Longitudinal dynamics - Simscape model

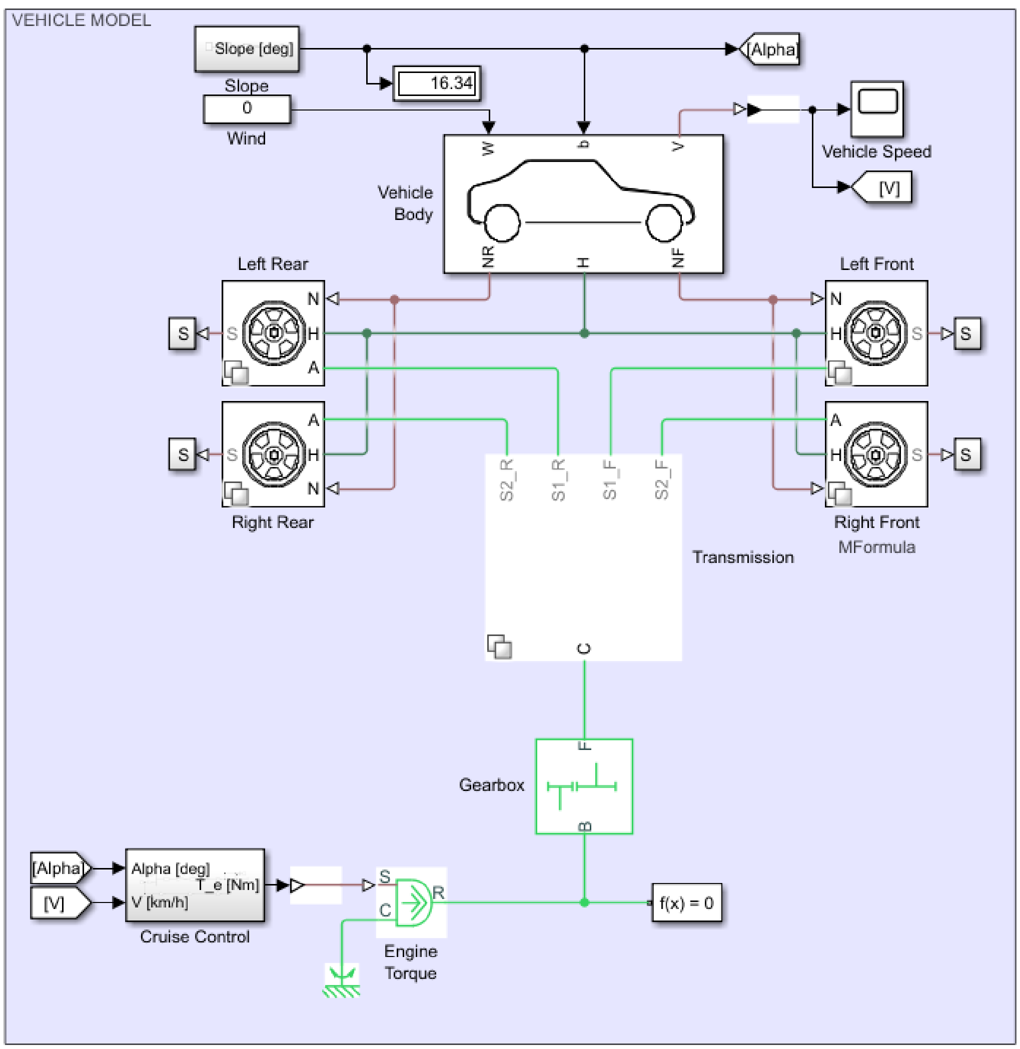
Introduction

The process of longitudinal dynamics evaluation is composed of the following steps:

1. Simulate acceleration manoeuvres (*done in previous models*)
2. Estimate the climbing performance for different driveline architectures (FWD, RWD, AWD) (*done in previous model and here*)
3. Test the vehicle performance with open, locked and limited slip differentials (*present model*)
4. Analyse braking dynamics (*next model*)

To assest the step number 2 and 3, in this exercise the Simscape vehicle block is adopted.

`Simscape` provide a block which simulate the vehicle body representing a two-axle vehicle body in longitudinal motion. The block accounts for body mass, aerodynamic drag, road incline, and weight distribution between axles due to acceleration and road profile. The vehicle can have the same or a different number of wheels on each axle. Optionally include pitch and suspension dynamics or additional variable mass and inertia. The vehicle does not move vertically relative to the ground.



