THE DIRECTION SENSITIVE LOCKING DIFFERENTIAL (DSLD)

- EXPERIMENTAL EVALUATION OF
A PROTOTYPE FOR A FWD SAAB 9^3 Aero V6

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Background

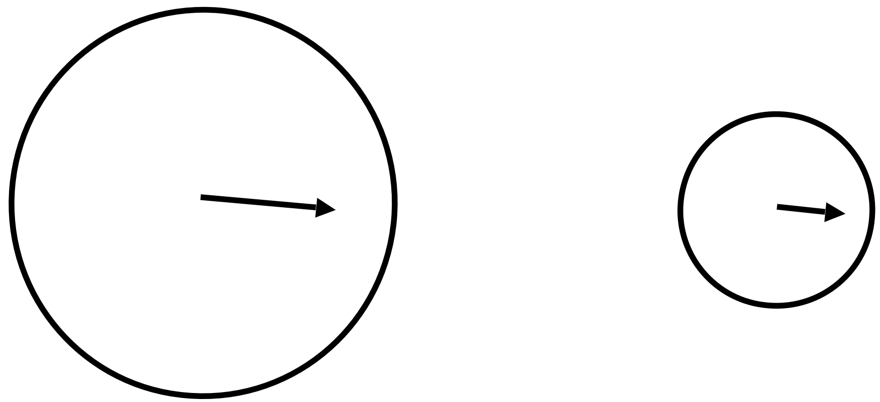
Steering kinematics and lateral force distribution for an axle:

- The lateral load transfer during cornering increases (decreases) the normal force of the corner outer (inner) wheel.
- Due to the steering kinematics, the slip angles of the wheels of one axle will be almost equal side to side.
- The lateral force of each tire is then proportional to the normal force of that tire.

Background

Steering kinematics and lateral force distribution for an axle

Conclusion: The kinematics of the steering system causes the wheels of an axle to contribute to the total lateral force of the axle in accordance to their ability.



Front axle in cornering, with no longitudinal forces

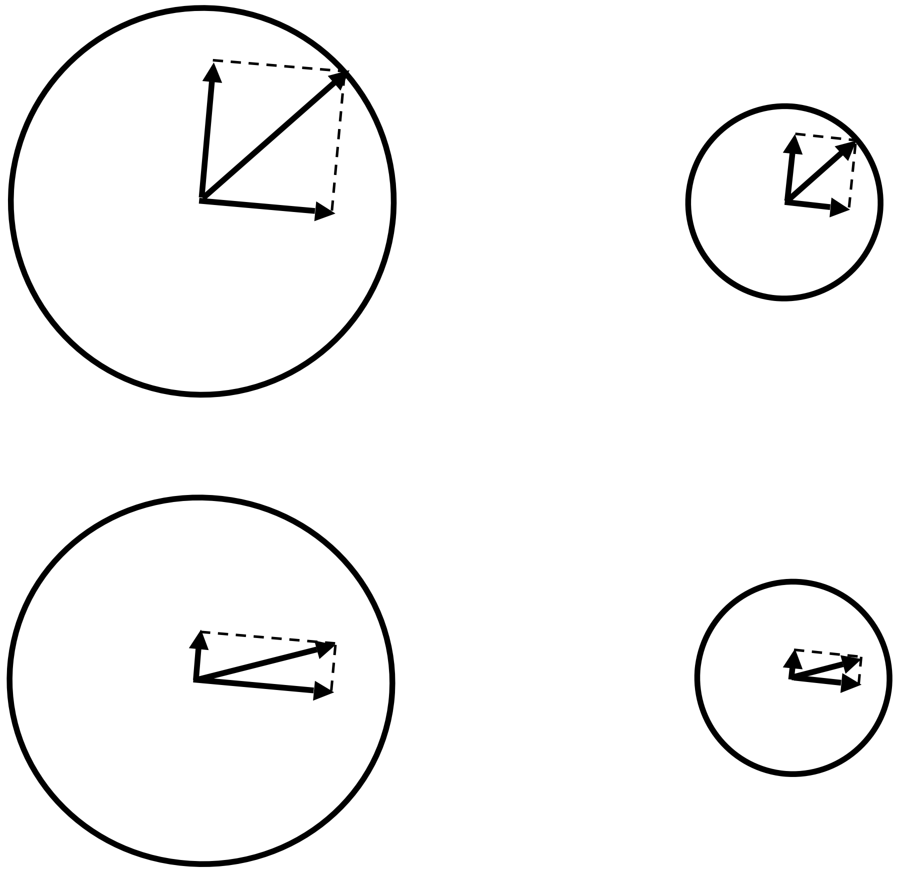
Background

Ideal differential for longitudinal force distribution for an axle:

- Taking the traction circle into account it would be beneficial to distribute the longitudinal forces in a similar way.
- To get equal longitudinal slip at both drive wheels of a driven axle requires a forced differentiation equal to the theoretical differentiation (track width/cornering radius).
- Forced differentiation in general can be accomplished by a torque vectoring system, e.g. redistributing drive force from a slower to a faster rotating wheel.

Background

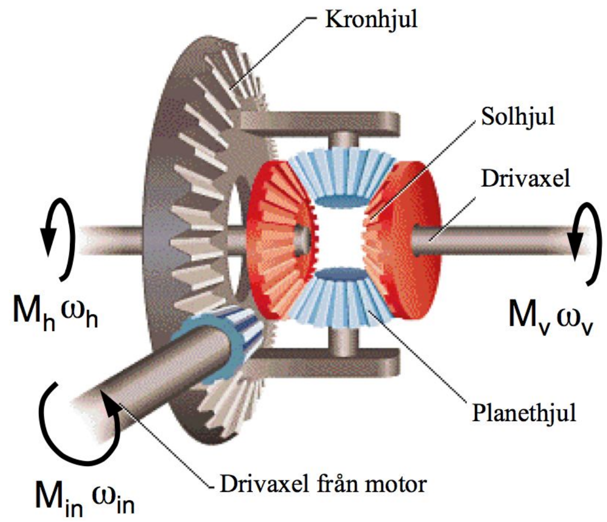
Ideal differential for longitudinal force distribution for an axle.



Front axles in cornering, with different amounts of longitudinal forces

The Limitations of the Open Differential

- The majority of cars are equipped with open axle differentials.
- The open differential divides the incoming torque evenly between the two output shafts by letting them differentiate freely.
- Individual slip rate of each drive wheel can vary almost infinitely.



The Limitations of the Open Differential

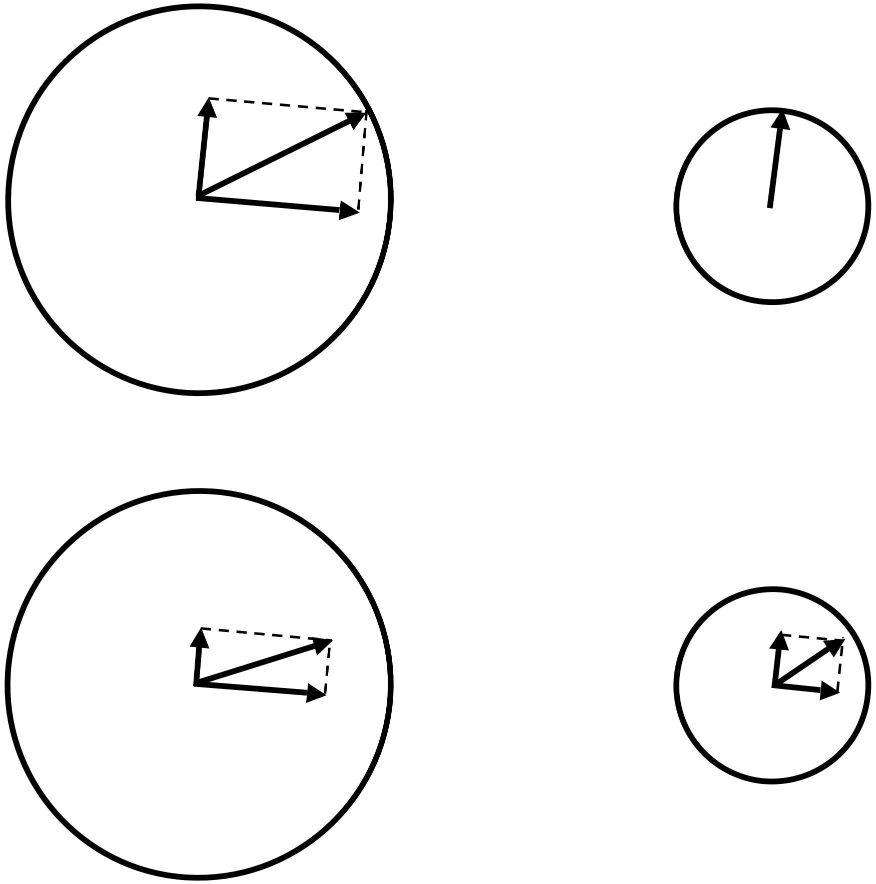
- The open differential only give the drive wheels the same individual rotational speed as the previously mentioned ideal differential when there is no incoming torque to the differential.

- For a positive torque the differentiation will be less than the theoretical differentiation.

- For negative engine torque or braking the differentiation will exceed the theoretical differentiation.

The Limitations of the Open Differential

Conclusion: The open differential forces both drive wheels to contribute equally to the generation of longitudinal forces without taking their individual capability into consideration.



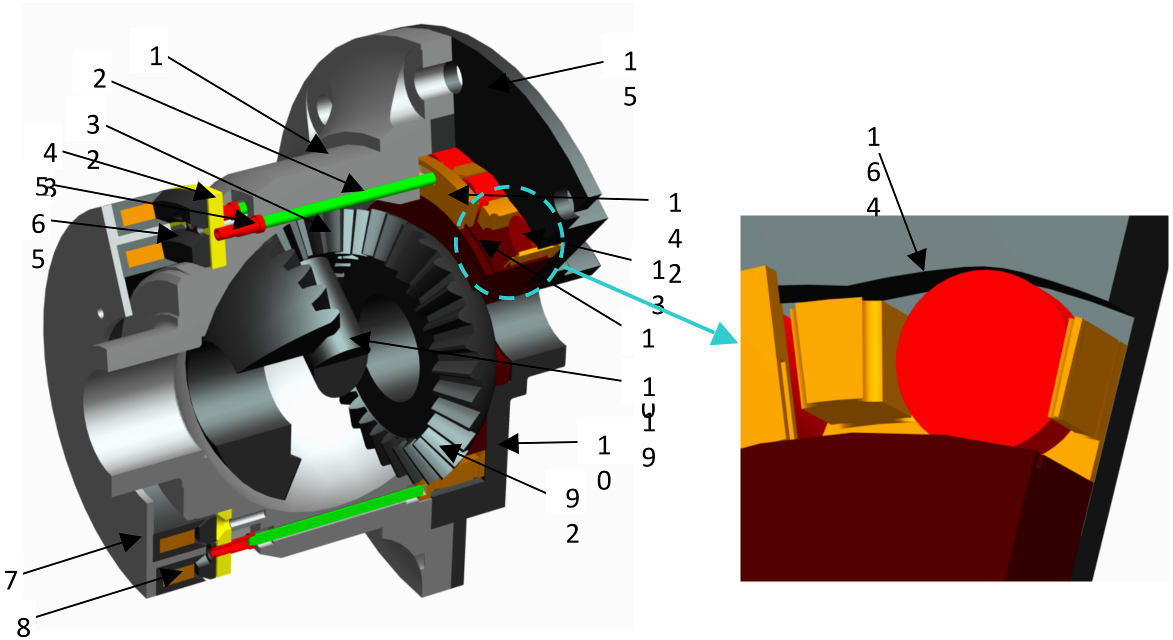
The Cross-over point

- The differentiation is changing direction when the difference of the slip of the inner wheel and the outer wheel is as big as the theoretical differentiation.
- The point where the differentiation is changing direction can be called the cross-over point, because at this point the locked differential changes from producing an understeering- to an oversteering yaw moment.
- At the cross-over point the drive forces of the axle are equal.
- A differential that is open below the cross-over point and locked above it can avoid many of the inherent weaknesses of the open differential.

