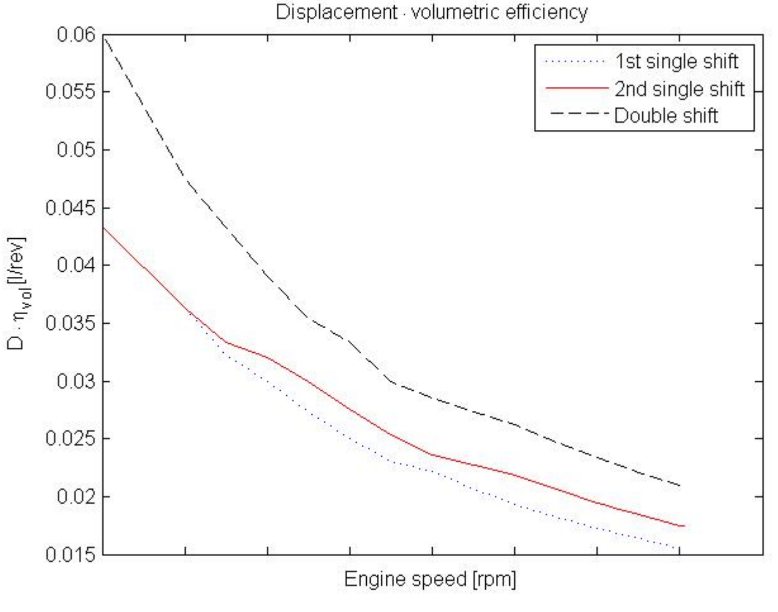

Figure 3.3: *Displacement · volumetric efficiency*

As seen in Table 3.1 and in Figure 3.3 the double shift demands the greatest displacement volume of 0.0600 l/rev and the first single shift demands the smallest of 0.0154 l/rev. Conclusions to draw from this is that the pump at least has to provide the hydraulic system with 0.06 l/rev in order to have a good shifting quality. Since there is a significant difference between the maximum and minimum volume it would be beneficial to be able to lower the displacement volume at high speeds to decrease the losses. Using the same displacement for all pump speeds means that oil is supplied but not used or needed by the system.

3.3 Other possible requirements

The flow and pressure have been the main reasons so far to determine the requirements of an oil pump in an automatic transmission. But there is also other requirements that can be important in the decision of pump.

In the vehicle industry cost is an important factor. Many components often increase the cost. But if the increased cost from components decrease other costs, for example fuel cost, then it may be a good alternative to increase the number of components. Another thing to consider, when it comes to components, is that they should be easy to integrate in the transmission. It is preferable to reuse components that already exist in the transmission and driveline instead of adding new components.

Another possible requirement is to be able to use the transmission even though the engine is not running. Hybrid vehicles are an alternative to reduce emissions from vehicles. Using batteries instead of an engine during some driving conditions then demand that the transmission is in use even though the engine is not running.

4

Oil pumps

The transmission needs components that supply the hydraulic system with oil. The oil creates pressure in the system that helps during gear shifting as well as helps with lubrication of all parts in the transmission. Oil pumps are the most common way of supplying oil to a system. Pumps can either have fixed or variable displacement. The engine crank shaft is often used to drive the pump but there is also other ways to drive it, one example is to use an electric pump.

4.1 Fixed displacement

Gear pumps and gerotor pumps, also called internal gear pumps, are commonly used pumps with fixed displacement. Both gear and gerotor pumps are driven by the crank shaft and hence has the same speed as the engine. The pumps takes oil from one side with low pressure fluid, uses the meshing of gears to increase the pressure and move the oil to the other side and out to the system. Since the pump has to handle high flow and pressure even during low speeds a fixed displacement pump often is over dimensioned for high speeds. The fixed displacement in combination with increased speed gives increased flow and power.

4.1.1 Currently used pump

The pump used today to supply the main hydraulic circuit with flow and pressure is a gear pump with fixed displacement. This pump is driven by the input shaft and has the same speed as the engine. The data sheet from the manufacturer gives flow and power from the pump at four speeds, see Table 4.1. The points are also plotted in Figure 4.1.

n [rpm]	Power [W]	Delivery [l/min]
600	485	29.12
1100	1721	51.63
600	492	29.53
1650	2737	82.10

Table 4.1: *Parts of data sheet from manufacturer*

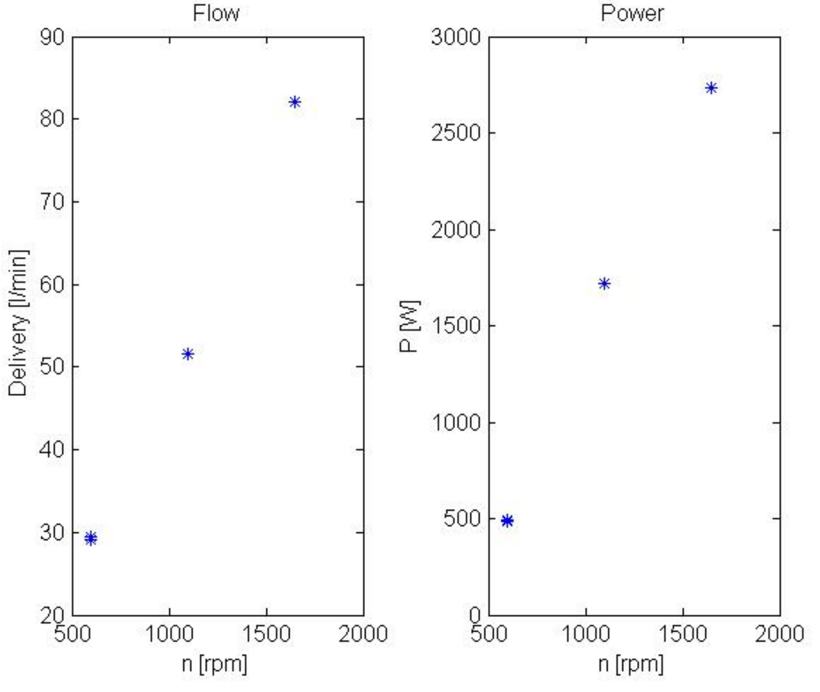

Figure 4.1: *Data from manufacturer*

As seen in Figure 4.1 both the flow and power is almost linearly increasing with pump speed, n_p. Using MATLAB and the tool linear in Basic fitting gives the linear equations (4.1) and (4.2) for flow, q_p, and power, P.

$$q_p = 0.05 \cdot n_p - 1.1 \tag{4.1}$$

$$P = 2.2 \cdot n_p - 780 \tag{4.2}$$

In Figure 4.2 the linearised flow and power from the existing oil pump are plotted with the demands that was decided in Section 3.2. The figure shows that the pump used today does not stand up to the demands for the double shift during low speeds. For the other two single shifts the pump supplies the system with more flow than necessary for all speeds. During high speeds the pump is over dimensioned for all gear shifts.

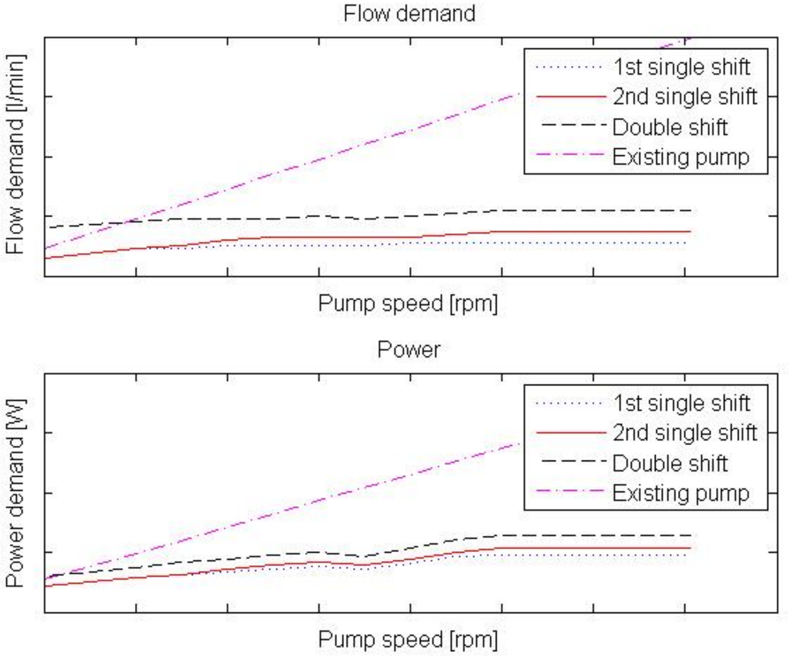

Figure 4.2: *Demands of flow and power compared with existing pump*

To get the displacement, D_p, for the pump (4.1) is used together with the common way to calculate flow using the pump speed, see (4.3). This gives a displacement of approximately 0.049 l/rev. Figure 4.3 shows that using the calculated displacement gives a flow that is similar to the flow calculated with the linearisation.