With respect to the other exercises, here the car is trying to move at a constant speed of 36 km/h meanwhile the slope gradually increases. Whne the vehicle starts to slows down, changing its velocity down to 25.2km/h, the value of the slope at this precise moment is taken as the maximum slope reachable.

The cruise control block acts as the input of the system, imposing to the vehicle to follow a constant 36 km/h motion, which is converted as an engine request.

Here lies the main part of the exercise, since it is of our interest to study the effects of different differentials configuration over the maximum slope (transmission block).

Wheels block simulate Pacejka tyre-ground contact behaviour.

RECAP QUESTION: Passing from the matlab model up to the Simscape, passing through the Simulink one, what further improvement has been adopted? What they implied?

-> Matlab simple longitudinal dynamics. Then on Simulink the traction system limitations due to slippage have been introduced, so as relaxation length and further minor chnages, then in Simscape also the differential influence have been included.

TASK 1. Estimate the climbing performance for different driveline architectures - Comparison FWD, RWD, AWD

- **Run simulations to evaluate the maximum angle and discuss results**

Models setup

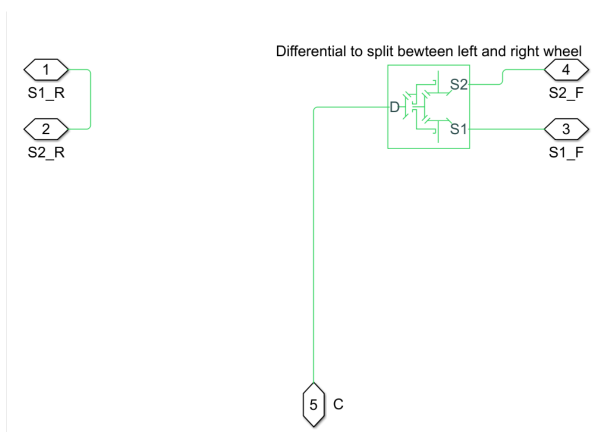
The initial task is to complete the Simscape (SSC) model of the three layouts:

FWD, RWD and AWD with 1/ = / = 1.01.

Regarding FWD nad RWD, the connection between the engine is a direct one, where there is only a differential to split the torque among left and right wheel. The differential ratio of this diefferential is given as data $ratioDiff = 4$.

NOTE: Launching file has the selection disabled since it has been done manually in tis livescript.

FWD

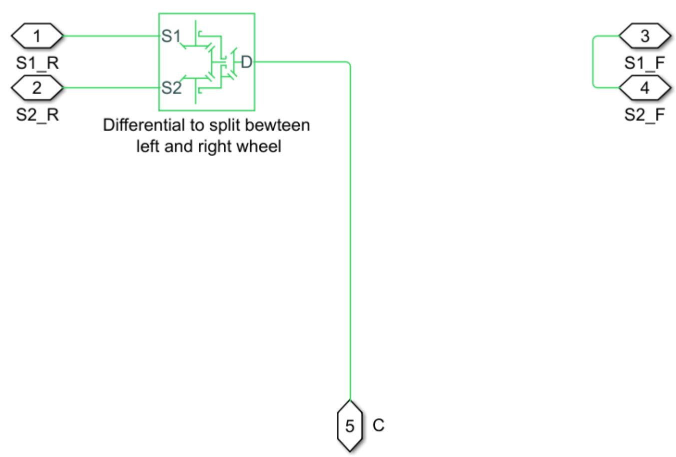



```
DRIVE = 2; % FWD selection
```

```
Init_ES03_LongDyn_SSC_stud
```

```
%-----------------------------FWD-----------------------------%
%                                                             %
ANALYTICAL MAX SLOPE
     45 % equal to 24 deg
%                                                             %
%-------------------------------------------------------------%
EXPERIMENTAL MAX SLOPE
The maximum slope reached is: 44.9106% equal to 24.1851 deg
%                                                             %
%-------------------------------------------------------------%
```

RWD




```
DRIVE = 3; % RWD selection
Init_ES03_LongDyn_SSC_stud
```

```
%-----------------------------RWD-----------------------------%
%                                                             %
ANALYTICAL MAX SLOPE
     55 % equal to 29 deg
%                                                             %
%-------------------------------------------------------------%
EXPERIMENTAL MAX SLOPE
The maximum slope reached is: 54.6608% equal to 28.6613 deg
%                                                             %
%-------------------------------------------------------------%
```