The Direction Sensitive Locking Differential (DSLD)

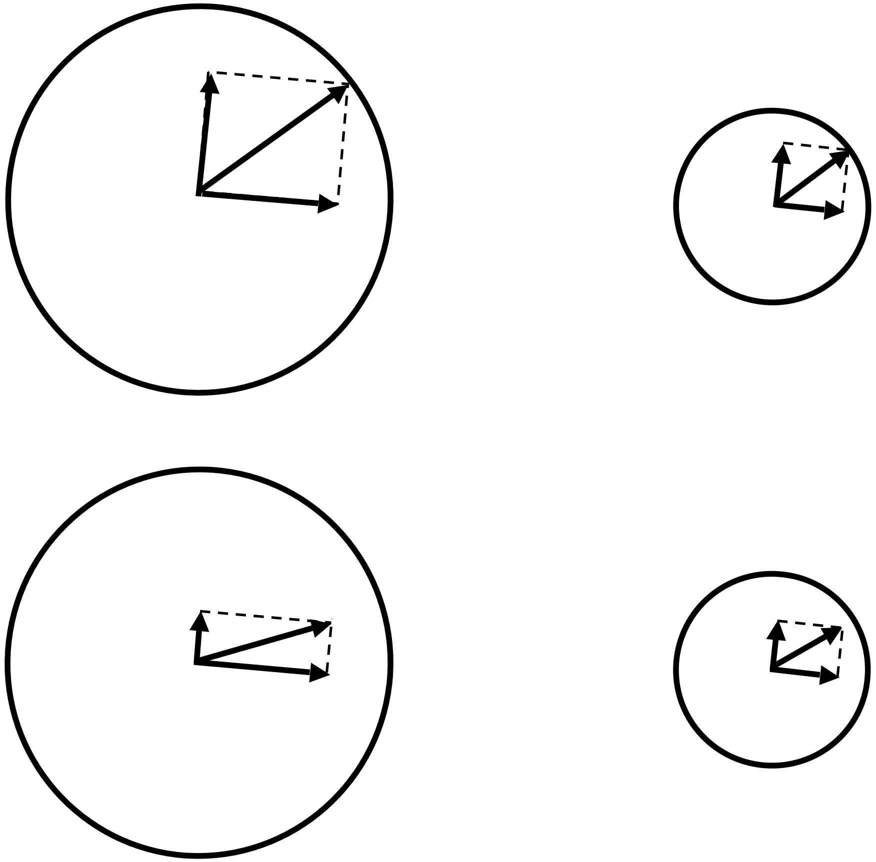
The DSLD is designed to react to the cross-over point by switching between the open or locked position.
This gives the DSLD the ability to give the same basic advantages that electronically controlled limited slip differentials (eLSD) can give. But with less need for advanced control, less complicated and hence cheaper mechanical design.

Working Prototype of DSLD:



The Direction Sensitive Locking Differential (DSLD)

By default, the DSLD works like an open differential below the Cross-over point. Above the cross-over point the DSLD locks and thereby lets both wheels contribute to overall force generation in close accordance to their individual capability.



The Direction Sensitive Locking Differential (DSLD)

- The DSLD can also be controlled to not allow differentiation below the cross-over point in order to give yaw damping for example in collision avoidance maneuvers.
- The DSLD can be used more preemptively because it gives yaw damping without the unwanted net speed decrease associated with ESC interventions.
- Additionally, the yaw damping from a locked differential (such as the DSLD or the eLSD) is mechanically self regulating (the more yaw motion the more yaw damping).

Basic DSLD Control Strategies

The main control of the DSLD is divided into two control modes:

- Cornering Performance Mode (default)

  Self locking above the cross-over point gives a yaw moment that counteracts the inherent understeer tendency.

- Yaw Stability Mode

  Gives a yaw moment that counteracts the yaw motion.

The yaw stability control mode can be entered for negative engine torque indicated by throttle position or steering reversals.

Special Control Mode:

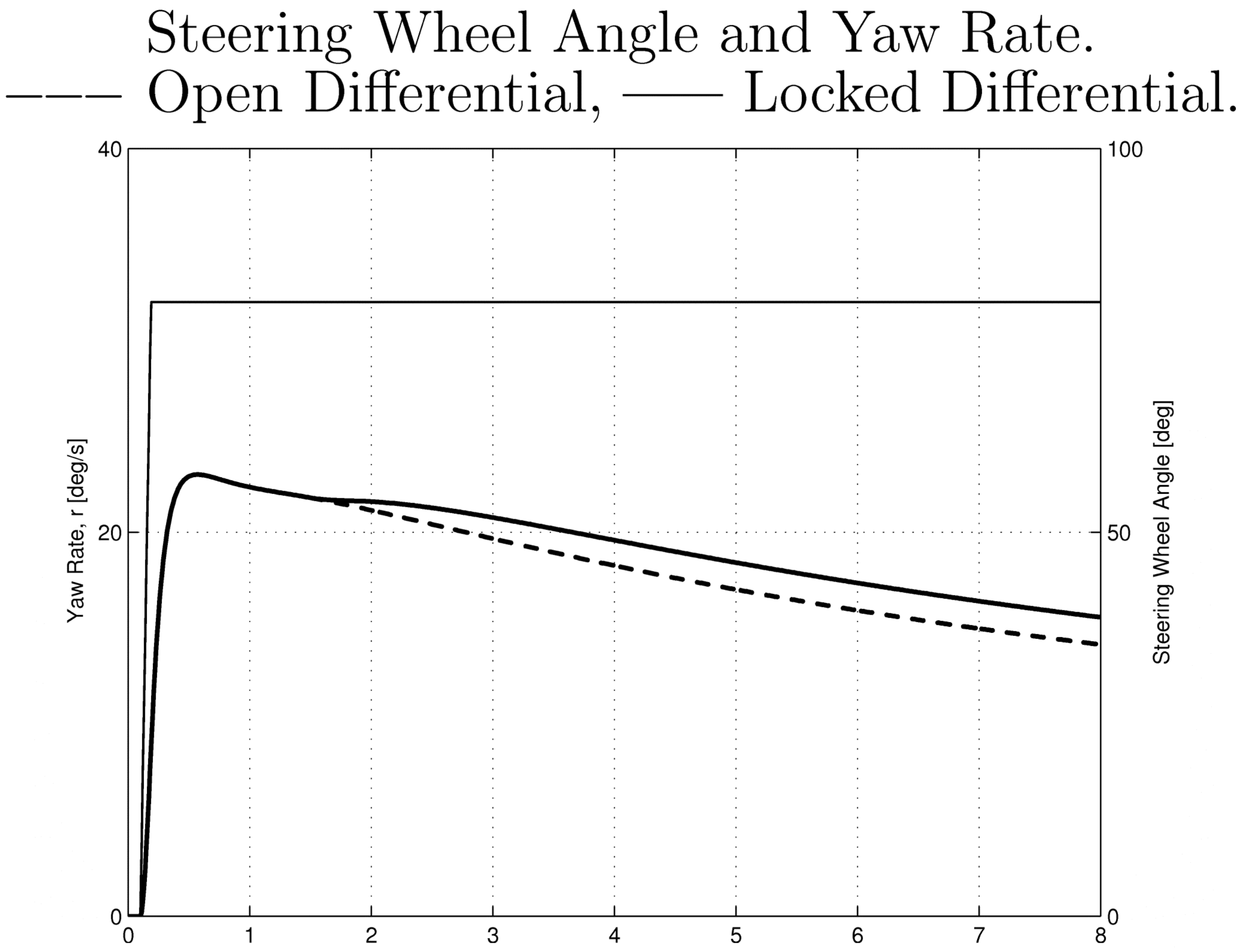
- Brake Based DSLD Control

  Unlocking of the DSLD from its locked state in yaw stability mode can be accomplished by a brief brake pulse at the corner outer wheel.

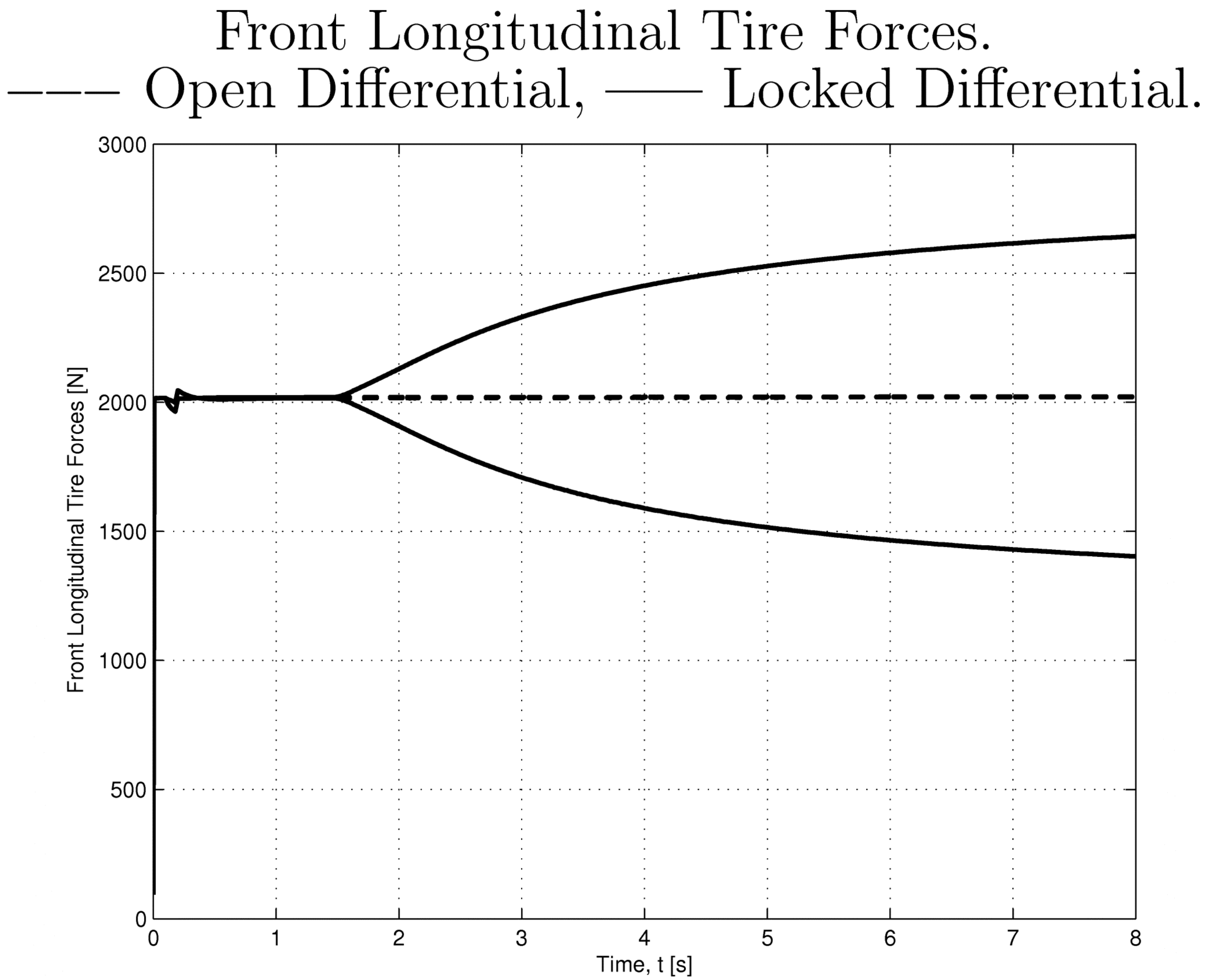
Transient Cornering Simulations

- The performance of the DSLD with various control strategies is illustrated for transient cornering maneuvers.
- All the maneuvers are simulated with open loop inputs with the FWD SAAB 9^3 in third gear on a high μ surface with ESC inactive.
- The maneuvers are performed with an open differential as a reference (indicated by dashed curves) and the DSLD in various control modes (indicated by solid curves).