$$0.05 \cdot n_p - 1.1 = D_p \cdot n_p \cdot \eta_{vol} \Rightarrow D_p \cdot \eta_{vol} = 0.05 - \frac{1.1}{n_p} \approx 0.049 \qquad (4.3)$$

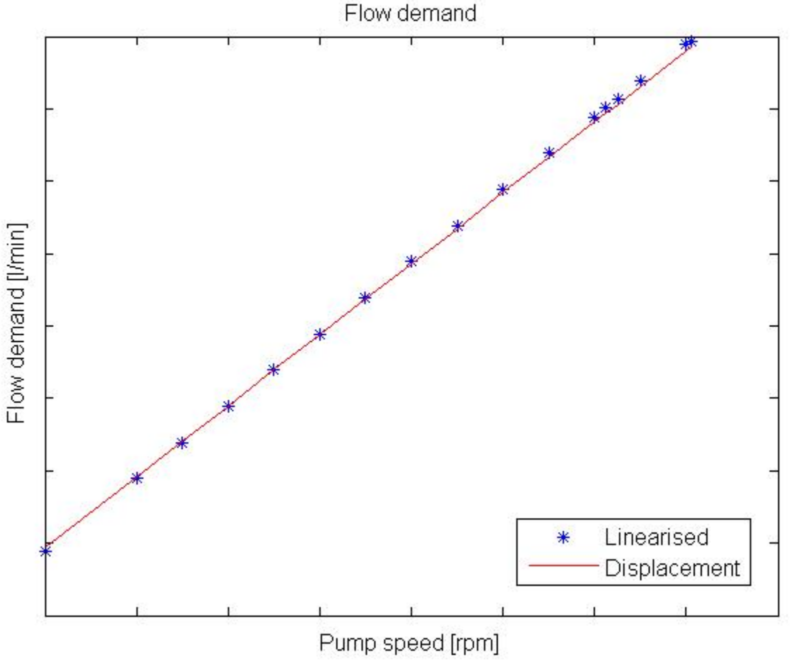

Figure 4.3: *Demand of flow calculated either with linearisation or with displacement*

4.1.2 Gear pump

The current pump does not meet the flow demands for low speeds and another pump is required. In order to meet the requirements with a fixed displacement gear pump the displacement and volumetric efficiency, $D_p \cdot \eta_{vol}$, has to be 0.06 l/rev, see Section 3.2. The flow, q_p, is calculated with (4.4) that comes from (3.3) where the displacement, D_p, is fixed and the pump speed, n_p, is the same as the engine speed.

$$q_p = D_p \cdot n_p \cdot \eta_{vol} \qquad (4.4)$$

Figure 4.4 shows the flow from the pump against increasing speed as well as the flow demand for three different shifts. It is seen that the pump meets the flow demands during all shifts for all speeds.

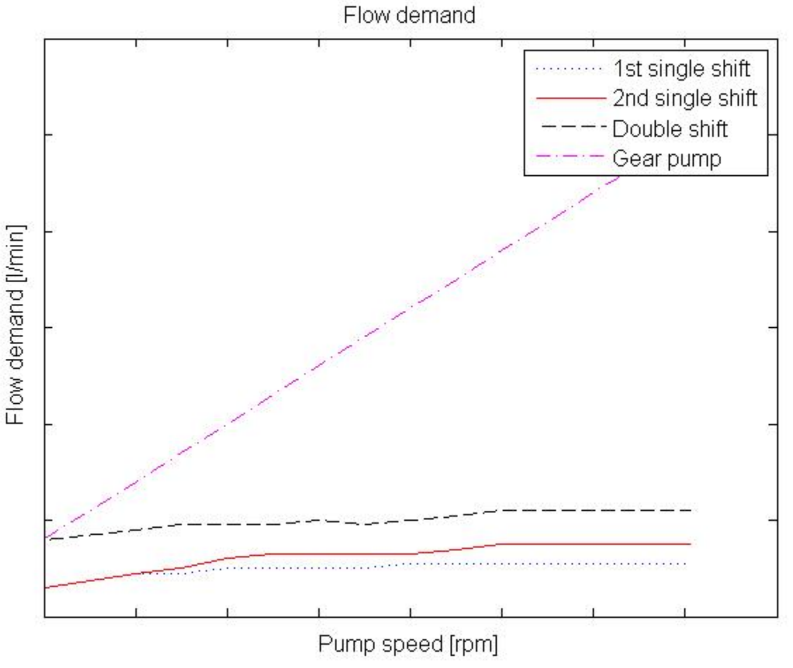

Figure 4.4: *Demands of flow compared and flow from a gear pump with fixed displacement 0.06 l/rev*

4.2 Variable displacement

Using a variable displacement pump that is driven by the crank shaft makes it possible to decrease the flow during high speeds, which decreases the losses. Variable displacement pumps exist in many different models. Most common are piston pumps and vane pumps. Piston pumps take more space than vane pumps and hence will not be discussed here as the transmission should be as small as possible.

4.2.1 Vane pump

The variable displacement pump is driven by the crank shaft. It has vanes that move back and forth in slots from the crank shaft when the rotor turns. The outer edge of each vane slide along the surface of the housing. The displacement is changed with the position of the cam ring. The cam ring can be controlled either with an adjustment screw or with a spring and hydraulic pressure. There are different structures of the pump depending on manufacturer. In this report will the case with a spring and hydraulic pressure be taken into consideration and the spring is located as in Figure 4.5 [Andriychuk et al., 2011].

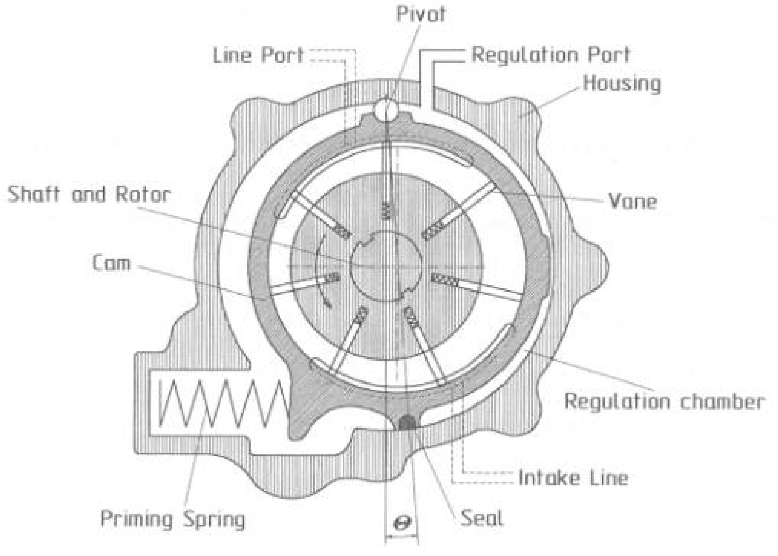

Figure 4.5: *Example of variable displacement vane pump [Andriychuk et al., 2011]*

When the spring is not under pressure the displacement is at its maximum. Applying oil and pressure in the regulation chamber that overcome the spring force moves the cam ring and the displacement decreases. When the crank shaft is centred in the cam ring the pump will not provide any flow or pressure to the hydraulic system.

A PWM valve of the same kind as used in the rest of the transmission can be used to control the regulation chamber and to compress the spring in order to change the displacement of the pump.

