I. INTRODUCTION

Fuel consumption and driveline efficiency are important issues in the automotive industry. Continuously Variable Transmissions (CVT) can cover a wide range of ratios. This makes it possible to operate a combustion engine in more efficient working points than stepped transmissions.

At the TU Eindhoven an electromechanical CVT is developed. The actuation system of this CVT has a lower power consumption in steady state situations and therefore a ratio strategy with causes the transmission to be in a constant ratio more of the time would be preferred [Klaassen, Meerakker]. Also for implementation of slip control it could be beneficial [Bonsen]. Therefore the fuel economy penalty for a stepped ratio approach in comparison to continuous ratio strategies is investigated.

To maximize fuel economy, the so called Optimal Operation Line (OOL) should be accurately tracked. However, the costs of this approach are drivability issues due to the lack of dynamic response of the vehicle. In this paper a comparison is made between different ratio control strategies possible for a CVT. The choice of ratio control strategy influences the fuel economy and drivability and therefore will always be a compromise between the two. A comparison is made between an OOL tracking strategy, continuous ratio strategies derived from an approximation of the OOL as shown in figure 2 and constant ratio strategies derived by quantizing the continuous strategies. These strategies are compared on fuel economy and acceleration times.

II. OOL

Optimal Operation Line tracking is the most fuel economical way to operate the driveline. However the power reserve is very low in most cases, therefore the drivability is influenced in a negative way.

The OOL as shown in figure 1 can be calculated from the engine map by minimizing the fuel consumption in [g/kWh] for a set of output power values. The OOL can be approximated using a third order polynomial. The result is also shown in figure 1. The smoothing of the OOL also improves the smoothness of the shifting.

III. RATIO CONTROL STRATEGY

From the OOL the optimal engine speed for a given throttle position can be obtained. If this strategy is used, the drivability of the vehicle is lowered, because the response to sudden throttle movements is slow. Since drivability is also an important issue for ratio control design, a new line has to be designed that finds a good combination of fuel economy and drivability. In this paper drivability will be evaluated using simulation.[Hofman]

The ratio control strategy is evaluated for fuel economy,
acceleration times of 0-100, 50-80 and 80-120.
A cost function is designed that is minimized:

\[ J = l_{fuel} \cdot \gamma_1 + t_{0-100} \cdot \gamma_2 + t_{50-80} \cdot \gamma_3 + t_{80-120} \cdot \gamma_4 \]

In this equation, \( \gamma_1, \gamma_2, \gamma_3, \gamma_4 \) are the weighting factors for the different measurement values.

\[ g_{1-4} \times +\times +\times +\times + = \]

\[ \text{fuel} \]

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\[ \text{Figure 3: Engine torque for given throttle positions at different engine speeds.} \]

The EUDC cycle is used to evaluate the fuel economy. [Yong Shen] acceleration simulations are used to evaluate the drivability.
The fuel consumption map of the IC engine used (the 2.0FSI engine of an Audi A3) is defined for a certain torque/engine speed combination. To obtain the relation of the engine torque with the throttle position the map in figure 3 is used.

The ratio control strategy can be calculated from:

\[ \omega_{engine} = f(x_{\text{throttle}}) \]

The engine speed is a function of the throttle position. For the OOL tracking this would look like the solid line in figure 1.

An alternative line is designed using the following method:

\[ \omega_{engine} = \min(\omega_{max}, \max(\omega_{min}, f(x_{\text{throttle}}))) \]

Where \( f(x_{\text{throttle}}) \) is a third order approximation of the Optimal Operation Line (OOL). A factor is added to increase the torque reserve of the engine, thereby increasing the responsiveness of the vehicle. This value is of course a compromise between agility and fuel consumption.

Furthermore rpm’s are increased with increasing driveshaft speed to enhance the feeling of the driver. The amount with which this is done is given by: \( \omega_{\text{increase}} \).

Three variables are subject to tuning:

\[ \begin{bmatrix} \omega_{min} & \omega_{\text{design}} & \omega_{\text{increase}} \end{bmatrix} \]

Dynamic programming is used to determine the best compromise. For all possible values of the design variables a simulation is done and the results are used to calculate the cost of each combination of the design variables. [Dimitri]

Implementation is done by calculating a 2D lookup table of desired ratios for each vehicle speed and throttle position combination. This is stored in a matrix in the TCM (Transmission Control Module).

Because of several reasons mentioned earlier a stepped ratio approach is investigated. For each of the possible combinations of the design variables also a stepped ratio control strategy is derived. For this purpose the continuous ratio strategy as stored in the 2D lookup table is quantized in a fixed number of evenly distributed steps given by:

\[ r_i = r_0 \cdot c^i \]

Where \( r_0 \) is the LOW ratio and \( c \) depends on the overdrive ratio and the number of steps \( (n) \):

\[ c = \left( r_{\text{max}} - r_{\text{min}} \right)^{1/n} \]

System constraints are:

| \( r_{\text{min}} \) (LOW) \ | 0.45[-] |
| \( r_{\text{max}} \) (OD) \ | 2.25[-] |
| \( \omega_{\text{min}} \) \ | 80[rad/s] |
| \( \omega_{\text{max}} \) \ | 550[rad/s] |

\[ \text{Torque [Nm]} \]

\[ \text{Figure 4: Engine efficiency map with the approximated OOL (- -) and the adapted OL (--)} \]
Examples of these ratio control strategies are shown in figure 7, 8 and 9. For smoothness reasons shifting is limited to 0.5Hz. This limits the drop in acceleration in kickdown situations. This however also limits the tracking of the designed ratio curve.