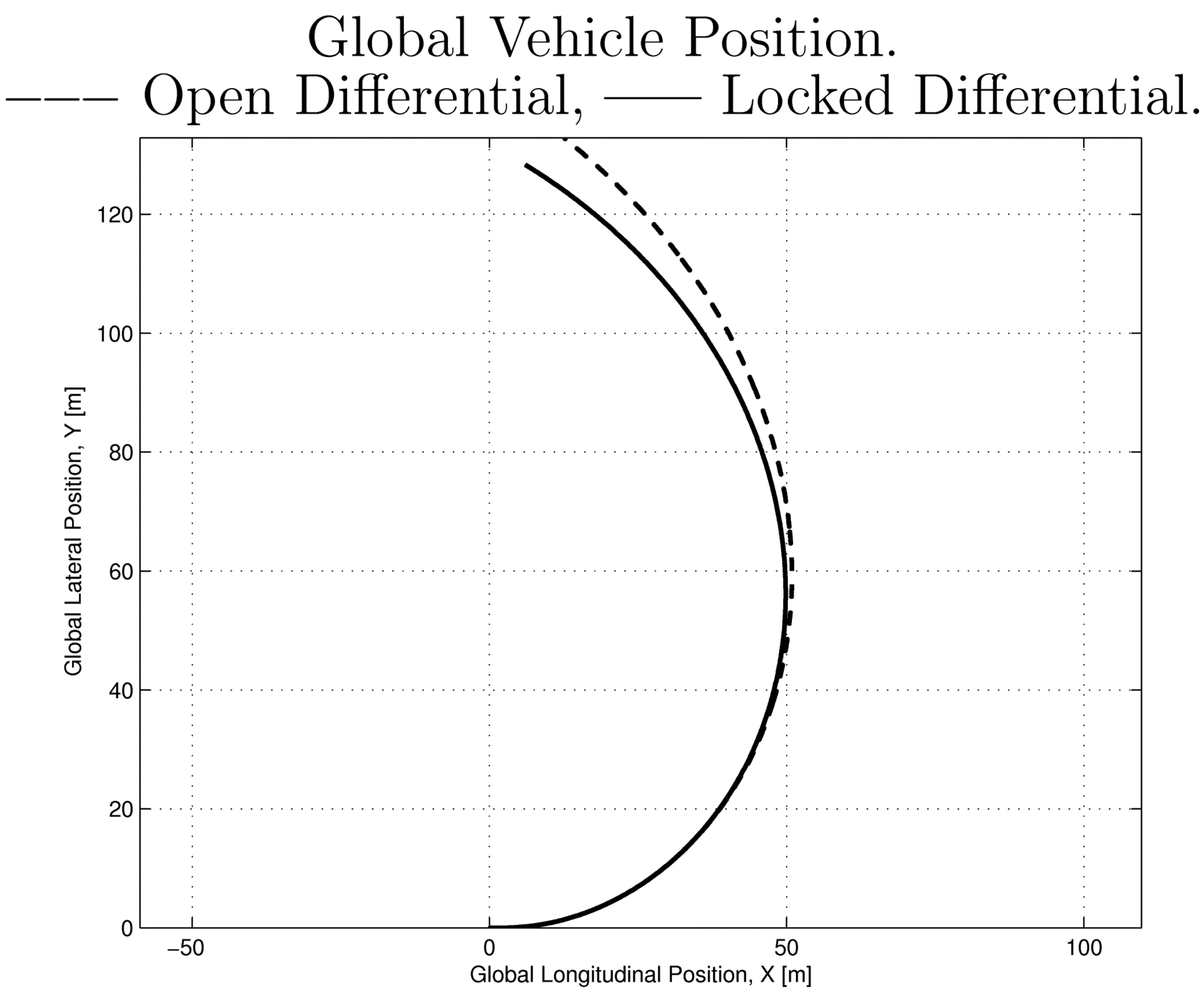
Step Steer in Throttle On



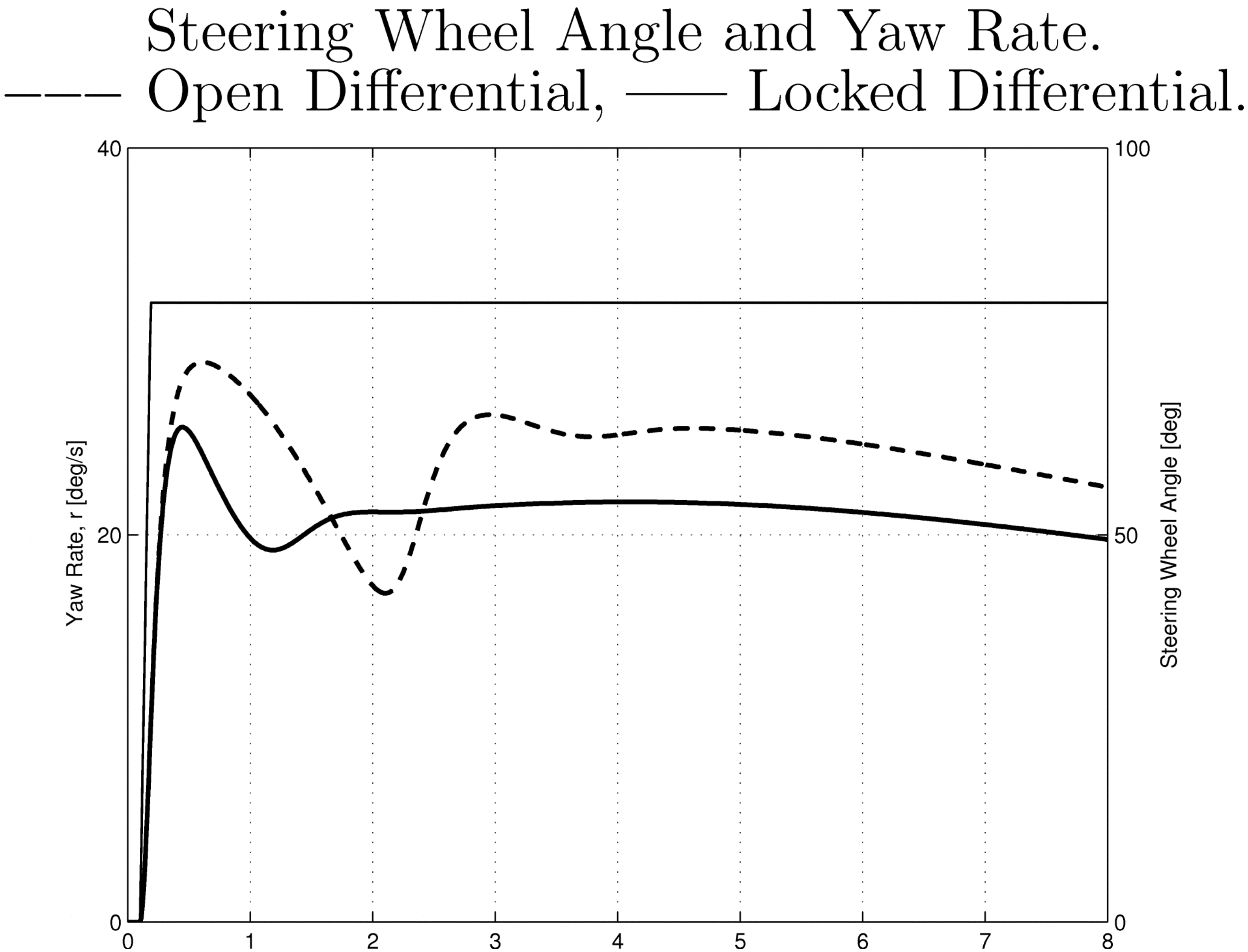
Step Steer in Throttle On



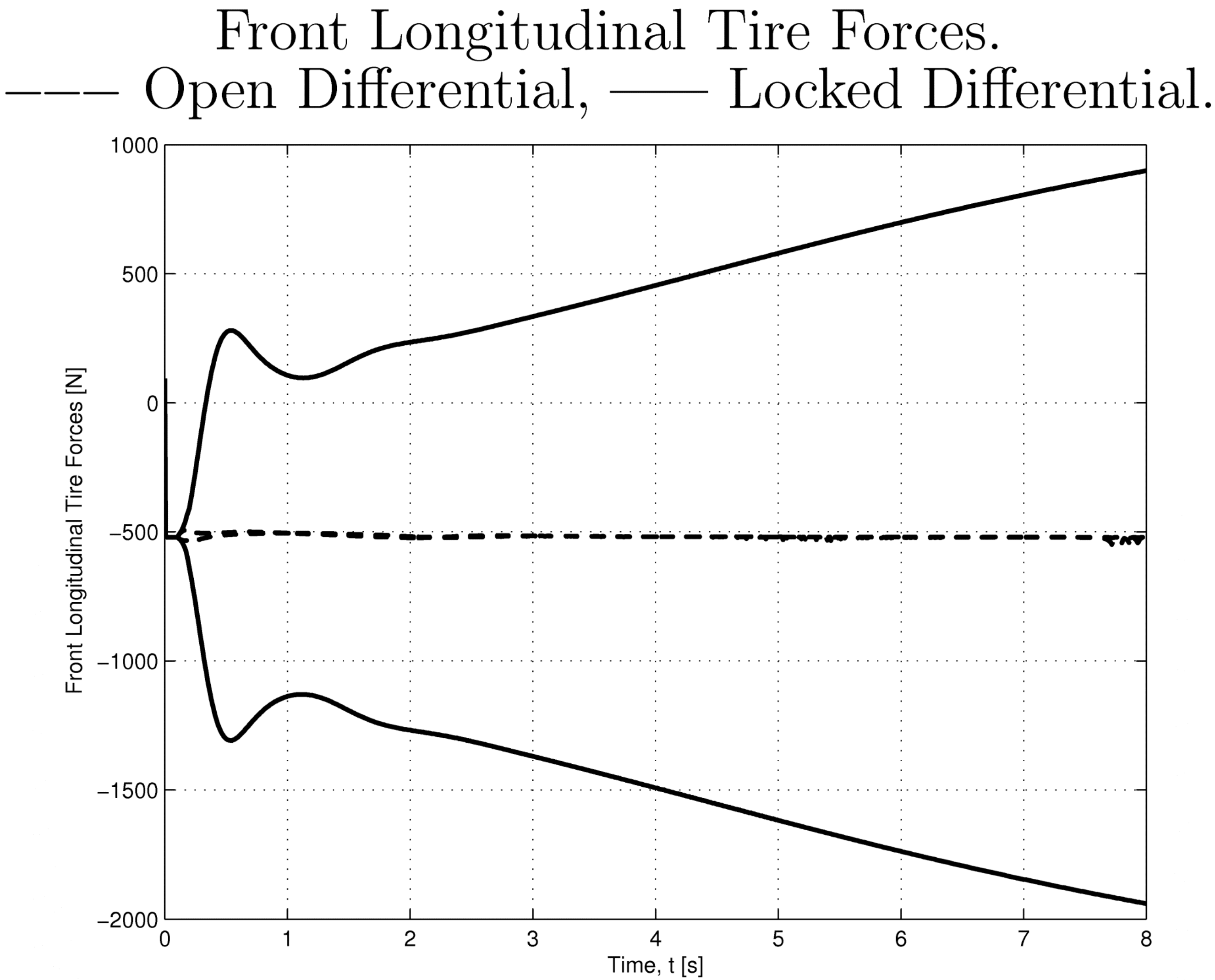
Step Steer in Throttle On



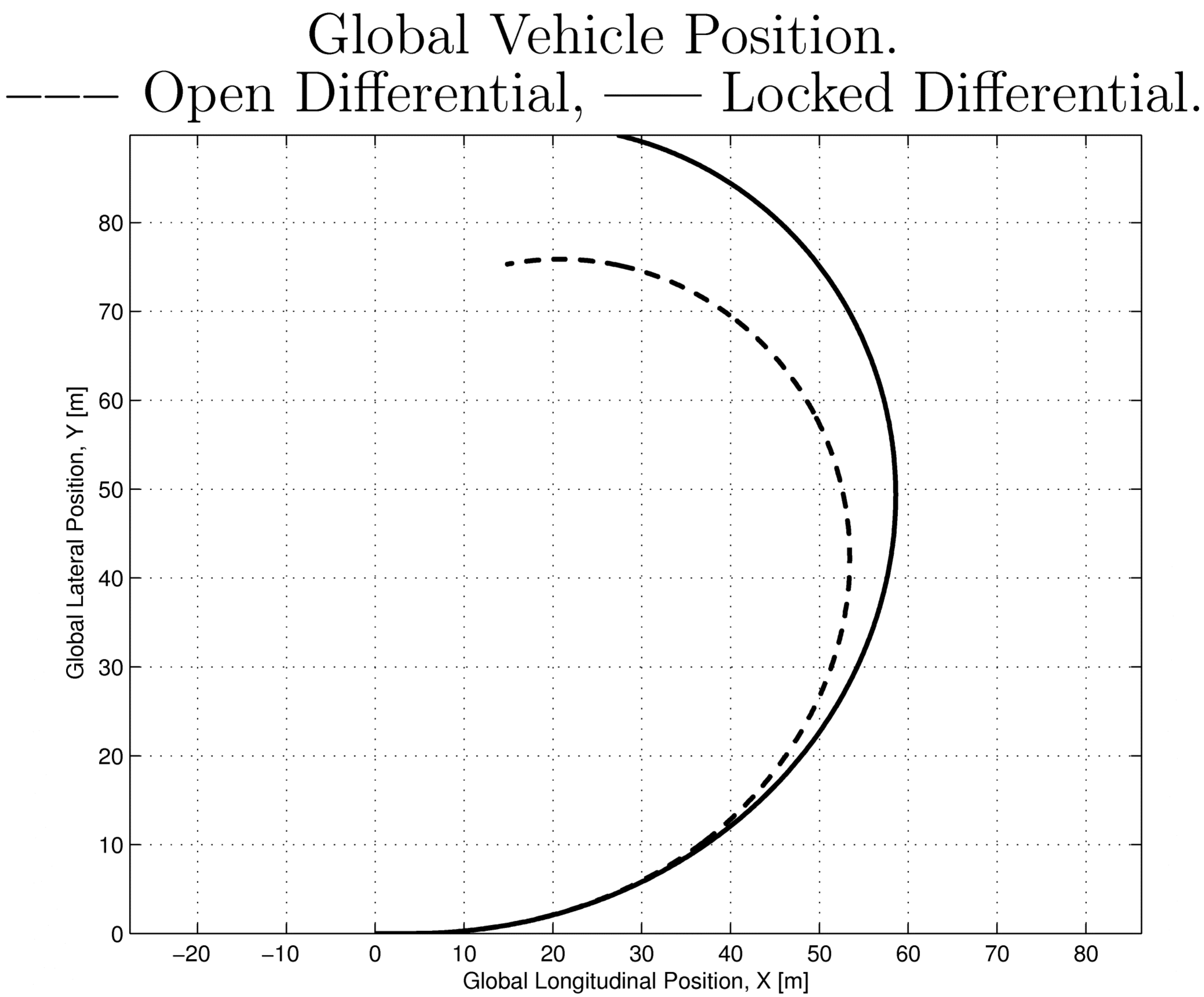
Step Steer in Throttle Off