From Section 3.2 it was decided that the maximum demand on displacement and volumetric efficiency, $D_p \cdot \eta_{vol}$, is 0.06 l/rev. By using equation (4.5) [LiU, 2008], for effective flow from the pump, the displacement setting, ϵ, can be decided to match the demand of flow, q_d, for shifts. The displacement setting indicates how much of the maximum displacement that is required to match the flow demand.

$$q_d = \epsilon \cdot D_p \cdot \eta_{vol} \cdot n_p \Rightarrow \epsilon = \frac{q_d}{D_p \cdot \eta_{vol} \cdot n_p} \tag{4.5}$$

In Figure 4.6 the displacement setting is plotted against pump speed to satisfy the flow demands of one double shift and two single shifts. The displacement setting varies from 100 % when when double shift occur during low speeds to approximately 26 % when the second single shift occur during high speeds.

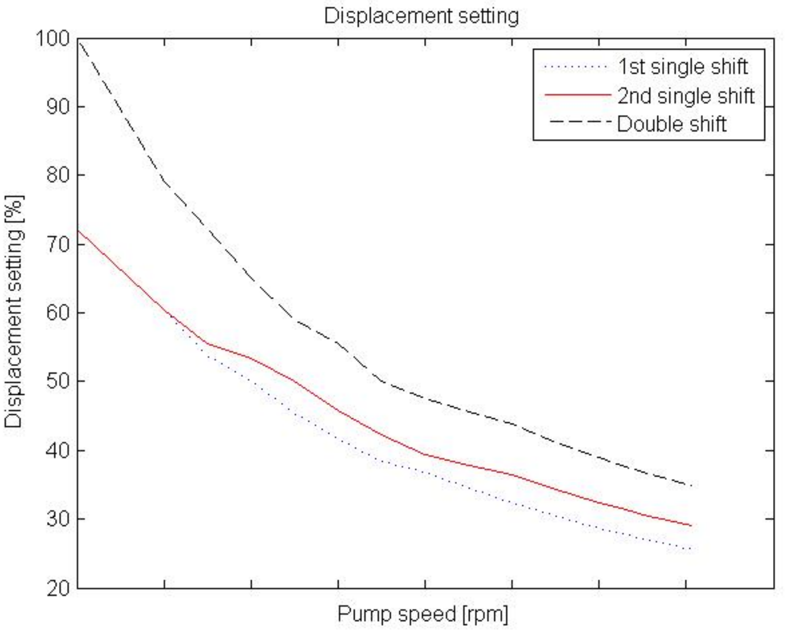

Figure 4.6: *Displacement settings for variable displacement pump*

The variable vane pump has greater displacement than a gear pump with the same size, which means that the vane pump takes less place [Neukirchner et al., 2002]. On the other hand a valve is needed to control the pump. To use a valve the hydraulic circuit needs to be redone and the valve also need current to open and close. Losses may occur when the valve is closed, just as in the case with the valves to the shift elements. Other losses is to fill up the regulation chamber with oil. The overall efficiency of a vane is approximately 85 % instead of 90 % for an internal gear pump [Casey]. Some further disadvantages with the vane pump compared with a gear pump is that it has more parts and the oil has higher demands of being clean than in a gear pump.

4.3 Electric pump

An electric oil pump is driven by an electric motor connected to a battery. With an electric pump it is possible to supply oil to the hydraulic system even when the engine is not running. It is possible to make the rotor vary in speed depending on the need of flow and pressure. Looking at the flow demand from Section

3.2 and assuming that the pump is of the type fixed displacement the speed, n_p, may be calculated as in (4.6). In this equation, the product of displacement and volumetric efficiency is, $D_p \cdot \eta_{vol} = 0.06$ l/rev and the demanded flows, q_d, are the same as in Section 3.2.

$$n_p = \frac{q_d}{D_p \cdot \eta_{vol}} \tag{4.6}$$

In Figure 4.7 the demanded speeds are for a fixed displacement pump plotted against flow for three different shifts. As seen only a speed of 700 rpm is needed to meet the flow demands for the double shift. It is possible to change the displacement and hence the demanded pump speed but this does not affect the energy consumed by the pump. Reasons to change displacement and speed have to do with the pressure from the pump. It is not desirable to have a pump with high displacement and low pump speed as the pressure will be quite low.

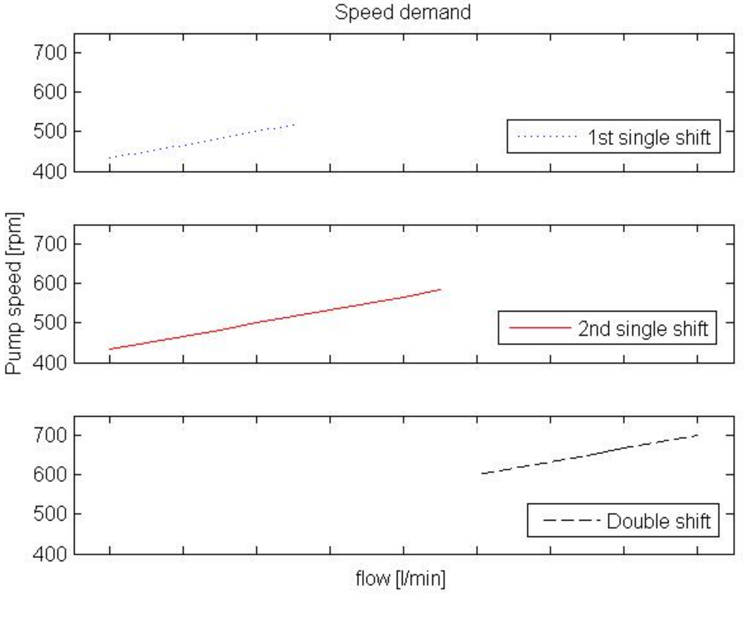

Figure 4.7: *Speed demand for fixed displacement pump during shift*

To use an electric pump a battery is needed to drive the pump. To charge a battery a generator is needed that converts the mechanical energy from the engine to electrical energy. Depending on what type of battery that is used it has different efficiency, about 90 % [HowStuffWorks, 2014]. Then of course the conversion between mechanical and electrical energy has some losses. Also the losses that occur when the pump converts electric energy to mechanical needs to be taken into account. Those losses needs to be taken into account as they affect the overall efficiency of the transmission. A generator commonly has an efficiency of 80-95 % and an electric motor 80-95 % [Hulscher].

4.4 Gear pump & electric pump

Instead of only use one pump it is possible to use two pumps, one ordinary gear pump driven by the crank shaft in combination with an electric pump. The gear pump should be of a smaller size and never supply the system with more oil than required during shift in high speeds. As the gear pump never supplies more than needed it will be under dimensioned for low speeds. If the gear pump is not too small the system pressure will be held and the electric pump is used when extra flow is required as for gear shift. When the electric pump is not required it can be shut of completely.

The double shift requires the greatest flow demands during shift. In Figure 4.8 the flow from three pumps with displacement 0.02 l/rev, 0.015 l/rev and 0.01 l/rev are displayed together with the flow demand for the double shift. The flow is calculated using (4.4). It is seen that the flow is not enough to supply the system with the demanded flow.

