Historical Background

Since 1998 Haldex Traction produces intelligent AWD systems. The first generation Haldex Limited Slip Coupling came in a VW Golf 4MOTION that same year and a year later it was presented in a Volvo S60 AWD. The first generation Haldex LSC was based upon a unique patented differential pump that created a hydraulic flow proportional to the difference velocity over the coupling. With help of a linear throttle valve, activated with help of a stepper motor, the ‘stiffness’ could be varied and the torque transfer controlled. One can see the Haldex system as a rotational damper with variable characteristics.

Later, in the year 2002 Haldex Generation II was introduced. This second generation of Haldex LSC is still using the unique differential hydraulic pump, but the linear throttle valve has been exchanged for a solenoid controlled proportional throttle valve. On top of that a pressure sensor is introduced and used actively for closed loop pressure (torque) control, which created performance improvements especially within the limits of tyre-road adhesion. However, the mechanical-intelligence¹ is still there for disturbances beyond the bandwidth largely determined by the CAN communication, e.g. slip control and μ-jump. Also it offers great robustness to poor signal quality and CAN signal loss. In case of a broken CAN bus the fall back is a certain predefined stiffness value, which is a compromise between traction and manoeuvrability. LSC’s without this differential pump have to shut off and leave you in the bush, because there is not such compromising pre-emptive torque. Too high and the drive line shows fatigue problems, too low and the lamellae will burn.

Generation III, on the market since 2004, is a further development of Haldex’ second generation. By adding a check valve the already available feeder pump (a small pump to activate the system) could, although limited, create pre-emptive torque capacity over the coupling. This solution is called pre-charge, PreX™. In later versions of this generation the pre-emptive torque capacity has been increased by means of a larger feeder pump.

To be introduced later this year (2007) will be the Haldex Generation IV. The cost driven developments has favoured the pre-emptive techniques from the heavy PreX solutions in Generation

¹ See reference [2]
Ill to a Haldex coupling without a differential pump. Also, the proportional throttle valve has been exchanged for a proportional pressure reducing valve. In order to create fast response of the coupling, a hydraulic accumulator is kept filled by the feeder pump. The pressure reducing valve controls the pressure drop between the accumulator and the piston which creates axial force onto the clutch package.

Soon after the introduction of Haldex Generation IV, the introduction of Cross Wheel Drive, XWD™, takes place in 2008 on a global platform. Although XWD existed in conjunction with former generations as prototypes, it will first come on the market together with the fourth generation of Haldex LSC. XWD is basically an electronically controlled limited slip differential that shares power pack and electronic with the AWD system. Smart design also enables the XWD to be sold as an option within the same platform.

**Hardware**

*Drive Line Configuration*

In order to give a better understanding for where the Haldex LSC and eLSD are placed the picture below gives a schematic overview of a vehicle’s drive line.

![Figure 2 Drive line layout](image)

The XWD to be introduced is on a front wheel drive platform. From a power take off a propeller shaft is connected via the Haldex LSC to the rear differential. The eLSD is placed between the crown wheel of the rear differential and one of the rear half shafts.

*XWD Design*

Figure 3 shows the XWD hardware and shows clearly the shared power pack and ECU. The power pack is fitted in the LSC and connected to the eLSD with two hydraulic lines, one high pressure side and one to tank. On the eLSD a pressure reduction valve, connected to the ECU by means of wires, is mounted closely to the hydraulic activated clutch pack.

The hardware is modular and can thus be sold as an option within the same platform. The eLSD package shall than be replaced with a cover without the hydraulics and valve onto the differential housing.
**XWD Features**

**ABS/ESC Compatible**
Today a product is viable only when it is fully compatible with anti-lock braking, ABS, and electronic stability control, ESC, systems. Of course the Haldex LSC is ABS compatible; the sheer existence of ABS on a large fleet of vehicles actually made the electronic controlled LSCs viable for mass production and Haldex pioneered this field during the mid-nineties. Even so the LSD is compatible with ABS/ESC and the existence of ESCs sensor cluster will boost performance and functionality of an eLSD. Of which this presentation is proof.