Step Steer in Throttle Off

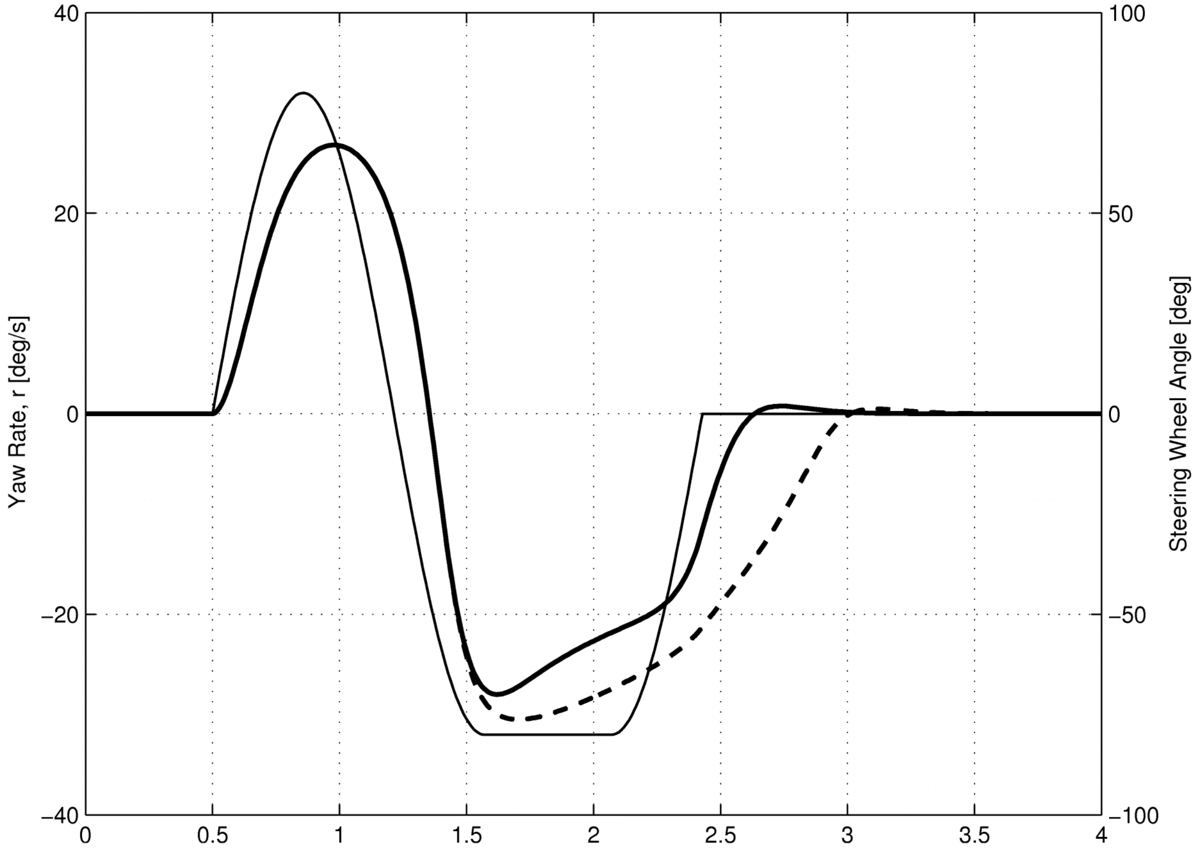


Step Steer in Throttle Off

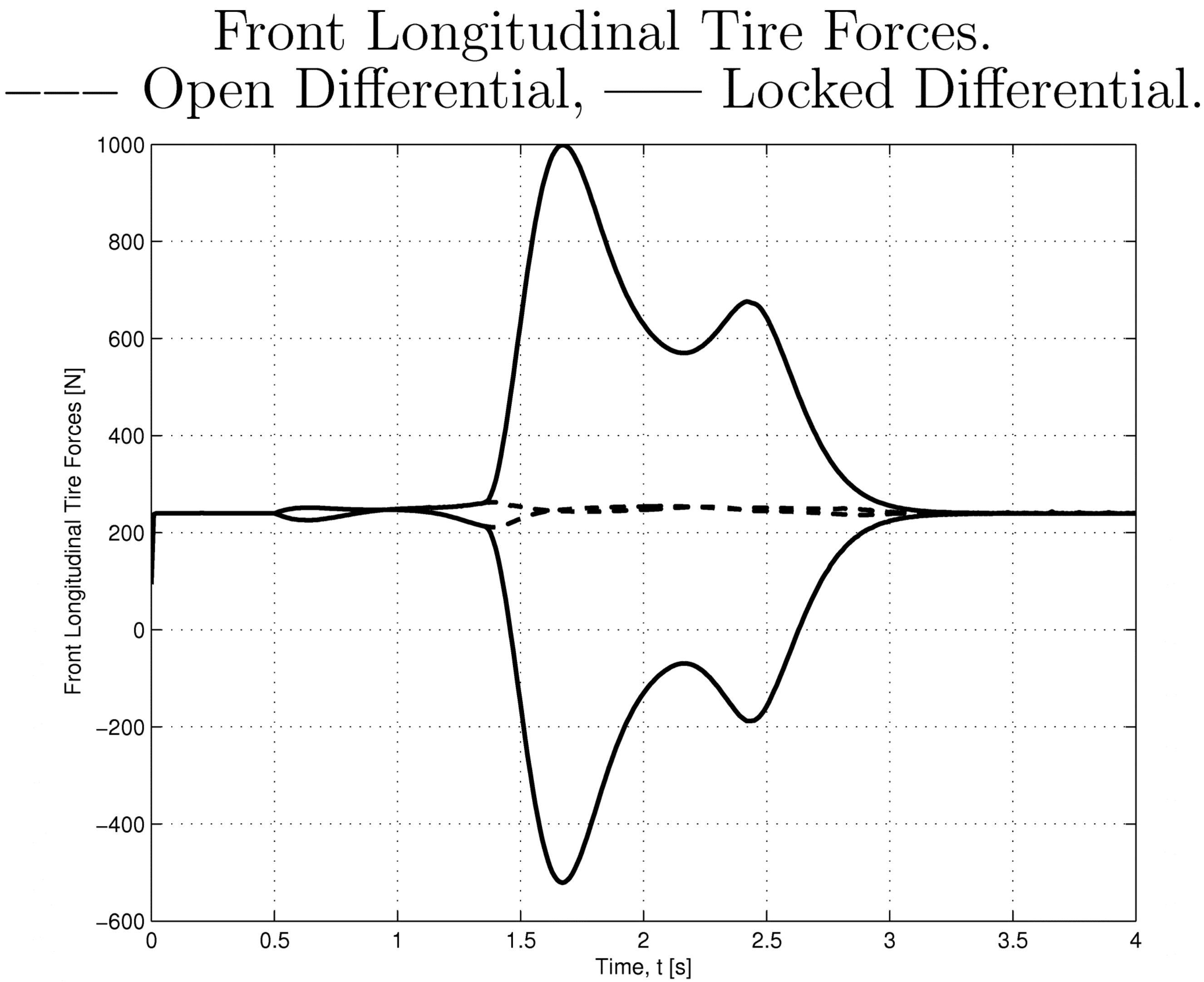


Sine with Dwell

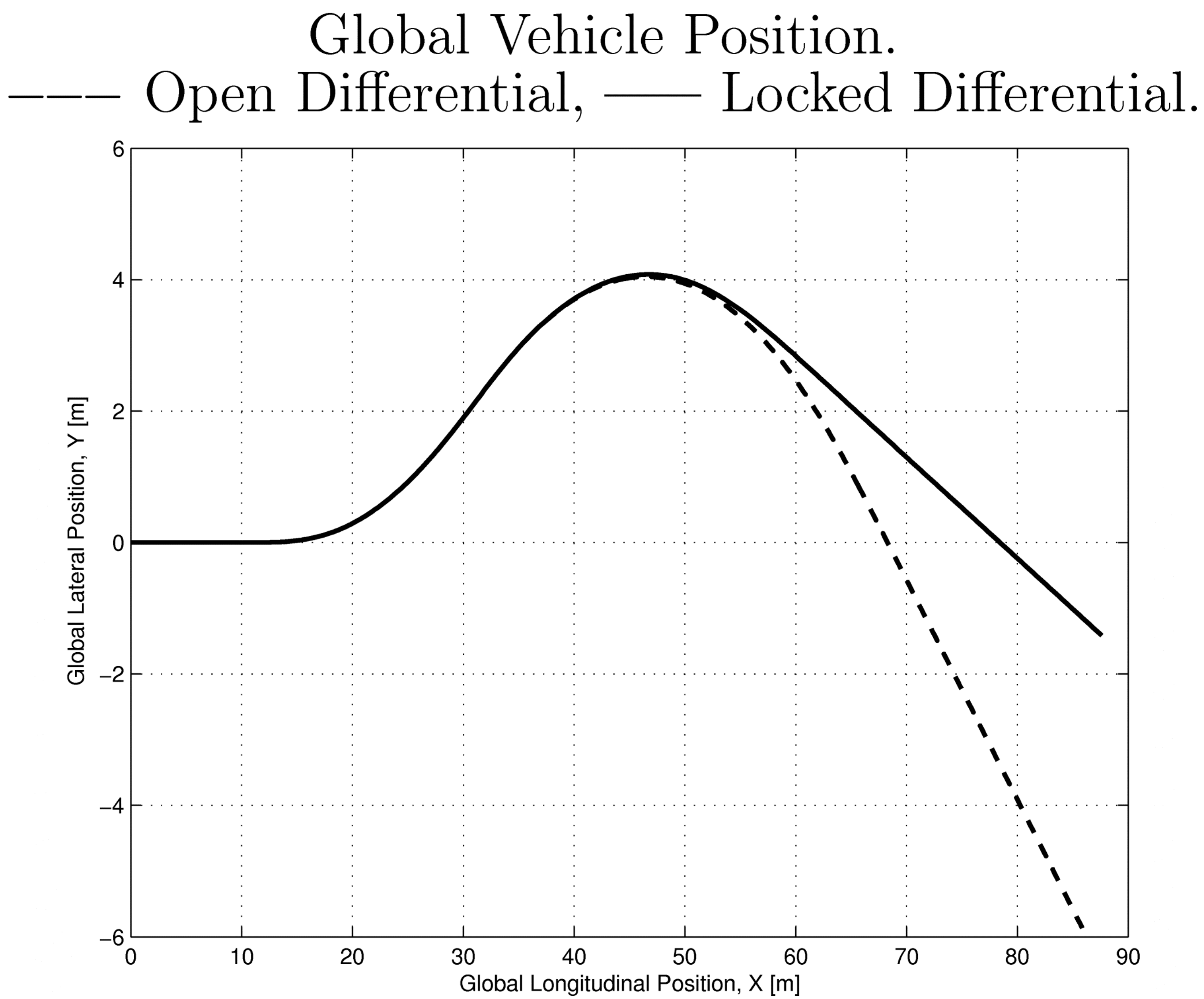
Steering Wheel Angle and Yaw Rate.
——— Open Differential, —— Locked Differential.