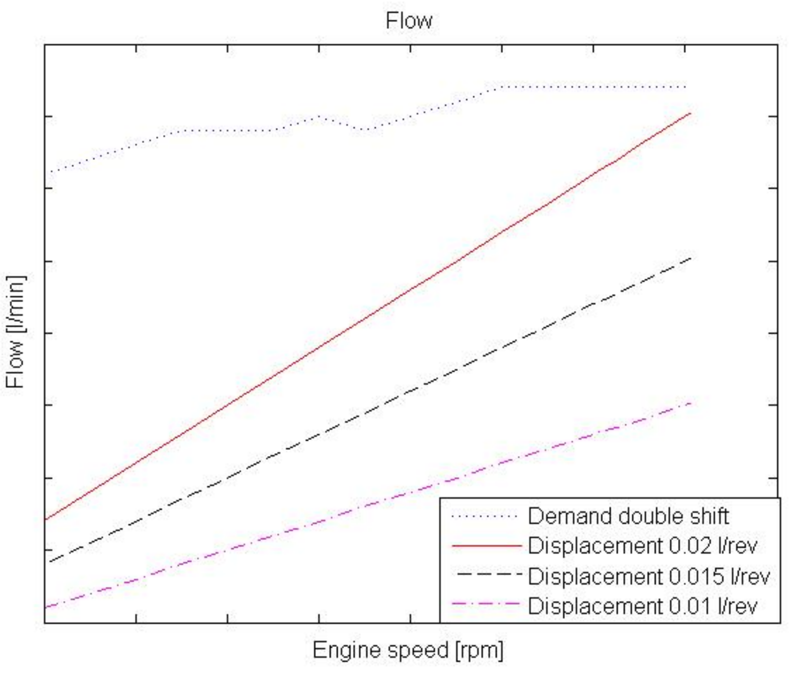

Figure 4.8: *Flow from gear pumps with displacement 0.02, 0.015 and 0.01 l/rev and the double shifts flow demand*

As the gear pumps do not supply enough flow to meet the demands an electric pump can be used. As the flow from the gear pumps are increasing with increased engine speed, the electric pump has decreased demands on flow with increased engine speed, see Figure 4.9.

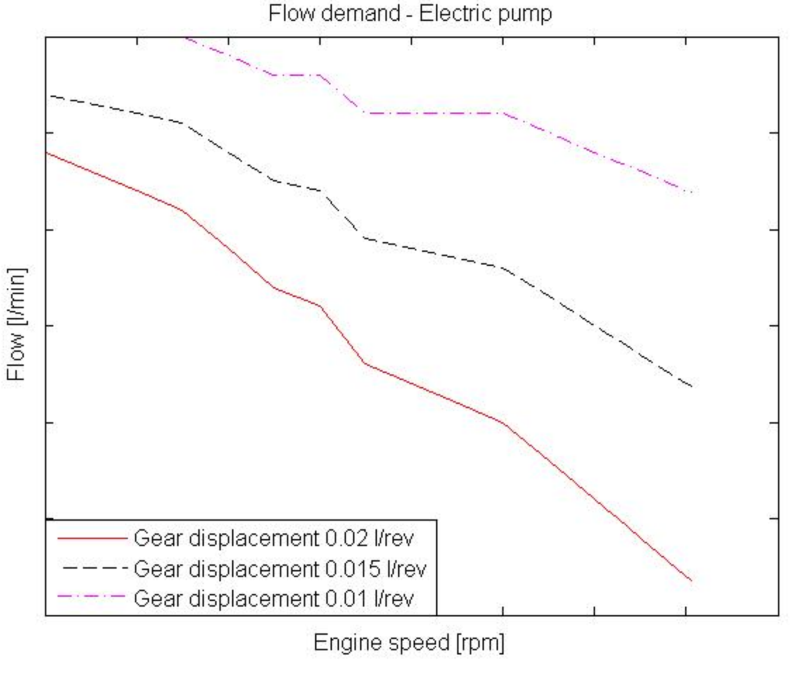

Figure 4.9: *Flow demands on electric pump when the gear pumps have displacement of 0.02, 0.015 and 0.01 l/rev*

Using (4.6) the speed demand of an electric pump with displacement 0.04 l/rev can be decided. A displacement of 0.04 l/rev is smaller than in Section 4.3, but not too small which would have required higher pump speeds. The flow demand used is the difference between the flow demand for the double shift and the supplied flow from the gear pumps in Figure 4.8. Figure 4.10 show the speed demands on the electric pump in order to meet the flow demand for the double shift.

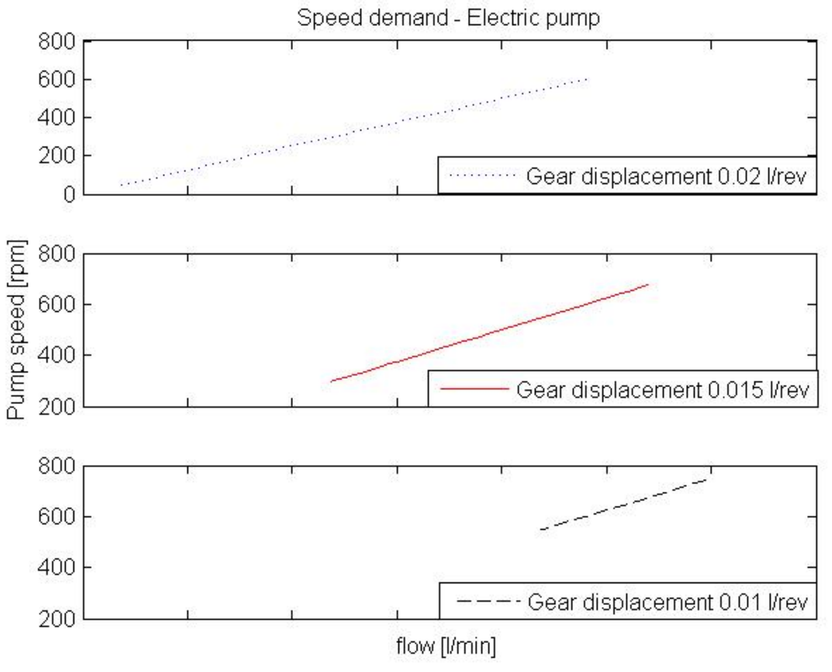

Figure 4.10: *Speed demands on electric pump when the gear pumps have displacement of 0.02, 0.015 and 0.01 l/rev. The electric pump has a displacement of 0.04 l/rev*

Using a gear pump driven by the engine crank shaft will also ensure that the transmission still work even if the electric pump breaks. It would not work as usual as the filling time increases and the pressure would take longer time to build up, but it would be possible to drive to a garage and get help instead of calling a tow truck.

5 Control strategies

The gear pump used today is connected directly to the engine crank shaft, which means that it always has the same speed as the engine. Since it is directly connected to the crank shaft and has a fixed displacement it is not possible to control it. But it is possible to control a variable displacement pump or an electric pump.

The control strategies are assumed to be used when the system pressure in the hydraulic system is already achieved and the engine is warm. When the vehicle is just started another strategy is needed to fill up the hydraulic system with oil and reach the system pressure. This is not taken into consideration in the strategies below. However, one possible strategy for start is to let the displacement setting be 100 % (or the electric pump speed be max) until the system pressure is achieved and then use the strategies below.

5.1 Variable displacement pump

A variable displacement pump is, as a gear pump, directly connected to the engine crank shaft. But it is possible to control it since the displacement may be changed by varying the displacement setting. By using a valve the displacement setting can be controlled, the more the valve is open the smaller the displacement gets. With a closed valve the displacement reaches its maximum.

The valve considered in this report is of the same kind as the ones used to apply different elements during gear shift and may also be controlled by the same software. The valve is applied with current in order to open and close.

To know the relationship between the applied current and the displacement setting an investigation needs to be conducted. Something that needs to be remembered is that the pump also demands oil in order to change the displacement setting and one way to come around this is to increase the displacement, in other words increase the applied current to the valve.

5.1.1 Engine speed

The easiest way to control an oil pump is to use the engine speed. Looking back at Figure 3.3 it is seen that the demand on displacement decreases with increased engine speed. Hence a very simple control strategy is to control the displacement by looking at the engine speed.

To ensure the flow demand for all shifts the shift with the highest demands will be used as a basis for the control strategy. A look up table can be used that takes engine speed and delivers the current that should be applied to the valve which in turn affect the displacement setting.

Figure 5.1 shows an example of how the displacement setting can be changed according to engine speed.

