Directional Stability of a Front Wheel Drive Passenger Car with Preemptive use of the Direction Sensitive Locking Differential (DSLD)

Mathias Lidberg[1][0000-0001-9506-3087] and Jonas Alfredson[2][0000-0002-8086-759X]

[1] Chalmers University of Technology, 412 96 Gothenburg, Sweden
[2] DsenseD technology AB, Bråta Ängsväg 6, 443 51, Lerum, Sweden
jonas.alfredson@dsensed.se

Abstract. The topic of this paper is the bigger picture of vehicle dynamics and handling characteristics of cars, with a focus on driving safety. More specifically, the directional stability gain obtained using the semi-active differential (DSLD) is experimentally verified in transient steering maneuvers using a prototype in a FWD Saab 9-3 Aero.

Stemming from the obvious need to enable low speed maneuvering, the open differential was developed already in the beginning of the automotive era and it has ever since maintained a position as the unquestioned solution almost irrespective of the driving situation. However, due to the inherent compromise between low speed maneuverability and high speed stability in road vehicle design, there are fundamental benefits of locking the differential more or less preemptively during for example expressway driving.

In recent decades electronic stability control (ESC) has become the go-to solution to improve driving safety by increasing the directional stability in transient maneuvers. However, similar but significantly greater stability gains can be accomplished by utilizing controllable differentials. All in all this means that the mentioned inherent compromise between maneuverability and stability can be circumvented and the overall handling characteristics of cars can be fundamentally improved.

Keywords: direction stability, yaw damping, sine with dwell, DSLD.

1 Introduction

The topic of this paper is the bigger picture of vehicle dynamics and handling characteristics of cars, with a clear focus on driving safety. The main outcome is the experimental verification of the substantial improvements of the directional stability of a front wheel drive (FWD) passenger car in transient maneuvers, through the preemptive use of the semi-active DSLD [1]. Previously, the influence of the DSLD on handling performance in transient cornering has been illustrated using simulations [2].

1.1 The role of the differential

Stemming from the obvious need to enable low speed maneuvering, the open differential was developed already in the beginning of the automotive era and it has ever since maintained a position as the unquestioned solution almost irrespective of the driving situation. The open differential divides the incoming torque evenly between its two output shafts by letting their individual rotational velocities differentiate freely. This means that the longitudinal forces of the two tires of an axle will always be equal, meaning that they can have no influence on the yaw moment of the vehicle, which then will be affected by the lateral tire forces alone. This feature of the open differential makes it the perfect solution at least when driving in tight corners at low speeds and with low to moderate input torque.

When considering the role of as well as the actual need of the differential it is however, of crucial importance to realize that the amount of (zero longitudinal force) differentiation for any specific level of lateral acceleration is a function of longitudinal velocity squared, as shown in Fig. 1. As can be deduced from the graph the actual need for the differentiation is strongly negatively correlated to increased vehicle speed, this is due to the fact that the minimum cornering radiuses that can be negotiated likewise increases in proportion to the square of the vehicle speed.

Due to lateral acceleration, which is an unavoidable consequence of taking corners at speed, the vertical load of the wheels will be differentiated meaning that the ultimate force generating capacity as well as the longitudinal tire stiffness will vary between corner inner and corner outer wheels. When applying longitudinal tire forces this difference in longitudinal stiffness means that the actual differentiation will vary depending on the level of lateral load transfer and the amount and direction of the longitudinal tire forces. Taking all of these considerations into account mean that, not only is there no real need for differentiation when the vehicle speed is high enough but rather that we will be better off with a locked differential or a differential that will self-lock as soon as differentiation tries to start, as is the case with the DSLD in its self-locking mode. This means that the car will be more linear with respect to different levels of longitudinal acceleration/deceleration in cornering situations, i.e. the differentiated longitudinal tire forces from the locked differential will tend to compensate for the longitudinal load transfer based differences in handling balance that normally exist with an open differential in the same driving situation. Apart from this, another important benefit of the locked differential, is that if and when attempting really aggressive maneuvering as in an avoidance maneuver there will be a big stabilizing effect derived from the differentiated longitudinal tire forces helping to prevent the car from spinning out.