Sine with Dwell

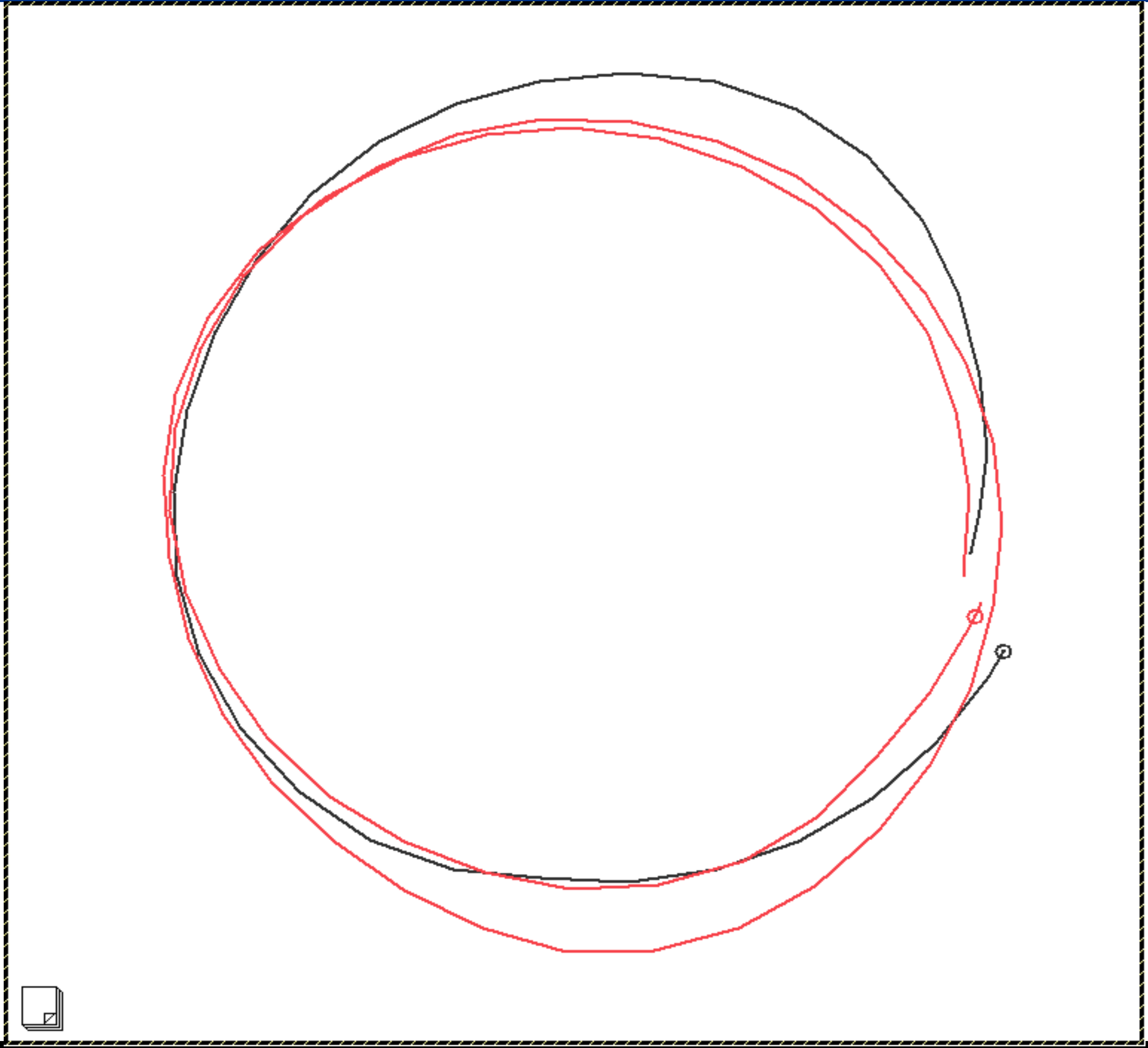


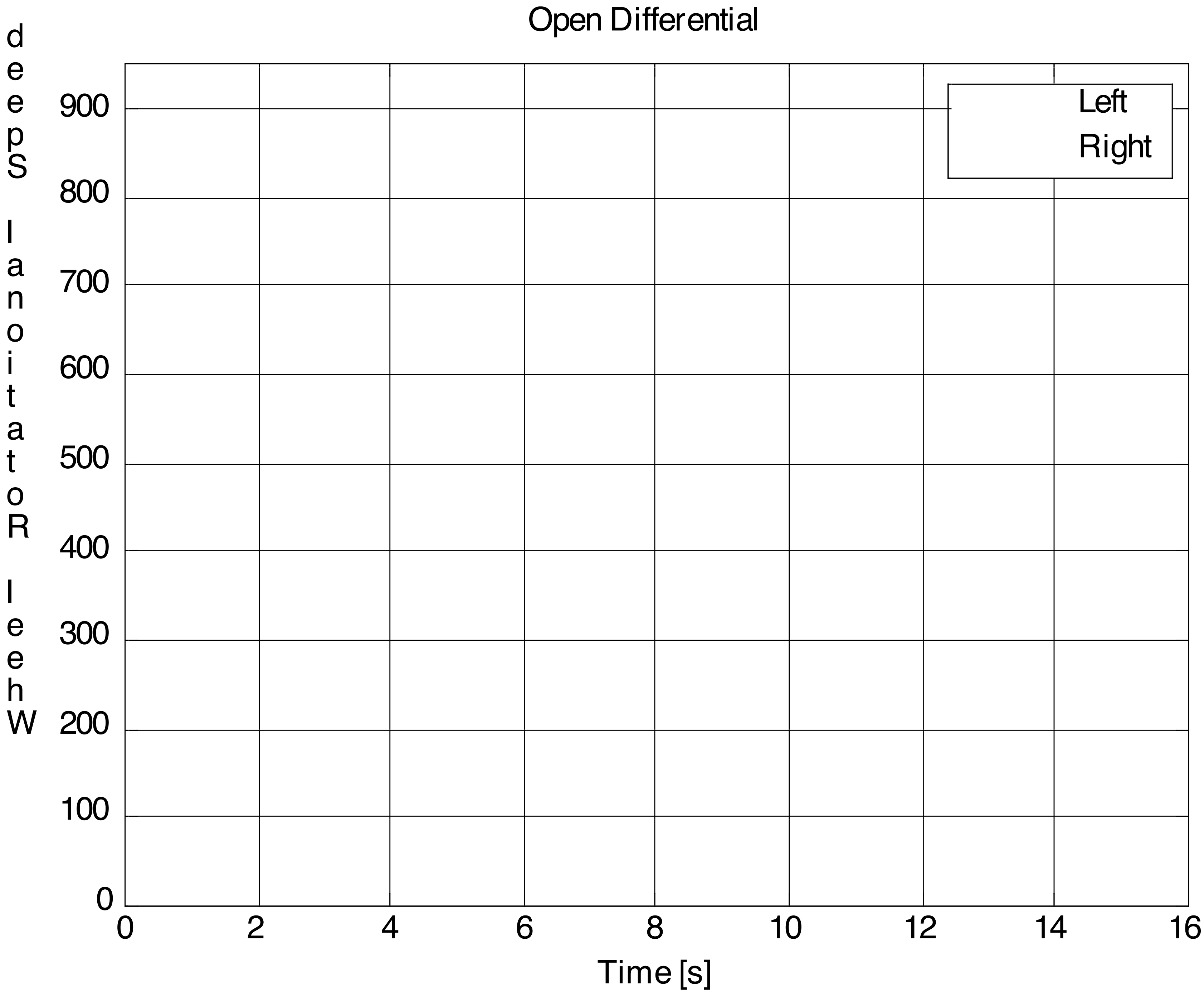
Sine with Dwell

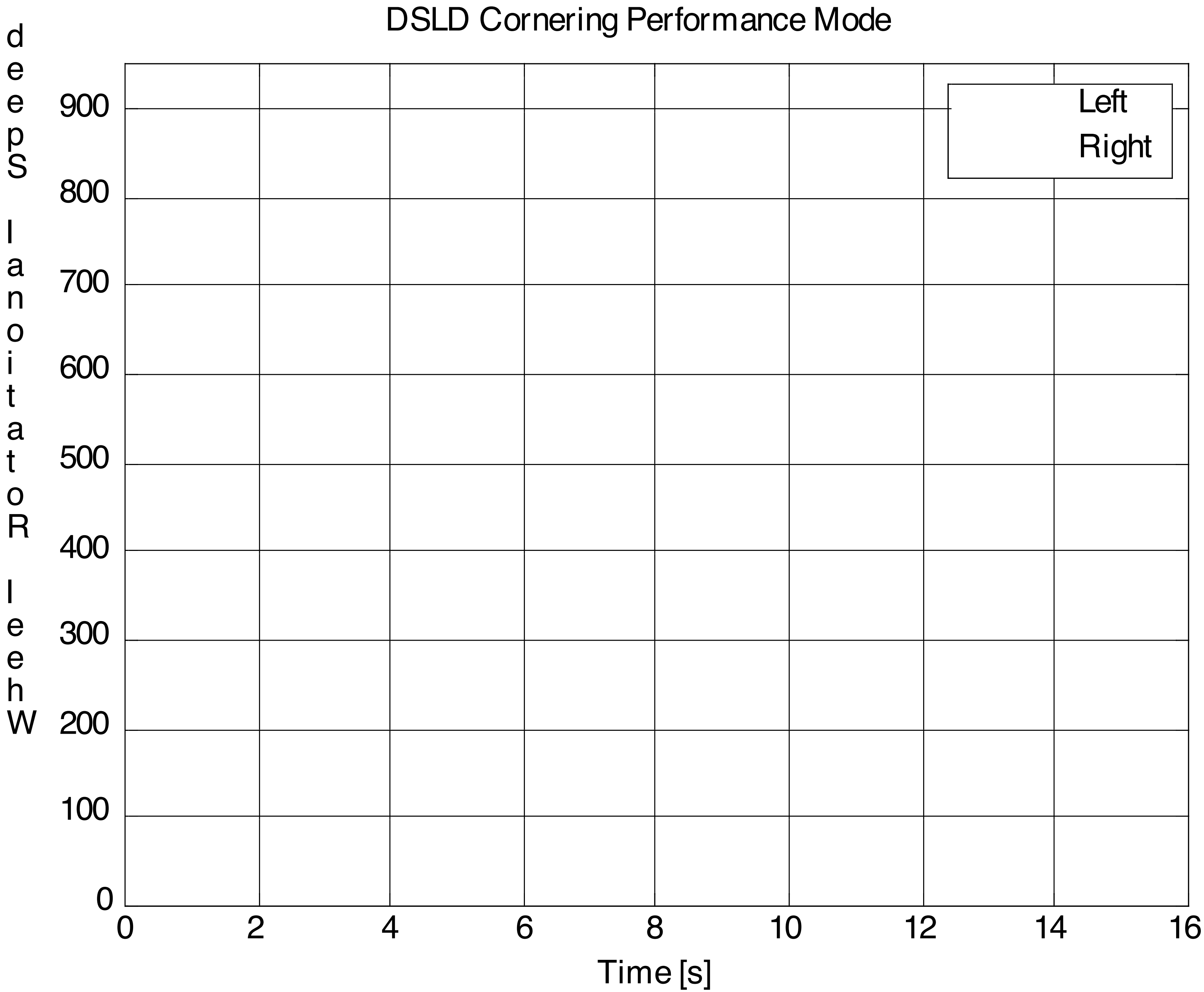


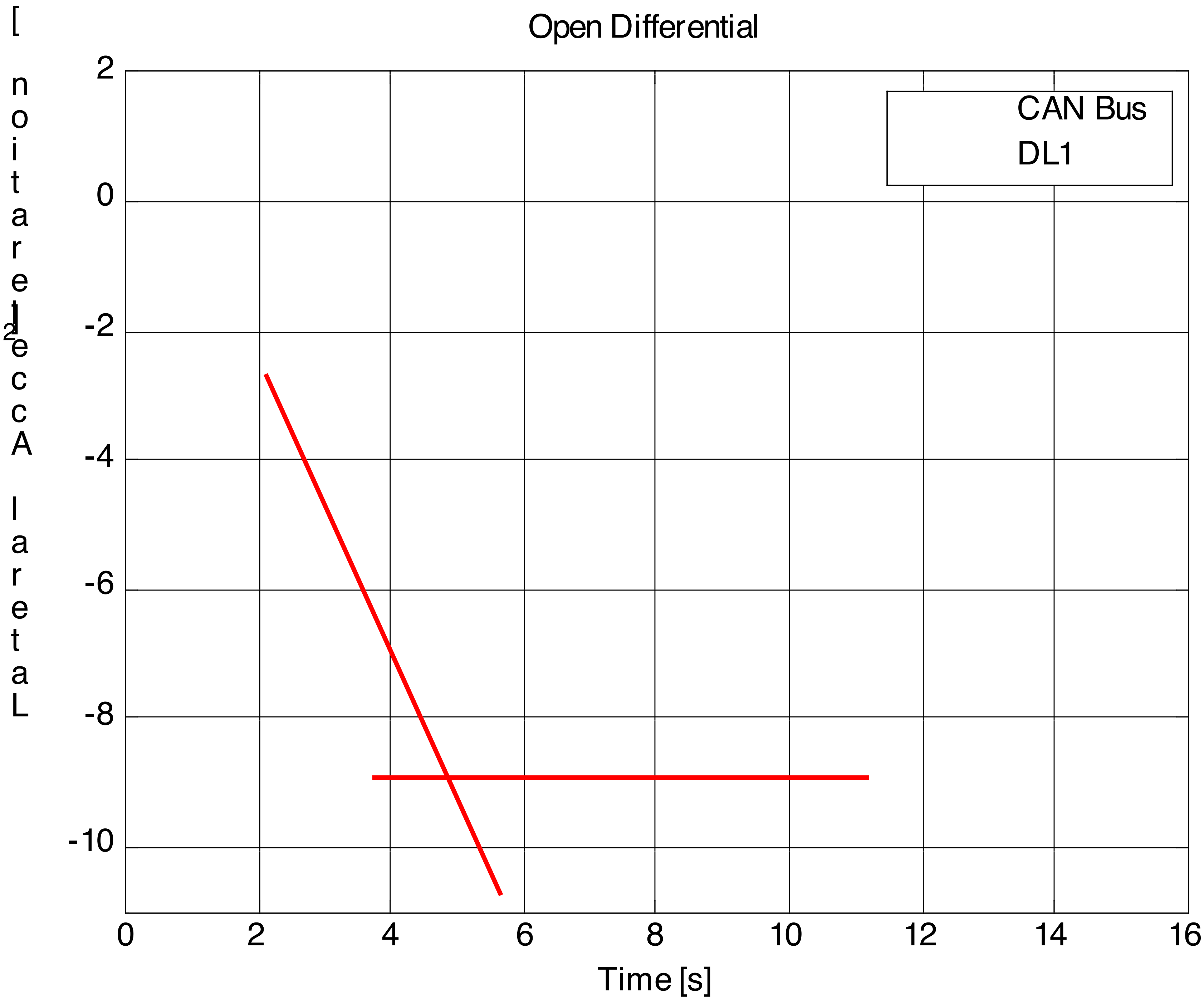
Experimental Results

- Maneuvere: Throttle On in a right hand curve
- Cornerning Radius: ~30m
- Test input: High but modulated throttle in 2nd gear starting at ~4m/s^2 latreral acceleration.
- Objective: Maximazing speed with maintained cornering radius.
- Main results: The DSLD gives better and more consistent cornering performance.
- Test vehicle: Saab 9^3 Aero V6 FWD
- Test Site: Stora Holm outside of Gothenburg
- Instrumentation: CAN, DL1 (Mathworks XPC Target)