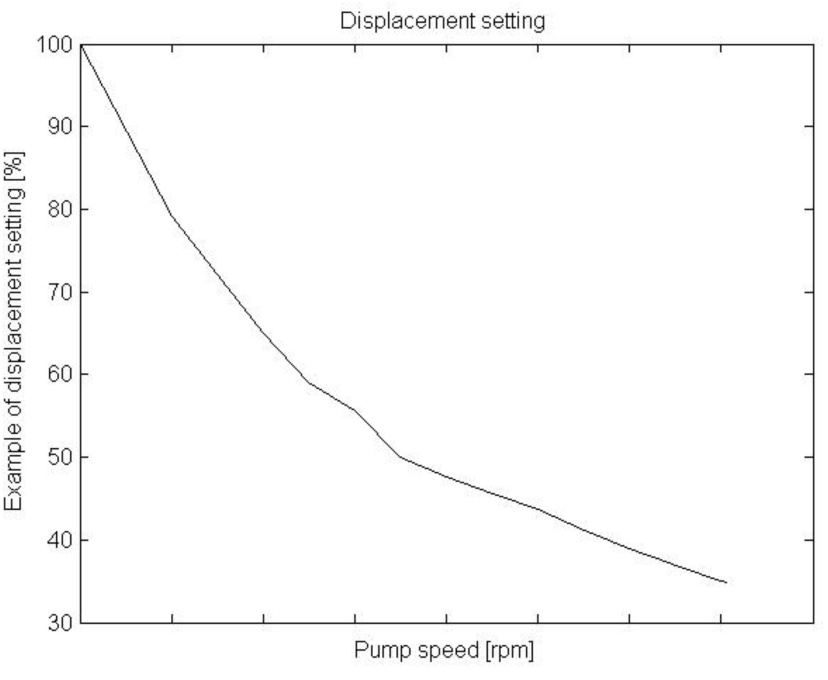

Figure 5.1: *Example of displacement setting for a variable displacement vane pump*

5.1.2 Engine speed and shift

Another way to control the variable displacement pump is by using the shift strategy and the engine speed. From the shift strategy it is possible to know if it is a double or single shift. A double shift demands greater flow than a single shift and hence needs more flow and greater displacement. As the flow also depends on the engine speed the displacement may be reduced for high speeds.

Figure 5.2 shows a control strategy that depends on engine speed and the type of shift.

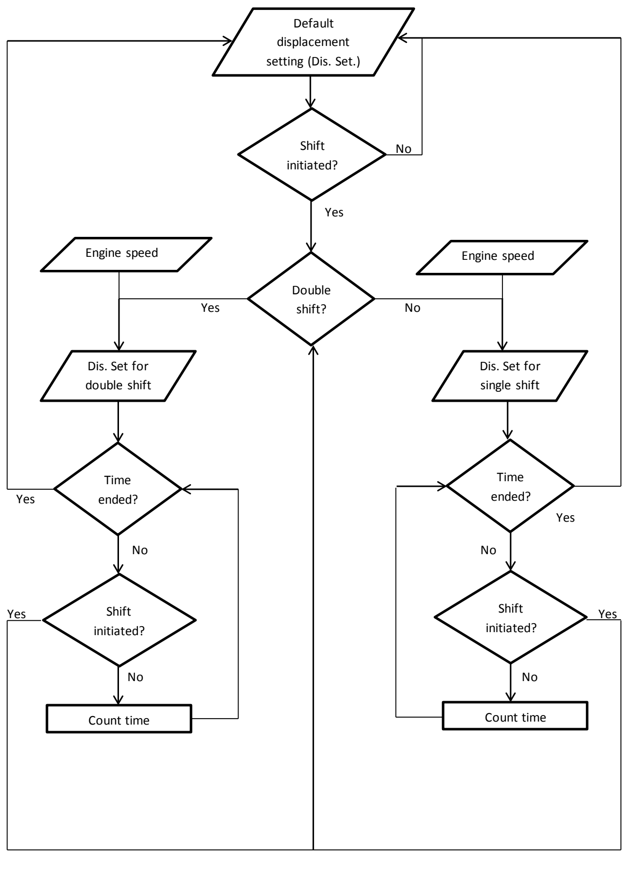

Figure 5.2: *Control strategy variable displacement pump*

When a shift occurs it is investigated if it is a double or single shift. A look up table can be used that depending on engine speed and type of shift gives a signal to the valve that affects the displacement setting. The same displacement is held for an amount of time in order to ensure that the shift is completed. After the shift the displacement setting returns to its value where the system pressure is held.

If a new shift occurs during the time that the previous shift is being performed the loop is aborted and the new shift is investigated. The same procedure is used for both single and double shift. When the safety time has ended the displacement setting returns to a default value that has been decided to keep the system pressure. This default value is set to prevent pressure drop due to for example leakage. If no shift occurs this default value is held until a shift is initiated.

5.2 Electric pump

With an electric pump it is possible to control the pump speed even if the displacement is fixed and hence get different flows during different conditions. An electric pump can start rotating as soon as the vehicle is started and in a hybrid vehicle it is then possible to shift even though there is no engine speed.

5.2.1 Engine speed

An electric pump can also be controlled using the engine speed. From Chapter 4 it is shown that the double shift has the greatest flow demands. With an electric pump with a displacement of 0.06 l/rev this is corresponding to a pump speed of approximately 600-700 rpm.

The control strategy suggested is that a fixed engine speed is chosen as reference and when the engine speed is over the reference speed the pump has a higher speed and when it is under a lower speed is used. The reference speed should be chosen according to where the flow demand is the same as for the mean value of required pump speed.

Since the flow demand is not possible to measure (4.6) can not be used. The engine speed is easy to measure and hence is a good choice for a simple control strategy.

5.2.2 Shift

The electric pump can be controlled using the shift strategy. This strategy to control an electric pump is similar to the control strategy for the variable displacement pump with engine speed and shift. The greatest difference from the variable displacement pump is that the engine speed is not taken into consideration. Depending on if it is a double or single shift different pump speeds are used and when no shift is initiated the default speed of the pump is used to maintain the system pressure. Figure 5.3 shows this strategy in a flow chart.

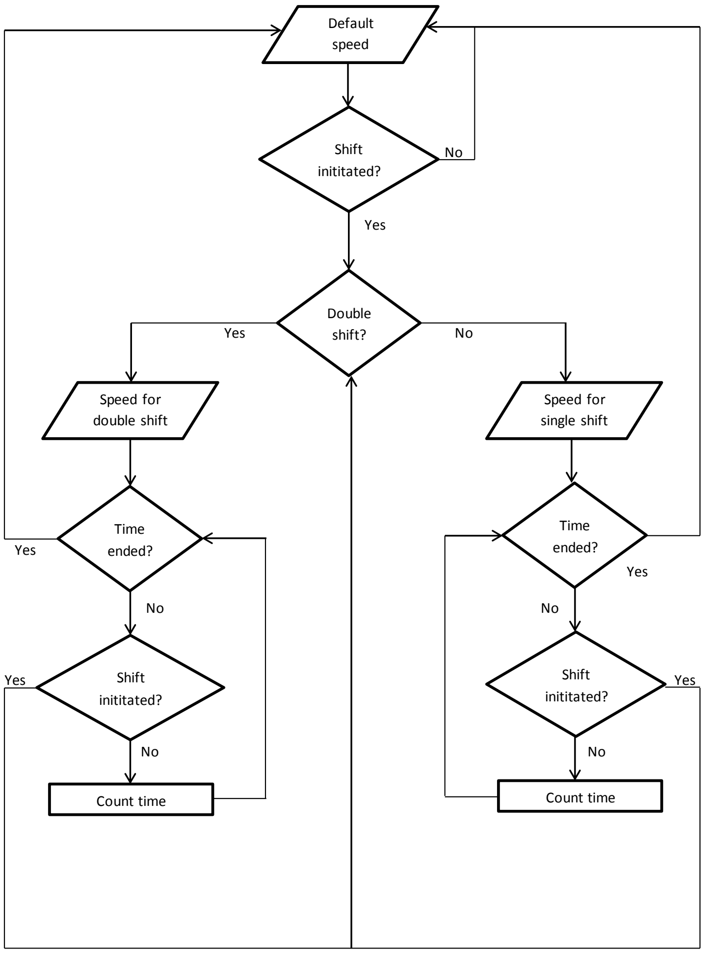

Figure 5.3: Control strategy electric pump

5.3 Gear pump & electric pump

As previously explained the gear pump is not possible to control but the electric pump is. A control strategy for the electric pump speed is presented below.

5.3.1 Engine speed

Also for this strategy the engine speed is used as reference. This is mostly because of that the gear pump supplies more flow during high speeds than low. The strategy is a mix of the previous strategies presented. The kind of shift is not taken into consideration but the higher flow is only held during the time it takes to ensure that the shift is fulfilled.