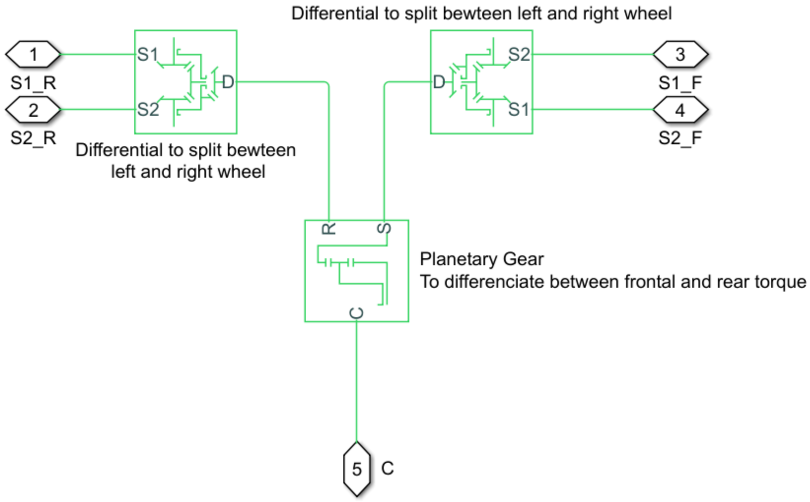
AWD

WARNING: name the differential blocks as follows:

- Front Differential

- Rear Differential

- Central Differential




```
DRIVE = 1; % AWD selection
K_T  = 1/1.01; % since the slides provide 1/Kt = 1.01
ratioDiffCen = 1/K_T;
Init_ES03_LongDyn_SSC_stud
```

```
Kt form slide = 1/1.01; K_opt = 0.5789
K_T = 0.5789

%---------------------------AWD PGS---------------------------%
%                                                             %
ANALYTICAL MAX SLOPE
     99 % equal to 45 deg
%                                                             %
%                                                             %
Optimal KT
     0.5789
%                                                             %
%-------------------------------------------------------------%
EXPERIMENTAL MAX SLOPE
The maximum slope reached is: 99.2265% equal to 44.7775 deg
%                                                             %
%-------------------------------------------------------------%
```

- **Run simulations to evaluate the maximum angle and discuss results**

The values founded have been reported into the launching file so to set them as a reference.

```
i_max_FWD =   tand(24.36);      % [%] Max slope for FWD configuration
i_max_RWD =   tand(28.76);      % [%] Max slope for RWD configuration
i_max_AWD =   tand(44.78);      % [%] Max slope for AWD configuration with constant K_T
```

As expected, bewteen all the possible traction systems the AWD shows the best performance in terms of maximum slope rechable. This is always due to the fact that having both axles with driving wheels permit to develop four traction forces. In this way it is like if each wheel helps the other to move the vehicle, having as a result a better grip development.

Between the two singel axle driving wheels, the RWD reaches higher slope since the load transfer put more wieght over the rear axle. Having more load the rear wheels are capable to develop higher longitudinal forces improving therefore the climbing capability. In a FWD on the contrary, the laod transfer reduce the load on the driving wheels, reducing in this way the longitudinal forces facilitating the total slippage of the front wheels axle.

- **Check the maximum slope achieved with Simscape model**

Kt = 1/1.01 -> *The maximum slope reached is: 80.8952% equal to 38.9712 deg*

Kt = 0.5789 -> *The maximum slope reached is: 99.2265% equal to 44.7775 deg*

Since the Kt calculation is based on the assumption that the braking system exert the maximum possible braking action, as expected, the optimal Kt computed analytically is the best option possible to reach the maximum slope.

Its value is $\alpha = 44.7775\,\mathrm{deg}$. Of course this is only a theoretical value, in fact te Kt calcualtion is based on the strong assumption the maximum braking force is obtained for both axles. In real life further effects enters (like lower mhu) which reduces this theoretical values.

Checking the results for low grip condition

Use the torque split previously computed and run the simulations with = 0.3

All the following simulations will be carried adopting only the AWD drive with Kt = Kt_opt = 0.5789 (since it .