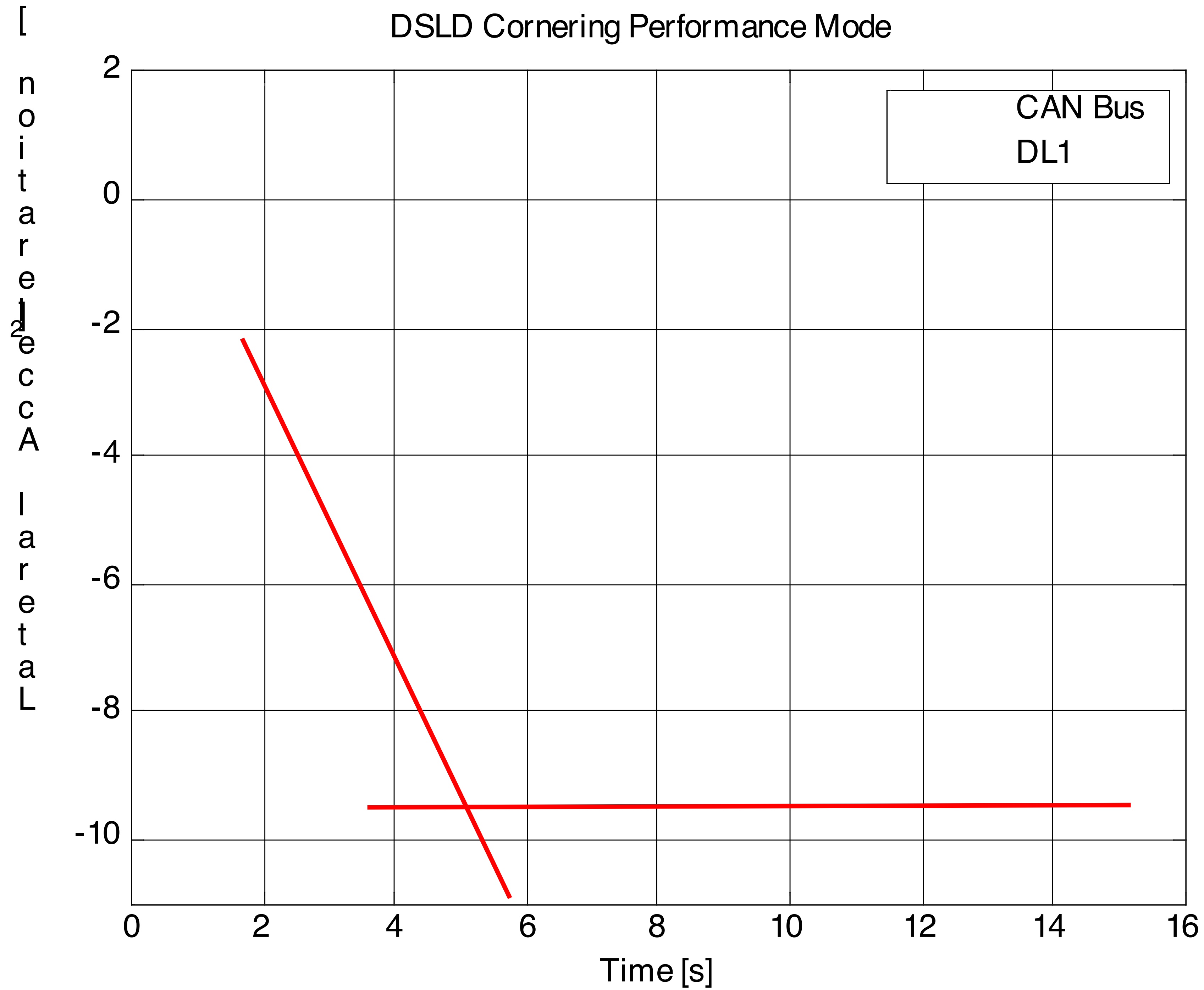


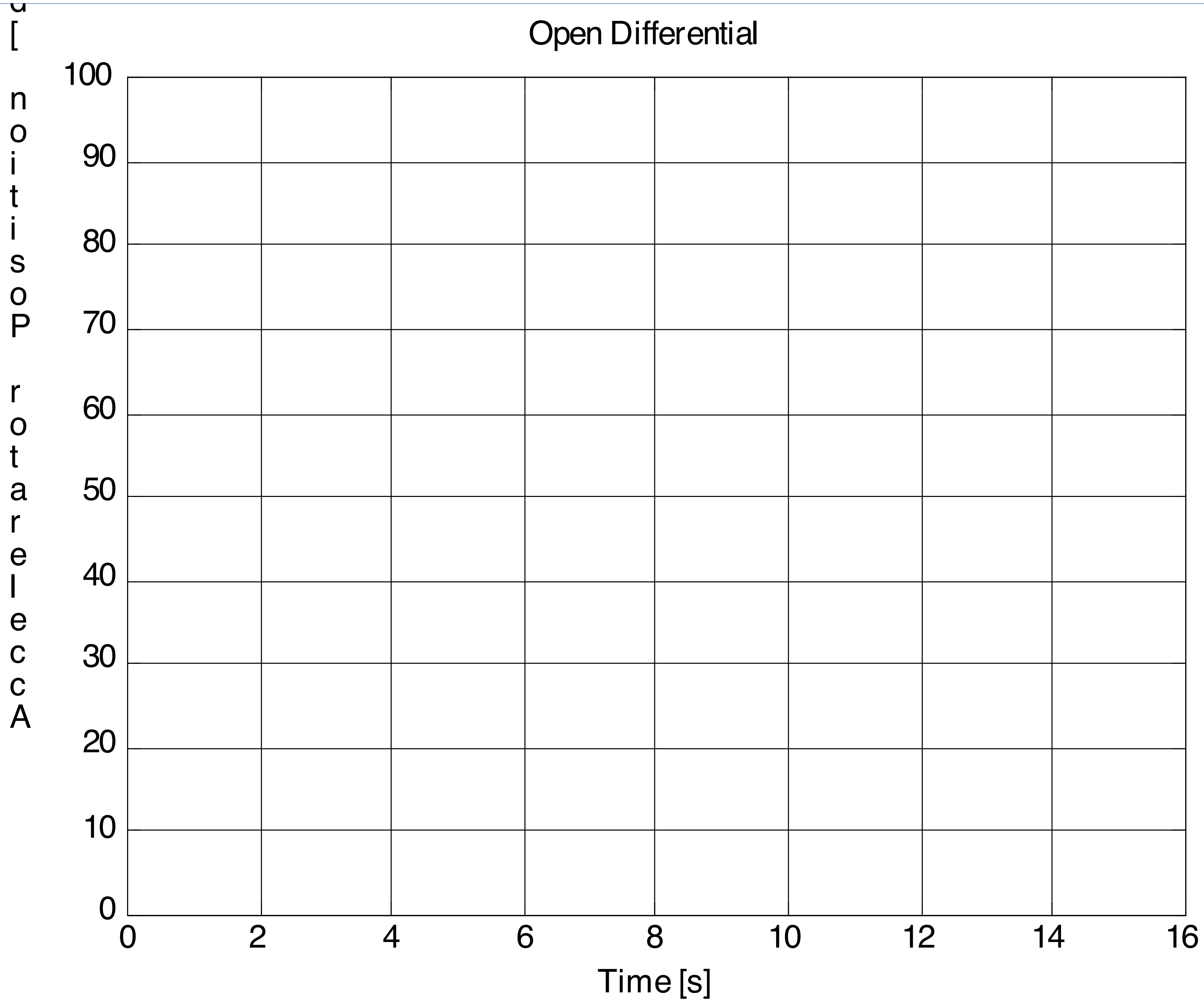

Open Differential
Left
Right
Wheel Rotational Speed
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
Time [s]


DSLD Cornering Performance Mode
Left
Right
Wheel Rotational Speed
900
800
700
600
500
400
300
200
100
0
0
2
4
6
8
10
12
14