When no shift is initiated and the electric pump does not need to supply extra oil to the system the pump is shout off and the speed is 0 rpm. When a shift is initiated a look-up table is used that takes the engine speed and sends a request of pump speed. The same speed is held during some time to ensure the shift. If a new shift is initiated during this time a new pump speed is requested and if the time ends the pump shouts off again. In Figure 5.4 a flow chart is presented for this strategy.

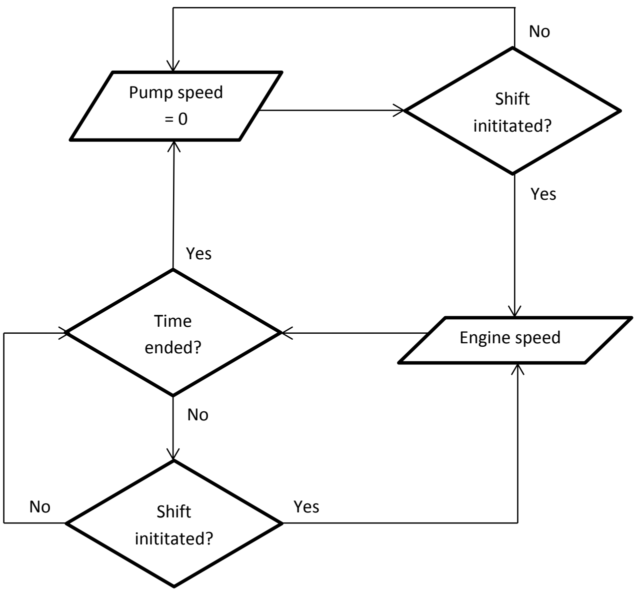

Figure 5.4: *Control strategy for an electric pump when in combination with a gear pump*

5.4 Other possibilities

Earlier in this chapter a few simple strategies were described, these are later analysed in Chapter 6. Below, a few other thoughts are described that could be used, or at least taken into consideration, when implementing a real model and system.

5.4.1 Development of strategy depending on shift

The suggested strategies for both the variable displacement and the electric pump only consider if the shift is single or double. This could be further investigated and adapted to each individual shift. Some elements require more flow than others and in the strategies presented above the elements that requires the most flow are chosen to represent all single and double shifts. The losses would be decreased if the settings were adapted to each shift since most shifts does not require such high flows that are used in the strategies above.

The development of the control strategy presented has not been conducted as not enough data and models were available. It is time consuming to do all the simulations deciding the demands of flow and pressure required for all gears during different engine speeds. Although would the measurements already be done in the choice of pump and when the demands are decided, see Chapter 3. The strategies presented in 5.1.2 and 5.2.2 are adapted to the values of demand from Chapter 3. Only three different shifts are available. For the single shift the shift with highest demands on flow is used. And the double shift is adapted to the only example available.

5.4.2 Pressure

Pressure is the main reason that the elements are applied in a gear. But if the pressure gets too high components in the transmission and hydraulic system may break. That is why a pressure relief valve is located close to the pump. When the valve is opened the oil is transported to the oil sump. If the oil is directly transferred to the sump before doing any good it is all wasted energy.

To prevent oil from being sent to the sump directly it is possible to lower the flow from the pump when the pressure gets close to the point where the valve is opened. If the pressure is decreased the relief valve will not be open for as long time or maybe not be opened at all which saves energy.

6 Analysis

In this chapter the pumps and their control strategies are analysed. To be able to compare the pumps all calculations are based on the same drive cycle. The drive cycle consists of up and down shifts for all nine forward gears. The commonly used drive cycles as NEDC and FTP are adapted to smaller transmissions that only have 5 gears. The drive cycle used in this thesis is classified and will only be referred to as the drive cycle.

The pressure is set to a constant value and all pumps except the existing, have the same maximum displacement. The current pump has a slightly lower displacement. The pumps are ideal, meaning that efficiency of the pump is 100 %.

Power, P, is calculated using a pressure, p, and the flow, q_p, in (6.1). The pressure is set constant as the variations in pressure are not known. The pressure is set to its high value in order to avoid a too low estimate.

$$P = p \cdot q_p \tag{6.1}$$

The flow is calculated differently depending on pump. The same equation (6.2) is used for all pumps. The displacement, D_p, is 0.06 l/rev for all pumps except the existing gear pump. The existing pump has a smaller displacement of 0.049 l/rev. It is also assumed that no losses occur in the pump that gives a volumetric efficiency, $\eta_{vol} = 1$.

$$q_p = D_p \cdot \epsilon \cdot n_p \cdot \eta_{vol} \tag{6.2}$$

The displacement setting, ϵ, is 1 for the gear pump and the electric pump. For the variable displacement vane pump the displacement setting is varied. For the variable displacement vane pump and the gear pump the pump speed, n_p, is the same as the engine speed. The speed for the electric pump is not the same as the engine speed but is varied according to the demands. Table 6.1 shows the settings for each pump.

Pump	Displacement [l/rev]	Dis. setting [-]	Pump speed [rpm]	Vol. efficiency [-]
Existing pump	0.049	1	Engine speed	1
Gear pump	0.06	1	Engine speed	1
Vane pump	0.06	Varied	Engine speed	1
Electric pump	0.06	1	Varied	1
Gear & electric	0.02 & 0.04	1 & 1	Engine speed & varied	1
Gear & electric	0.015 & 0.04	1 & 1	Engine speed & varied	1
Gear & electric	0.01 & 0.04	1 & 1	Engine speed & varied	1

Table 6.1: *Settings for the pumps to calculate the flow.*

The energy produced by the pump is calculated by taking the integral of the pump power, see (6.3).

$$E = \int_0^t P dt \tag{6.3}$$

6.1 Gear pump

The gear pump is not possible to control. It has fixed displacement, no displacement setting and the speed is the same as for the engine. The displacement is smaller for the existing pump and therefore the energy is smaller. Figure 6.1 shows the power plotted against time during the drive cycle for the existing pump and for the gear pump that satisfies the flow demands in all points.

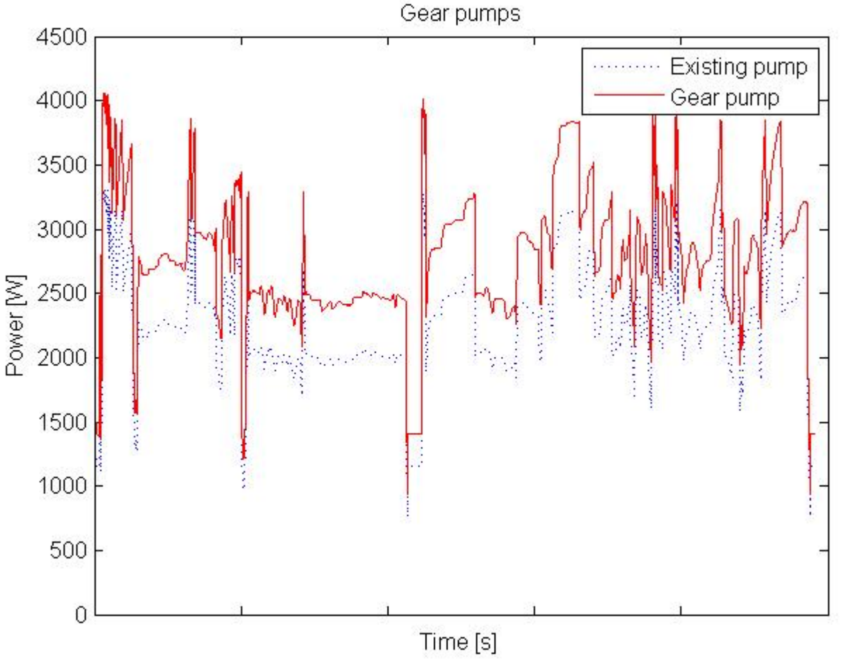

Figure 6.1: *Power for gear pumps against time during the drive cycle*

6.1.1 Existing pump

In Chapter 4 two different ways of calculating the flow was introduced. Since the flow was not exactly the same, though similar, it is of interest to see the difference this gives in the power and energy calculations. Figure 6.2 shows the difference in power by using the displacement or the linearisation when calculating the flow. The figure shows that the difference by using different ways of calculating the flow does not give a great change in power.