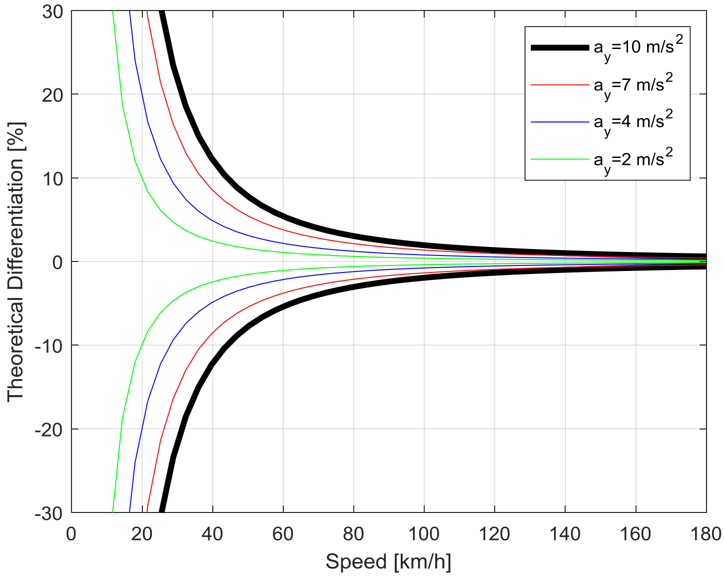


Fig. 1. Theoretical (zero input torque) differentiation (@a_y=2, 4, 7, 10 m/s^2).

1.1 Controlling the ability to differentiate instead of relying on Electronic Stability Control (ESC)

By not allowing free differentiation when a car is turning, the tires of each drive wheel will get differentiated longitudinal forces, most of the time this will lead to a lower yaw rate and therefore more stability. Thanks to the reactive nature of controlling the relative rotational speed of the wheels within an axle, controllable differentials can be used in a more preemptive way than brake based stability control systems such as ESC, resulting in faster reaction times as well as less intrusive interventions as there is no net speed decrease involved due to the fact that the yaw resisting moment comes from actually redistributing longitudinal forces in between the drive wheels instead of just producing negative longitudinal tire forces at a corner outer wheel. The mentioned reactive nature of utilizing a locked differential is partly due to the simple fact that, the more yawing motion there is the more yaw resistance there will be but also to the fact that the yaw resisting moment gets modulated by the instantaneous longitudinal stiffness of each drive wheel tire resulting from lateral load transfer. This also means that the practice of locking the differential has a high degree of self-regulation which mean that there is far less need for advanced control to achieve the wanted result as compared to regulating the yawing motion of the vehicle by utilizing the brakes.

Also, when locking a differential in transient maneuvers there will actually be some limited amount of differentiation taking place even after the locking of the differential itself when measured at the drive wheels, this is due to a wind up of the drive shafts, acting as a torsional spring which will get released again in the subsequent steering input in the opposite direction and or in the eventual straitening of the vehicle path. This springing action of the drive shafts is very powerful in reducing the delay between the steering input and the actual yawing motion in between consecutive steering inputs, making the car feel much more responsive and easy to manage during critical avoidance maneuvers. This feature is of course physically impossible to achieve with brake based stability systems.

Within the industry the electronically controlled limited slip differential (eLSD) has been developed. However, due to the increased hardware cost the big commercial break-through for eLSDs has not happened yet. Also, the way in which eLSD systems have been controlled up until now means that their role have been more or less limited to improve other aspects of vehicle dynamics than the ultimate directional stability. ESC systems have also been regarded as more safety critical which means that the ESC system has been mandated to take precedence in critical driving maneuvers such as evasive maneuvers at speed.

However, as shown in this work, a more preemptive use of the stabilizing properties of locking a differential such as eLSD or DSLD, significantly postpones the need for ESC interventions and in most situations even render the help from a brake based stability control system unnecessary. The results show that the stability improvements in many cases substantially surpass those achieved with the ESC system.

Finally, all of this can be achieved in spite of and thanks to less complicated and faster reacting feed forward control strategies.