16
Time [s]

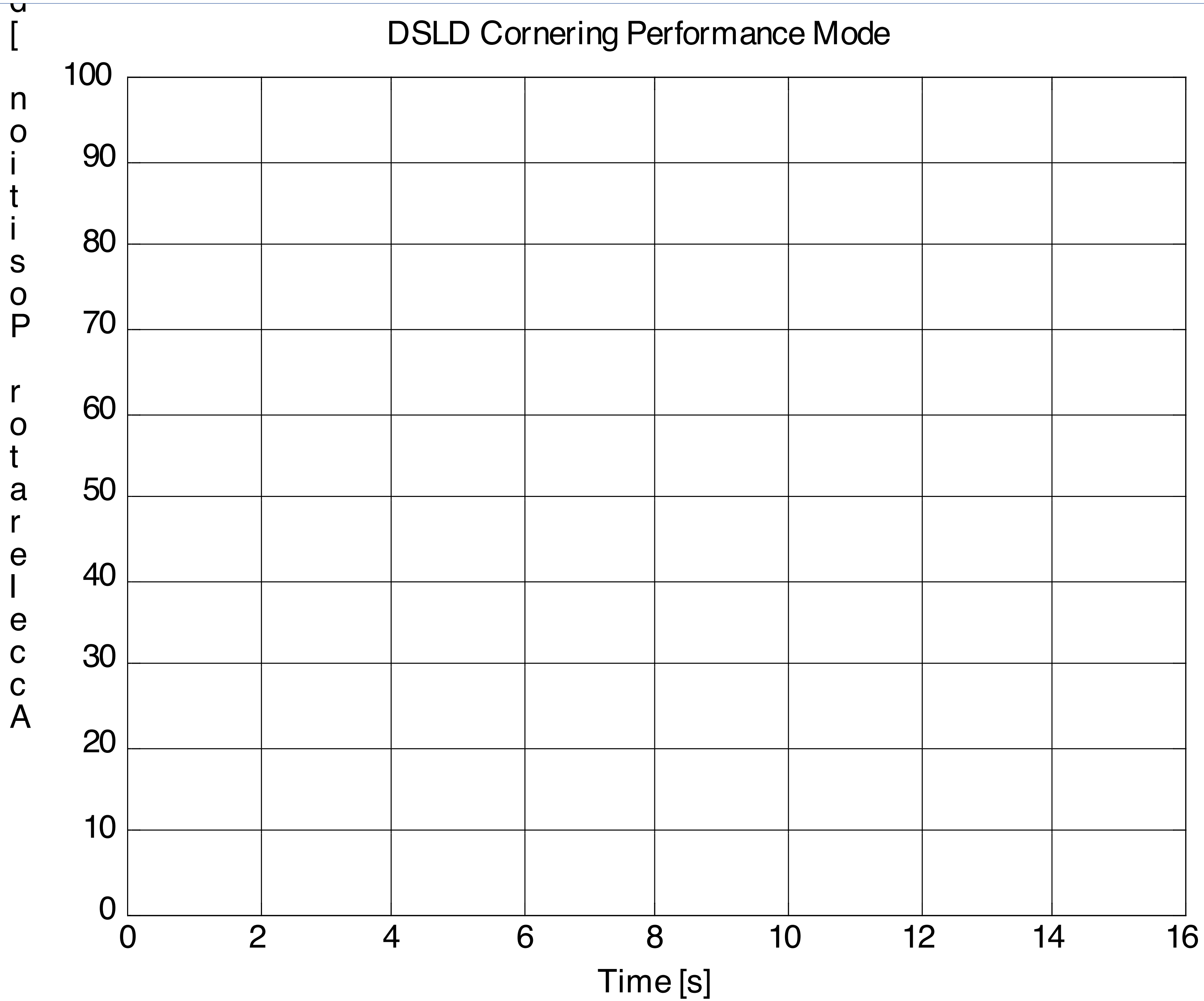


Open Differential
CAN Bus
DL1
Lateral Acceleration [ ]
2
0
-2
-4
-6
-8
-10
0
2
4
6
8
10
12
14
16
Time [s]

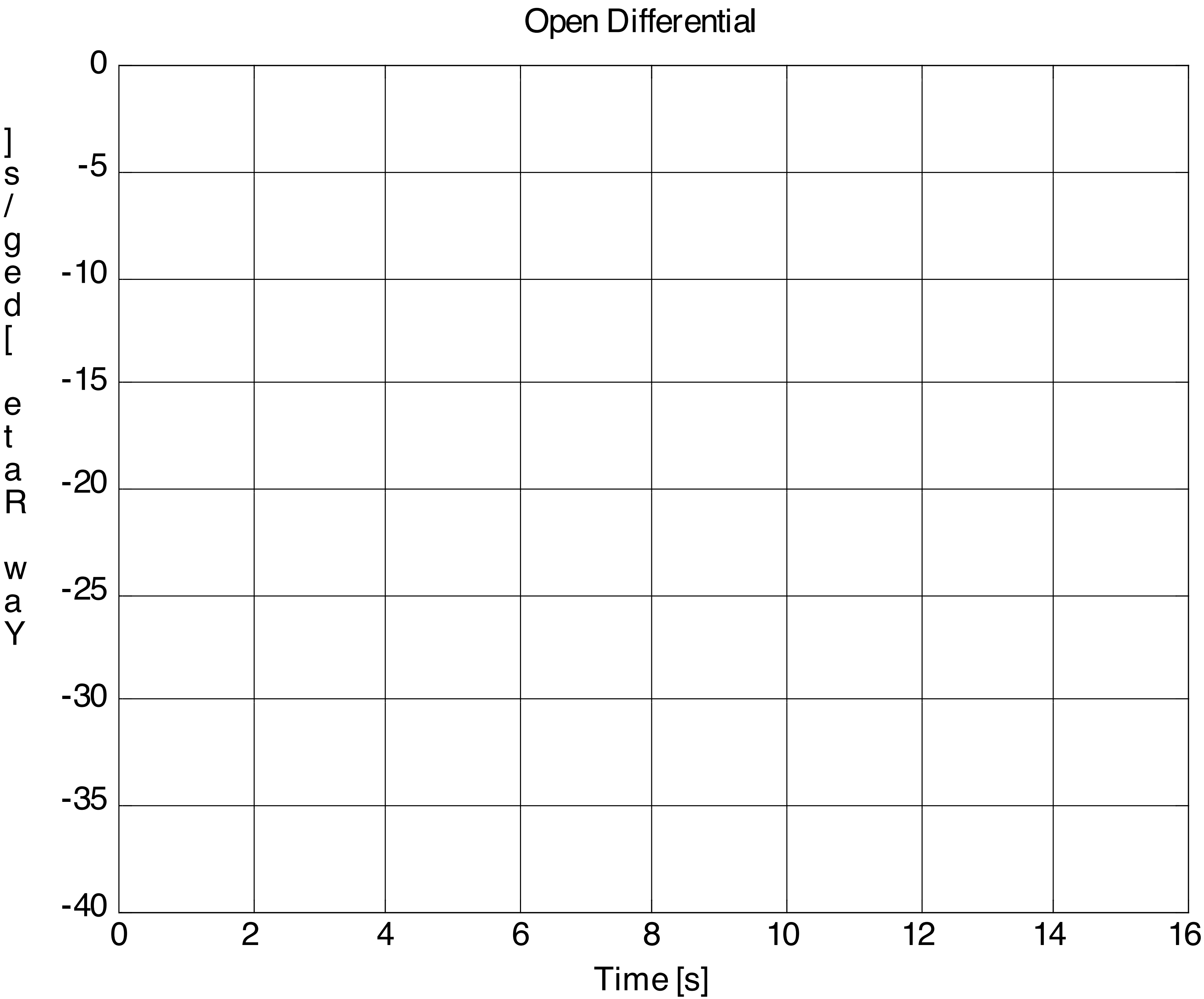

DSLD Cornering Performance Mode
CAN Bus
DL1
Lateral Accel [m/s²]
2
0
-2
-4
-6
-8
-10
0
2
4
6
8
10
12
14
16
Time [s]