**Shared ECU and Power Pack**
The XWD design shares two relatively expensive parts of the complete system; the power pack and ECU. Because these two systems are shared, the on-cost for eLSD is relatively small.

**Effective Traction Enhancement**
Because diagonal spin can be prevented with two clutch packs arranged as shown above, traction is improved tremendously in an energy-effective way compared to brake-based systems. Also, the system operates without comfort intrusion that some brake based systems show. Because the LSD limits the wheel speed difference across the rear axle, the locking torque dissipates energy by means of the relative speed difference. Because the LSD transfers torque between one (1) half shaft and the crown wheel, it becomes actually half the relative wheel speed difference. This relative wheel speed difference is far lower than the absolute wheel velocity that is dissipating brake energy with an electronic differential lock, EDS, system.
Furthermore, the slip controller across the rear axle automatically ensures excellent traction performance possibly without any EDS brake intervention. Depending on the design requirements from the OEM, the allowed torque capacity across the rear axle may be limited, and an EDS intervention may increase traction even further, albeit less energy effective.

**Handling Performance Boost**
Handling performance of AWD vehicles on high-µ surfaces are quite often limited by the down load on the curve inner wheels. Accelerating at high lateral g’s quite often lead to inner wheel spin, which limits the longitudinal acceleration. By limiting the (relative) slip of the rear inner wheel the total traction capacity increases and the power under steer is reduced. For adequate control ESC sensor cluster is required.

**Safety Enhancements**
Below the safety enhancement that can be obtained with XWD will be discussed more in detail.
Transparent for the Driver
Since control algorithms in the ECU are fully automatic controlling all the functions for traction and handling, the system is completely transparent for the driver. The XWD control software does use available ABS/ESC and engine management signals only.

Cost Effective
Because the on-cost of XWD consist mainly in the additional clutch pack and hydraulic valve, the cost benefit ratio is outstanding. Certainly when the shared power pack and ECU have a substantial contribution to the overall system cost. Where the on cost is moderate, the additional features or benefits are significant: excellent traction, boost handling and added dynamic driving safety.

Yaw Damping

*Figure 4 Step responses of vehicle with and without locked LSD*

**What is Yaw Damping**
The term yaw damping is widely used in publications; however its technical content may differ significantly and may not always be used correctly in a strict physical meaning. The word damping is used for signals whose oscillatory behaviour diminishes over time when the so called damping ratio is larger than zero. It is thus a measure of transient system behaviour.

Under steering ground vehicles show decreasing yaw damping (and yaw natural frequency for that matter too) with increasing vehicle forward velocity (see reference [1]). Over steering ground vehicles may have increasing yaw damping with velocity, but they will reach an unstable velocity, so called critical velocity, and is not a normal case for production vehicles.

Locked LSD in the rear axle can create under steering moments only. This implies that the only way to influence the vehicle yaw motion is to create under steer. From literature we know that increased under steer requires larger steer input for the same curvature and it decreases damping too, which is the opposite effect we are looking for. To exemplify this statement simulations with a simple vehicle model with non-linear tyres are carried out. One vehicle runs with an open rear differential the other has a locked one. The simulation results clearly show the larger required steer angle in order to obtain the same steady-state lateral acceleration, which is a measure for the increased under steer. Also, the yaw rate overshoot is larger as a measure of decreased yaw damping. Figure 4 shows yaw rate multiplied by vehicle velocity, which is equivalent to the steady-state lateral acceleration.

The above discussion shows that a more intelligent control than just closing the eLSD is necessary in order to increase yaw damping. If yaw damping is seen as counter acting the yaw velocity rate of
change (in other words: yaw acceleration) firing the eLSD at the right time with the right magnitude could result in the desired performance. The yaw damping control is thus a control that only activates the eLSD in transient manoeuvres like an accident avoidance manoeuvre.