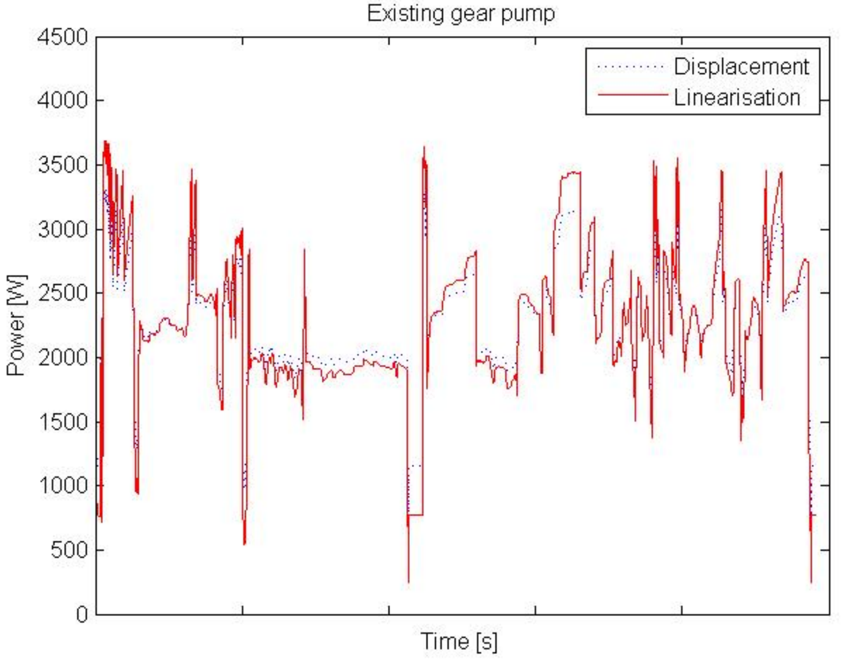

Figure 6.2: *Power for existing gear pump against time during the drive cycle. The power is based on flow calculated using either displacement or linearisation.*

6.2 Variable displacement pump

The vane pump with variable displacement is controlled in two different ways. Either by only looking at the engine speed or by looking at the engine speed and shift. Figure 6.3 shows the power against the time for both control strategies. The figure shows that using the gear shifting strategy combined with the control strategy gives a lower power than control by just using the engine speed.

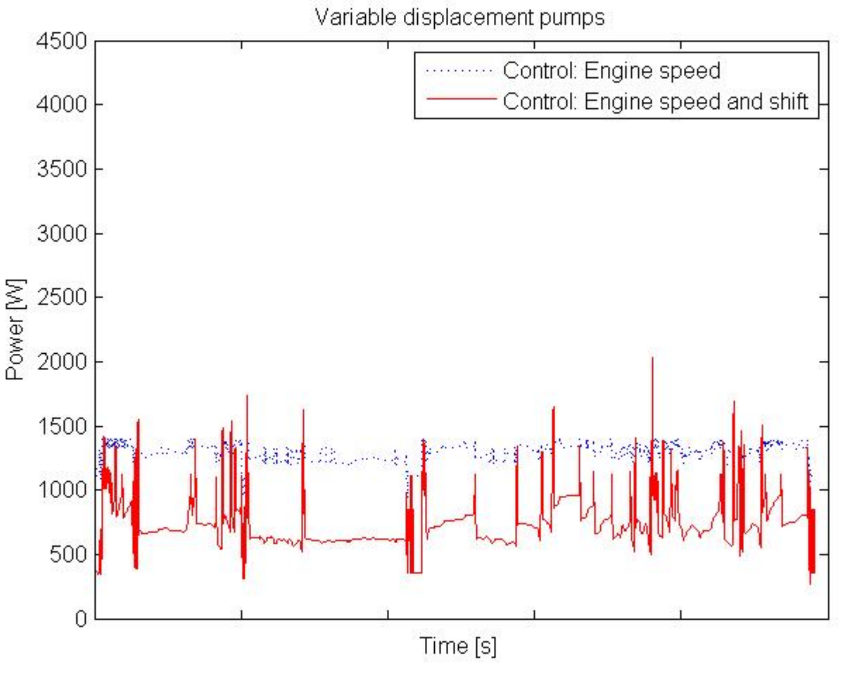

Figure 6.3: *Power for variable displacement pumps against time during the drive cycle*

6.3 Electric pump

The electric pump is controlled in two different ways. Either by only looking at the engine speed or by looking at the engine speed and shift. Figure 6.4 shows the power against the time for both control strategies. Using a control strategy based on the engine speed gives higher power than using a strategy based on shift strategy.

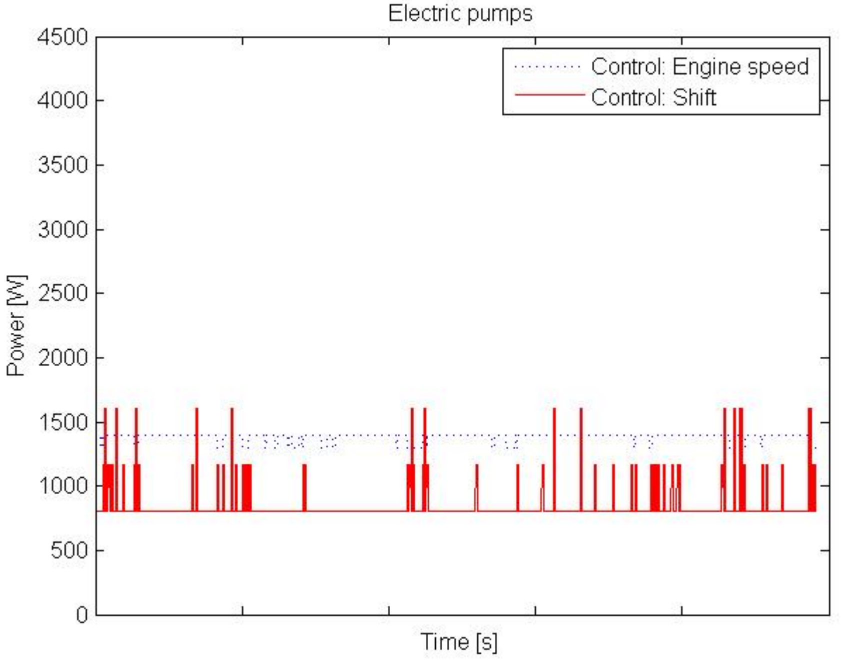

Figure 6.4: *Power for electric pumps against time during the drive cycle*

6.4 Gear pump & electric pump

The electric pump has controlled pump speed depending on the engine speed when a gear pump and an electric pump are used in combination. Figure 6.5 shows the power for three pump combinations against the time during the drive cycle. The combinations consists of an electric pump with displacement 0.04 l/rev and a gear pump with displacement 0.02, 0.015 or 0.01 l/ rev. The combinations are called 02, 015 and 01, respectively. The combination with the smallest displacement gives the lowest power.

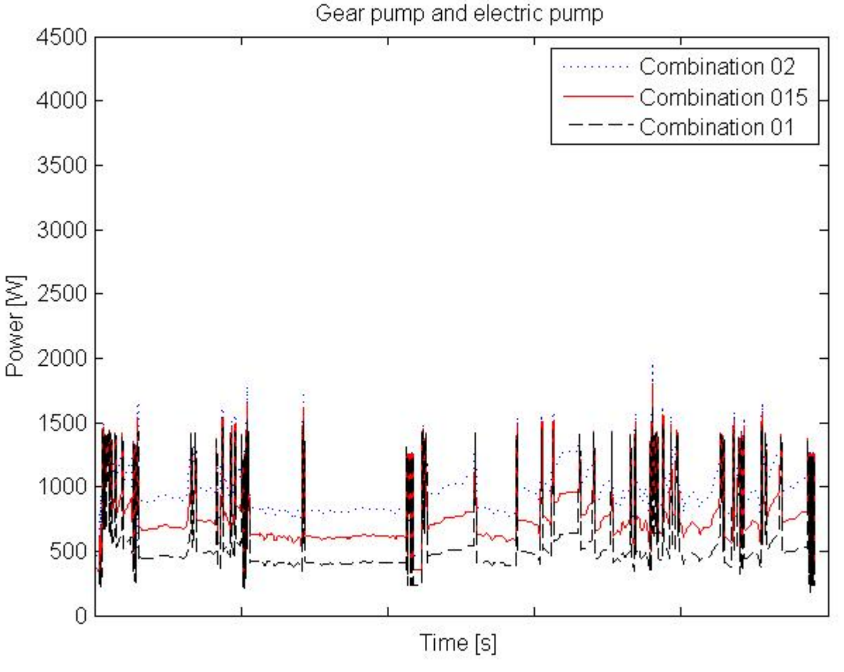

Figure 6.5: *Power for combinations of gear pump and electric pump against time during the drive cycle*

6.5 Energy

The energy for the different pumps and combinations with their control strategies are shown in Table 6.2. The energy is the energy from the pump that is produced during the whole drive cycle.