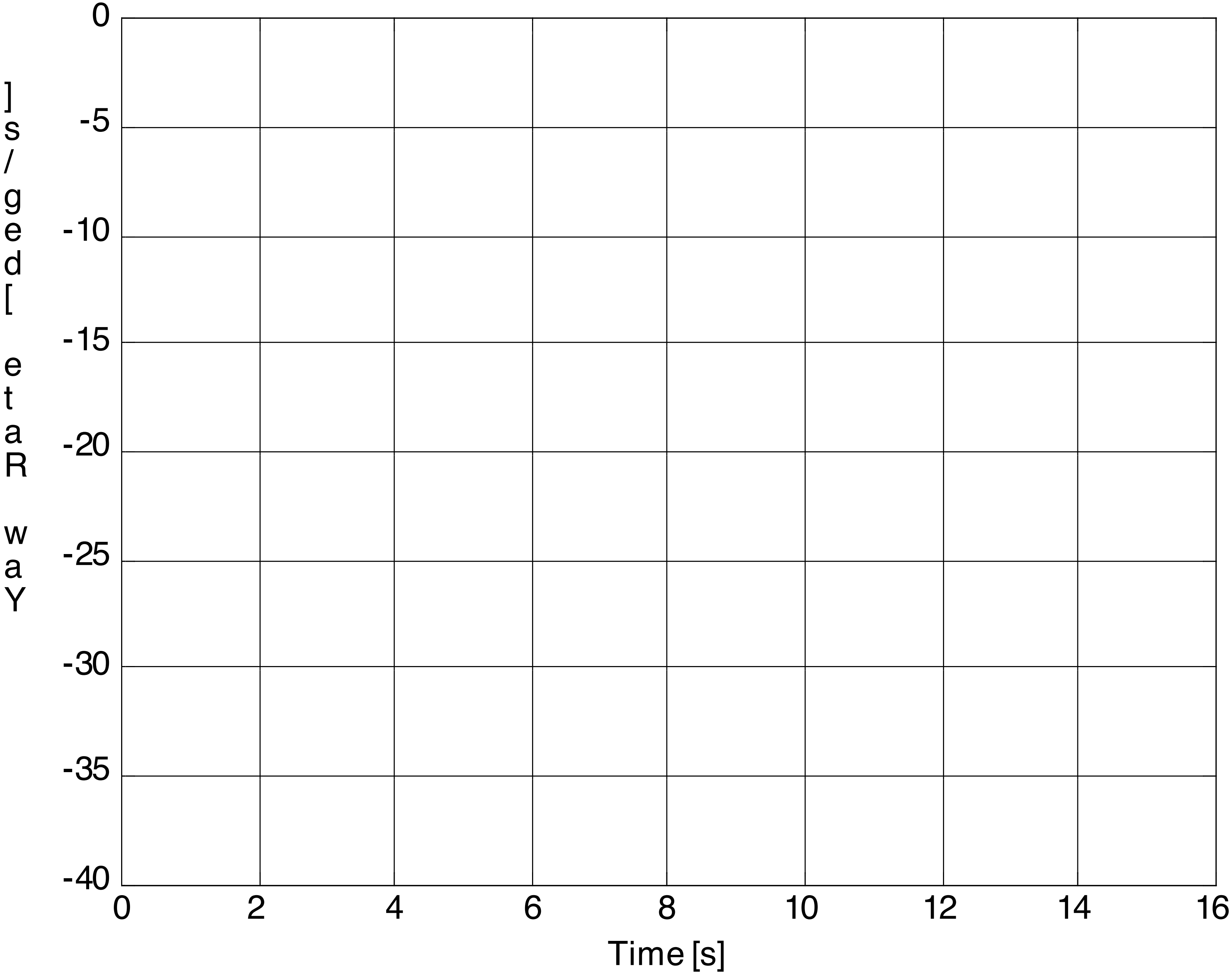
Open Differential
Accelerator Position [d
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
Time [s]

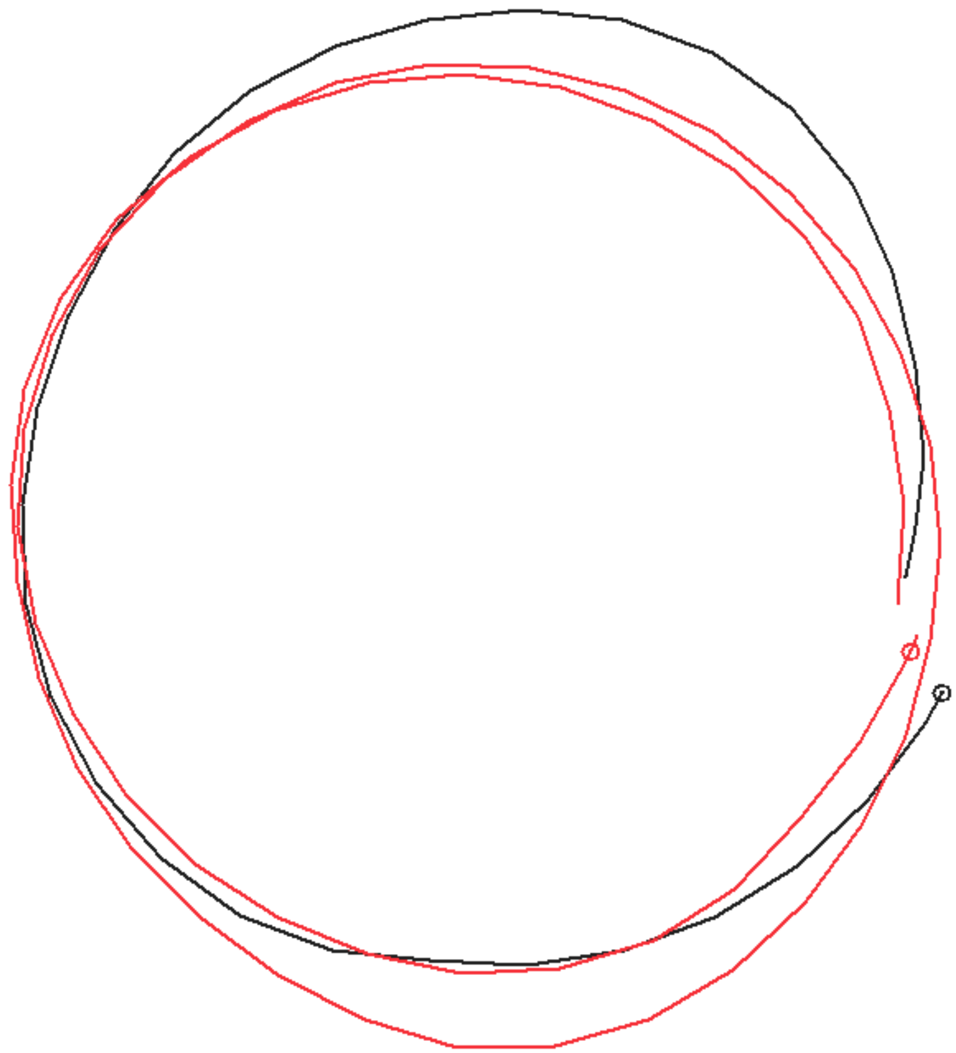


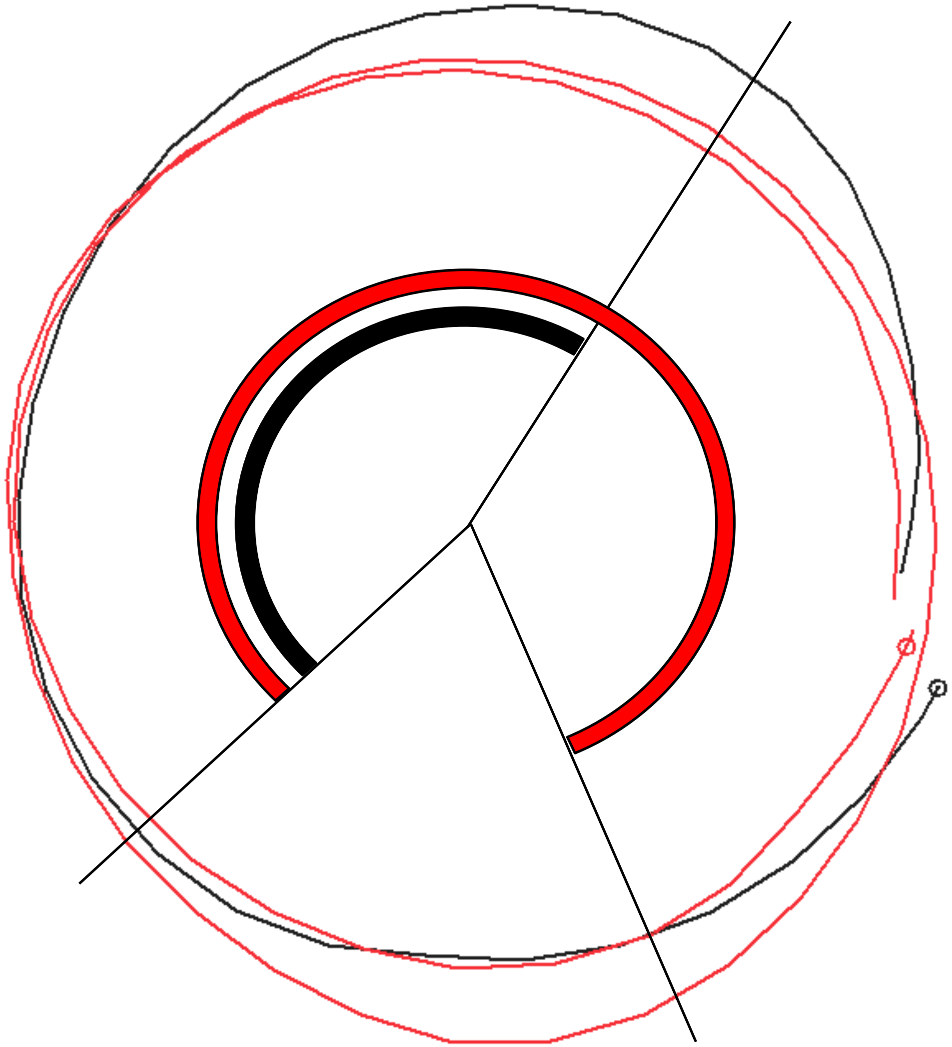
DSLD Cornering Performance Mode
Accelerator Position [
100
90
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
Time [s]


Open Differential
Yaw Rate [deg/s]
0
-5
-10
-15
-20
-25
-30
-35
-40
0
2
4
6
8
10
12
14
16
Time [s]

DSLD Cornering Performance Mode







Conclusions and Future Work

- The DSLD opens up the possibility to significantly increase the cornering performance of front wheel drive passenger cars.

- To verify the performance and the stability of the DSLD in more detail it is needed to continue the experimental work with more maneuvers as well as deeper analysis of existing results.

Thank you for your attention!