**Control Requirements**

Chassis tuning is considered the primary source of handling characteristics like under steer. These characteristics can be influenced by longitudinal and lateral drive torque distribution. In this document we concentrate on the eLSD part of the product XWD. A lock torque in the eLSD creates an under steering yaw moment across the rear axle. This means a lock torque present during steady-state cornering will degrade handling performance by means of increased under steer (see chapter above). The lock torque for yaw damping purposes across the rear axle may thus only be applied in transient manoeuvres.

The control algorithms shall be robust against surface friction property and tyre property variations. The use of observer techniques is thus omitted. In prototype vehicles the use of this technique may show wonderful results, but using state-of-the-art for production in many of thousands individuals may lead to compromising results.

![Figure 5](image.png)  
Figure 5 Comparison of open, locked or controlled eLSD in the rear axle in a single sinusoidal lane change

**Simulation Results**

Before implementing the control algorithms in a prototype vehicle, tests in a simulation environment are carried out. The advantage of simulation is the control over environmental parameters and the fast iteration of control parameters and algorithms.

The simulations results presented are based on a single sinusoidal lane change and an accident avoidance manoeuvre. Yaw rate is scaled (multiplied) by the vehicle velocity in order to present the signal as lateral acceleration. This signal also allows a better feeling for how close the vehicle is to its limits.
**Single sinusoidal lane change**

Firstly we compare the results for open, locked and controlled eLSD in a single sinusoidal lane change. This manoeuvre is closed loop sinus on the lateral acceleration signal, which results in identical driven paths. Figure 5 shows the results for yaw rate (scaled by vehicle velocity to lateral acceleration) and steer angle. It can clearly be seen that both the locked and controlled eLSD return faster to a straight line than the open differential in the rear axle. One may even conclude that the closed eLSD performs better. However, a closer look at the steer effort shows significant differences. The first peak in steer angle shows a significant increment for the locked eLSD, e.g. increased under steer. 

Where as the peak-to-peak steer angles for the open and the locked system are similar, the controlled eLSD shows a great improvement to the open system. Figure 6 shows a more complete signal comparison of the open and controlled eLSD. The followed paths are identical (upper left corner). The cause of the small steer angle peaks at the peaks at about 1.45s and 1.8s can be found in the non-minimum phase characteristics of the slip angle (upper right corner). But active yaw damping, AYD, is reducing the magnitude of this non-minimum phase behaviour at the same vehicle velocity.

![Figure 6](image)

**Figure 6** Comparison of open and controlled eLSD in the rear axle in a single sinusoidal lane change

**Accident avoidance**

The steer input to the model for the two cases with or without yaw damping active is such that the followed path is (almost) identical. Keep in mind that the yaw damping algorithms influence transient response and may thus influence the followed path if the open loop steer input is identical in both cases (please refer to Figure 4 for this matter).

The results in Figure 7 show clearly the benefits of a yaw damping algorithm in an accident avoidance manoeuvre. The yaw rate, presented as lateral acceleration, is clearly smaller for the controlled system. Even so the body slip angle in the transient manoeuvre is smaller. Especially the peak-to-peak value is. The steer effort with yaw damping has improved. The steer angle magnitude itself is not significantly different; initial they are identical and the second is invisibly smaller, but the endurance for the controlled system is longer. The driver has more time, almost 0.2s.
Step Steer Response

For verification of the algorithm a step response test has been conducted with the simulation model. The results are shown in Figure 8. The steer angle step is applied at the same time with the same magnitude. The final lateral acceleration and the body slip angle are identical. The transients however, are clearly better for the yaw damping controlled vehicle. The reader is encouraged to compare the results with the results shown in Figure 4. Because this test is an open loop test the followed paths differ slightly.
Test Results

Test vehicle

The tests are performed with a Volvo XC90 AWD 2.5T. The standard Haldex LSC has been exchanged with Generation 4 based XWD. The torque capacity of the eLSD is 2.4 kNm, which is about the skid torque of one rear wheel.