2 Assessment of lateral stability and responsiveness using the sine with dwell maneuver

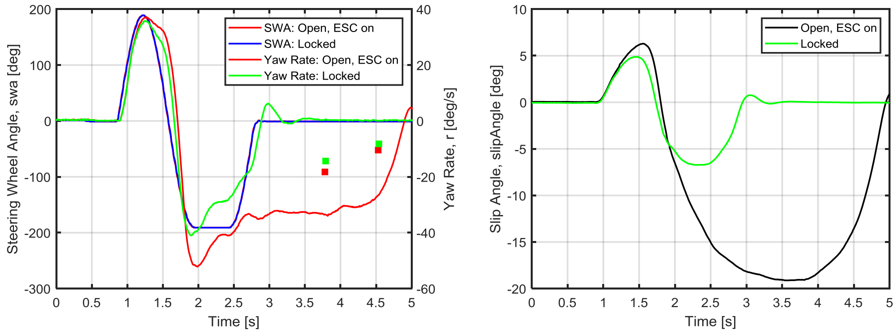
A prototype of the DSLD is implemented in a FWD Saab 9-3 Aero (see Fig. 2) for the experimental verification and quantification of the stability gain obtained by locking the differential (DSLD) as compared to the behavior accomplished by the brake based stability control system (ESC). The standardized (open loop) test maneuver sine with dwell is performed using a steering robot (Fig. 3) and a (closed loop) double lane change maneuver is carried out with a test driver.

Fig. 2. The DSLD prototype.

Fig. 3. Steering robot.

2.1 Sine with Dwell (Open Loop)

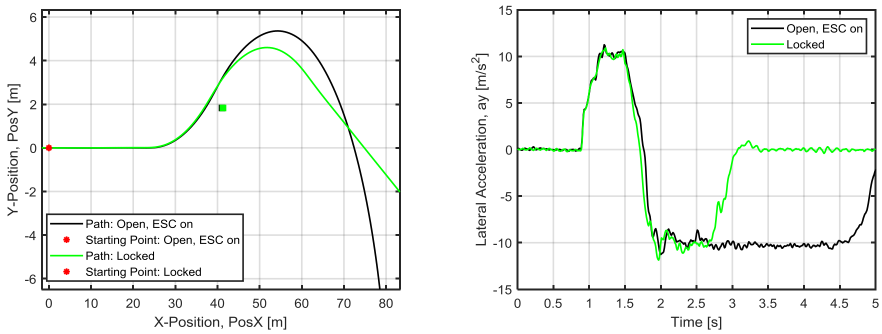
The yaw response of the vehicle with locked differential is compared to that of the vehicle with open differential with ESC on in Fig. 4a. The body side slip angles for the same maneuver are shown in Fig. 4b. In Fig. 4c and d the vehicle path and lateral acceleration are shown, respectively.



a. SWA & Yaw Rate

b. Body side slip angle

Fig. 4. Sine with dwell maneuver with 190 deg steering amplitude (80 kph).



a. Vehicle path

b. Lateral Acceleration

Fig. 5. Sine with dwell maneuver with 190 deg steering amplitude (80 kph).

2.2 Double Lane Change (Closed Loop)

The double-lane change course used for an evasive maneuver is shown in Fig. 6. The vehicle entry speed is adjusted to both the vehicle handling limits and the prevailing track conditions.

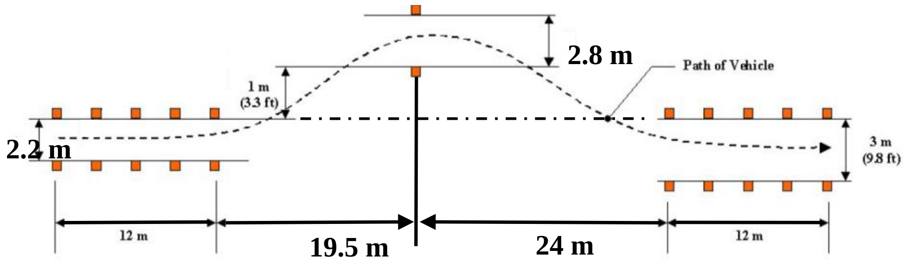
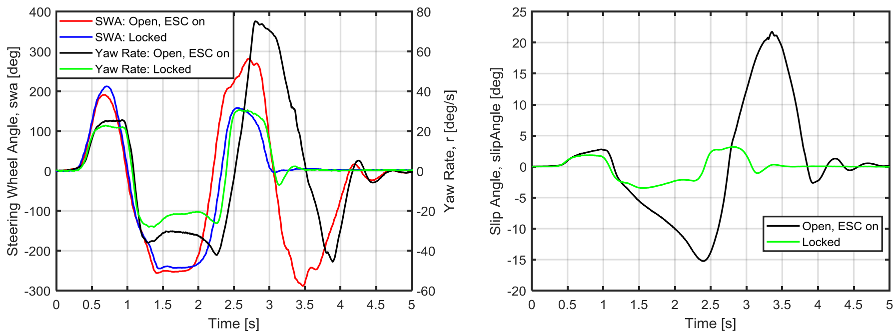