IV. COMPARISON

Each strategy is compared on fuel economy on an EUDC cycle, 0-100km/h acceleration 50-80km/h acceleration and 80-120km/h acceleration with full throttle. In these simulations transmission efficiency was calculated using a constant torque-loss in the transmission. This is not entirely accurate, but is close to realistic loss values [Veenhuizen].

Comparison is made using the cost function:

\[ J = m_{fuel} \cdot \gamma_1 + t_{0-100} \cdot \gamma_2 + t_{50-80} \cdot \gamma_3 + t_{80-120} \cdot \gamma_4 \]

In this function the weighting parameters are chosen to normalize the variables for typical values of these variables. The weighting of the fuel consumption is taken higher, because the importance is high within this project.

<table>
<thead>
<tr>
<th>Table 1: Weighting function</th>
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<tbody>
<tr>
<td>$\gamma_1$</td>
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<tr>
<td>2*0.15</td>
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The fuel economy is calculated using an EUDC cycle which is simulated by calculating the power needed and tracking back which ratio would have been chosen and then calculating the working point of the IC engine. From the enginemap a fuel consumption estimate can be made. The acceleration is simulated starting at a given speed $v_0$ and then going from 0% throttle to full throttle in 0.1s. When not starting at $v_0=0$[m/s] this maneuver includes a shift from overdrive to the desired ratio.

<table>
<thead>
<tr>
<th>Table 2: Comparison of different strategies</th>
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<tbody>
<tr>
<td>Strategy</td>
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<tr>
<td>OOL tracking</td>
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<tr>
<td>CVT</td>
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<tr>
<td>CVT increasing speed</td>
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<tr>
<td>7 speed</td>
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<td>6 speed</td>
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<td>5 speed</td>
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V. RESULTS

The result of the comparison of all different strategies is given in table 2. For each strategy the values are given with the minimal cost for this strategy. The OOL tracking is about 5 to 7% better then the other CVT modes. What is surprising however is that the stepped ratio modes show better fuel economy then the CVT modes. This result is probably partly caused by the limitation on the shiftspeed. Furthermore it can be seen from table 2 that OOL tracking gives a slow performance with the acceleration tests.

<table>
<thead>
<tr>
<th>Table 3: Optimal design values</th>
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<tr>
<td>$\omega_{design}$</td>
</tr>
<tr>
<td>OOL tracking</td>
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<tr>
<td>CVT</td>
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<td>CVT increasing speed</td>
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<td>7 speed</td>
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<td>6 speed</td>
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<td>5 speed</td>
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Here the CVT strategy with increasing engine speed with increasing vehicle speed gives high performance with the acceleration tests, with slightly higher fuel consumption. When the continuous modes are compared to the stepped modes, it is seen that the stepped ratios with 5, 6 or 7 speeds are comparable to the continuous modes with respect to fuel economy and sometimes better when acceleration times are compared. The first is partly a result from the shiftspeed limitation. The second is due to the sometimes higher engine rpm’s which is slightly less economical, but facilitate faster acceleration. In table 3 the values for the design variables are given. These indicate that the same ratio strategy is valid for stepped or continuous shifting.

Figure 5: Ratio map for a strategy with increasing engine speed with increasing vehicle speed

If the fuel consumption map of the vehicle is plotted for vehicle speed compared to the road load, plotted in figure
6, it is seen that the maximum speed of the car will be around 200 km/h. Also maximum efficiency is only reached when accelerating. The fuel consumption given in this plot is the minimal fuel consumption attainable with the cvt and the 2.0 FSI engine.

VI. DRIVABILITY

The winning strategy is implemented in a Audi A3 equipped with a Nissan CK2 CVT transmission. Also a 7-speed strategy is adopted for the sport-mode program. People who drive the A3 find the strategy where the engine speed relates to the vehicle speed more pleasant, because they can better perceive vehicle speed. Stepped ratio strategies are perceived as more sporty even though the actual acceleration is not higher.

VII. CONCLUSIONS

From the simulations can be concluded that the stepped ratio approach does not pose a large penalty on the fuel economy compared to continuous ratio strategies. This is especially true if a 6 speed stepped ratio control strategy is used, but since this test was only on the EUDC cycle it is probable this does not hold in general.

When raising the operation line higher then the OOL a small fuel economy price is paid. The engine can be operated 25[rad/s] faster than the OOL with a small fuel economy penalty. However to maintain good transient behavior a higher $\omega_{\text{min}}$ needs to be maintained, lowering the fuel economy. This costs 3-7% in fuel economy.

In this study parameters like jerk, dead time and maximum acceleration are not examined. These will be examined in the car, since these are very subjective variables.
Figure 10: 7-speed ratio map

VIII. REFERENCES