Low-µ

On a low-µ surface at Haldex’ test facilities in Arjeplog, Sweden, many avoidance manoeuvres are carried out in order to verify the robustness and working of the yaw damping algorithms. The manoeuvres are performed both with and without active yaw damping algorithms. The time series for the hand wheel angle and the yaw rate, scaled with actual vehicle velocity, are presented in Figure 9 and Figure 10. In these diagrams we clearly see the benefit of scaling the yaw rate with actual vehicle velocity. Without doing so the time series are very hard to compare as yaw rate amplitude response declines with speed, despite the fact that the yaw gain may increase with vehicle speed in this speed range. In real life tests the velocity shows (often unintended) variation from one test to the other and would thus influence the results more than it will with the scaled signal.

Yet the problem; how to draw conclusions from these time series? An attempt is made to create a scatter plot for the performances of all individual tests as presented in Figure 11. The underlying computations are as follows. A Matlab script automatically finds the first and third peak of both the hand wheel angle and lateral acceleration (yaw rate). The third peak, which represents the return to straight ahead, is normalized by the first peak, the avoidance manoeuvre entrance level of the analyzed traces. The mean value of these normalized numbers with the yaw damping system off will be the reference point. This reference point is presented in the figure as a cross-hair, e.g. the mean value of the red triangles. The bleu circles represent the results with the yaw damping system on. The mean value in this case is indicated with a blue cross in the same diagram.
The result is a significant improvement in stability and steering effort, because the return amplitude of yaw rate is smaller and the accompanying hand wheel corrections are smaller too. The aim of the algorithms is to move the result towards the left-bottom corner, which it does. Do mind the log scale, it is a measurable improvement.
High-μ
On Haldex’ test facilities in Ljungbyhed, Sweden, high-μ tests are carried out. Similar manoeuvres are run as in Arjeplog. The data is again analyzed in the same way and presented in a scatter plot (see Figure 12). The improvement on high-μ turns out to be even larger.
Why these scatter plot analysis? Well, the high-μ results show clearly the benefit of the used method. With one measurement for each condition with the system on or off could proof the system to be outstanding or proof it to be a complete failure. There exists a result with the system off that is far better than the worst result with the system on: complete failure. On the other hand the best performance with the system on is incredible much better than the worst performance with the system off: outstanding performance. By a systematically analysis of the available measurement data a more realistic value of the improved vehicle performance by the yaw damping algorithms can be presented.

Conclusions
This presentation has proven the safety benefits of XWD. The benefits related to traction and limit handling performance are mentioned briefly. In total we can conclude that the Haldex XWD offers improved safety, increased performance envelope and increased traction ability for a reasonable on cost. The XWD system has a good cost benefit ratio.
Active Yaw Damping High-$\mu$ Measured Results

- Stable - Stability Index - Instable

\begin{align*}
\sigma_{\text{On}} &= 0.08 \\
\sigma_{\text{Off}} &= 0.36
\end{align*}

Figure 12 Scatter plot for high-$\mu$ results

References

Abbreviations

- ABS  Anti-lock Braking System
- AWD  All Wheel Drive
- ECU  Electronic Control Unit
- EDS  Electronic differential lock (Elektronische Differentialsperre)
- ESC  Electronic Stability Controller
- FWD  Front Wheel Drive
- LSC  Limited Slip Coupling
- LSD  Limited Slip Differential
- OEM  Original Equipment Manufacturer
- PreX Pre charge; Haldex pre-emptive system
- RWD  Rear Wheel Drive
- XWD  Cross wheel drive; combination of electronic controllable LSC and LSD
- AYD  Active Yaw Damping