Fig. 6. Double lane change maneuver with entry speed of 77 kph.
Throttle off in 5th gear.

The Emergency Avoidance Performance Index (EAPI) is used as the key performance indicator for the DLC maneuver [4]. The EAPI is determined as the area which is integrated along the curve of steering angle with respect to the yaw rate. It is generally known that the better the vehicle handling quality, the smaller the value of EAPI [4].

$$S = \frac{1}{2}\int_0^T \left(\delta_{sw}{}^2 + r^2\right) d\left(\tan^{-1}\left(\frac{r}{\delta_{sw}}\right)\right) = \frac{1}{2}\int_0^T \left(\delta_{sw}\,\dot{r} - \dot{\delta}_{sw}\,r\right)dt \tag{1}$$

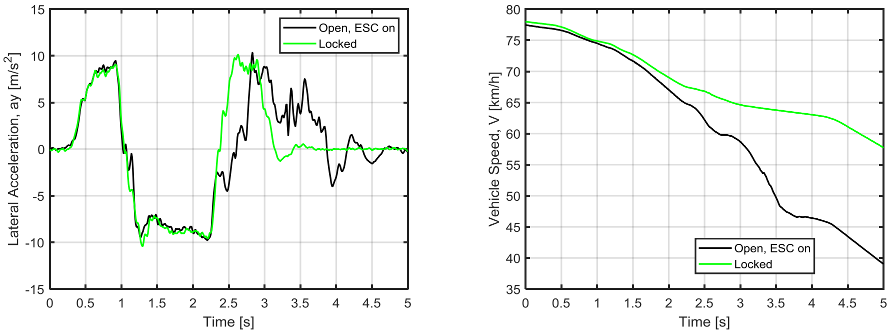
The yaw rate and body slip angle are shown the double lane change maneuver in Fig.6a and b.



a. SWA & Yaw Rate **b.** Body side slip angle

Fig. 7. Double lane change maneuver with entry speed of 77 kph.
Throttle off in 5th gear.

The lateral acceleration and the vehicle speed are shown for the double lane change maneuver in Fig. 8a and b.



a. Lateral Acceleration

b. Vehicle Speed

Fig. 8. Double lane change maneuver with entry speed of 77 kph.
Throttle off in 5th gear.

The value of the EAPI is reduced from 17 to 2.4 rad^2/s for the vehicle with locked differential compared to the vehicle with open differential and ESC on. This indicates a better emergency avoidance performance of the driver-vehicle system for the vehicle with DSLD [4].

Conclusions

In this paper the comparison is limited to open and locked differentials. Based on these results, preemptively locking the differential is advocated for higher speed intervals as in expressway driving. However, for the medium speed interval the idea is to trigger the locking of the differential by feed-forward control based on steering wheel rate and amplitude [3], meaning that the differential will be open for differentiation during the first instant of a steering maneuver only to lock as soon as the locking conditions are fulfilled for the present steering maneuver.

The preemptive use of the DSLD in transient maneuvers leads to a wind up of the driveline components between the drive wheels, this wind up acts as a torsional spring assisting in the dynamics during the subsequent straightening of the steering wheel and in the potential new steering input in the opposite direction. All of this means that the effect of the locked differential is to oppose excessive yawing motion and also to speed up the willingness of the vehicle to adhere to the drivers input in consecutive steering inputs.

References

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