Pump	Control strategy	Energy [MJ]
Existing pump - displacement	-	22.30
Existing pump - linearisation	-	22.38
Gear pump	-	27.31
Vane pump	Engine speed	12.70
Vane pump	Engine speed & shift	7.35
Electric pump	Engine speed	13.62
Electric pump	Shift	8.45
Combination 02	Engine speed	9.63
Combination 015	Engine speed	7.64
Combination 01	Engine speed	5.65

Table 6.2: *Energy and control strategy for all pumps and combinations*

The pumps and other components have an efficiency that affect how much energy that is required in order to produce the energy listed in Table 6.2. The efficiency of a gear pump is approximately 90 % and for a vane pump 85 %. The electric pump uses a battery, a generator, an electric motor and a gear pump. The total efficiency for an electric pump with all its components is approximately $0.9 \cdot 0.9 \cdot 0.9 \cdot 0.9 = 65.61$ % which is the product of the efficiencies for each component. The energy required to use the pumps and combination of pumps are listed in Table 6.3. The required energy is calculated by dividing the the pump energy from Table 6.2 with the efficiencies.

Pump	Control strategy	Efficiency [%]	Req. energy [MJ]
Existing pump - displacement	-	90	24.78
Existing pump - linearisation	-	90	24.87
Gear pump	-	90	30.35
Vane pump	Engine speed	85	14.94
Vane pump	Engine speed & shift	85	8.64
Electric pump	Engine speed	65.61	20.76
Electric pump	Shift	65.61	12.88
Combination 02	Engine speed	90 & 65.61	10.92
Combination 015	Engine speed	90 & 65.61	8.83
Combination 01	Engine speed	90 & 65.61	6.74

Table 6.3: *Required energy included the efficiencies*

If the required energy is decreased the fuel consumption will be decreased. As seen in Table 6.3 the vane pump, the electric pump and the combinations require lower energy than the gear pump. Switching pump will then improve the fuel consumption.

6.6 Discussion

Having a gear pump that is not under dimensioned has the highest required energy of 30.35 MJ. The pump used today is under dimensioned and hence require less energy, under 25 MJ. By changing the single gear pump to a variable vane pump, an electric pump or a combination with a gear pump and an electric pump would decrease the energy consumption, Table 6.3, and hence the fuel consumption.

A variable displacement pump would be the best choice since it is driven by the engine crank shaft and no other components needs to be fitted in except one more valve. It is seen that the control strategy affect the required energy. Using a control strategy that takes shift and engine speed into consideration instead of just the engine speed decrease the energy to 8.64 MJ from 14.94 MJ. If a control strategy more adapted to each shift is used the energy consumption would probably decrease further. The advantage with a vane pump is that when the flow needs to be increased the pump itself does not demand more oil, but less, which means that the oil that was supposed to keep the displacement setting instead can be used to the oncoming elements. A variable displacement vane pump has more parts than a gear pump and hence it is probably more costly. The cost is a big disadvantages for the vane pump as well as the fact that if it has more parts it is a greater risk that something breaks.

An electric pump also has lower energy requirements than the gear pump and it is shown here as well that the controls strategy affect the energy. The required energy was decreased from 20.76 MJ to 12.88 MJ when the shift was used in the strategy. The disadvantages with an electric pump is that more components, generator and battery, needs to connect to the transmission. Connecting more components require more space and is not preferably. But if and when heavy duty vehicles are introduced as hybrids an electric pump is necessary in order to be able to shift even when the engine is not running. The advantages with an electric pump is that the displacement and pump speed can be changed. With a greater displacement the pump speed may be decreased and if the displacement is decreased the speed has to increase to have the same result.

It is also possible to use an ordinary gear pump, but of a smaller size than today, and support with an electric pump when higher flow is required. The gear pump would in this case only supply the oil to maintain the system pressure and the electric pump could be used during gear shift and shut off otherwise. With this solution there would be less troublesome if the electric pump brakes, the transmission would still work but it would take longer time to perform shifts. The energy consumption is decreased compared to the existing gear pump. The displacement of the gear pump affects the required energy, with decreased displacement the required energy is decreased. With a displacement of 0.02 l/rev the energy demand is 10.92 MJ compared to 8.83 and 6.74 MJ when the displacement is 0.015 and 0.01 l/rev. Using a combination with a small displacement of the gear pump requires the least energy of all presented pumps. The disadvantage with a combination is that the electric pump needs a lot of components connected to the transmission and more space is needed when two pumps are used.

7

Conclusions, reflections and future work

7.1 Conclusions

As seen in previous chapter it is possible to reduce the losses from the oil pump in an automatic transmission. The existing gear pump consumes less energy, approximately 25 MJ, than the gear pump that has a displacement of 0.06 l/rev, 30.35 MJ. The vane pump with variable displacement, the electric pump and the combination of pumps consumes even less energy during a drive cycle. For the vane pump and the electric pump it is also shown that adapting the control strategy will decrease the energy consumption. For the vane pump the energy is lowered from 14.94 to 8.64 MJ with a more adapted strategy. For the electric pump the energy is decreased from 20.76 to 12.88 MJ. The combination of an electric pump and a gear pump requires the least energy with a gear pump that has the displacement 0.01 l/rev, 6.74. If the displacement is increased to 0.015 or 0.02 l/rev the required energy becomes 8.83 or 10.92 MJ.

By looking at the energy consumption it would be beneficial to change the existing pump to a vane pump with variable displacement, an electric pump or the combination of two pumps. The vane pump is preferable since it is driven in the same way as the existing gear pump and other components do not have to connect to the transmission. As the energy consumption affects the fuel consumption in the vehicle the goal is to have as low energy consumption as possible to decrease the fuel consumption. The electric pump is necessary when hybrid heavy duty vehicles are introduced but is not the first choice today. The combination can be used both today and in hybrid vehicles, but the control strategy has to be changed compared to the one presented in the report. Even though the combination require the least amount ofenergy it is not the first choice since it has to connect other components to the transmission to get the electric pump to function.

7.2 Reflections

From the beginning the plan was to investigate the energy demand from the transmission to make a choice of oil pump. The thought was to calculate the necessary energy, the gear shifting, and if it was time also the unnecessary energy, depending on for example leakage losses. Due to poor knowledge of hydraulics a lot of incorrect assumptions were made in the beginning of calculating the necessary energy demand. With a better knowledge weeks could have been saved and time could have been spent on more important areas.

A reasonable value for the necessary energy demand was, despite the problems with the hydraulics, calculated. But because of a mistake in the calculation the result is not valid. And unfortunately not enough data was available to recalculate the necessary energy demand. The unnecessary energy, losses from leakage and friction, could also have been calculated if more data was available.

It would have been really good to have access to a model in Simulink (or similar) of a transmission and hydraulic system. An attempt of creating a model was started but it did not take a long to realise that it would take too much time to finish during the thesis period as well as the fact that not enough data was available.

7.3 Future work

If this work is to be developed a model would be a good start to have something to lean back against. To develop this report a model is necessary where the pumps with their control strategies can be implemented and to be able to make adequate conclusions. A model is also necessary to be able to investigate which demands concerning flow and pressure that a pump needs to meet.

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