- **What is the maximum slope?**

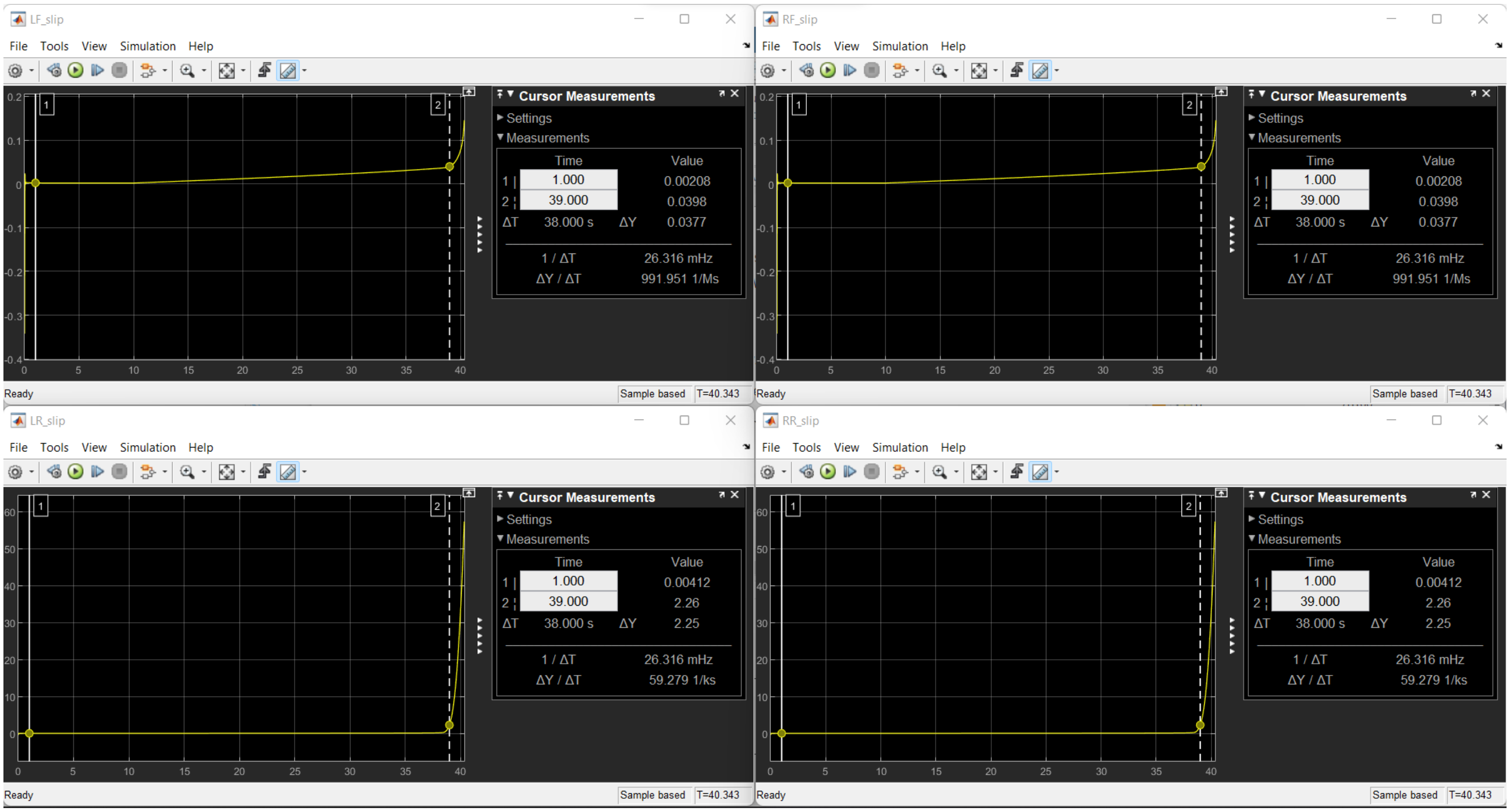
The maximum slope reached is: 24.17% equal to 13.5878 deg.

Of course having less grip implies less traction force, consequently the vehicle has more difficulty in climbing up.

- **Check the behaviour of slip and tyre forces for front and rear tyres. Which tyre slip first?**

Having a mhu of 0.3 put under critical conditon the climbing performance of the vehicle. Due to this, it is expected to observe higher value of slip and lower values of forces respect to before and higher slip values.

AWD Kt = 0.5789 (ideal) mhu 0.3 - Slip:

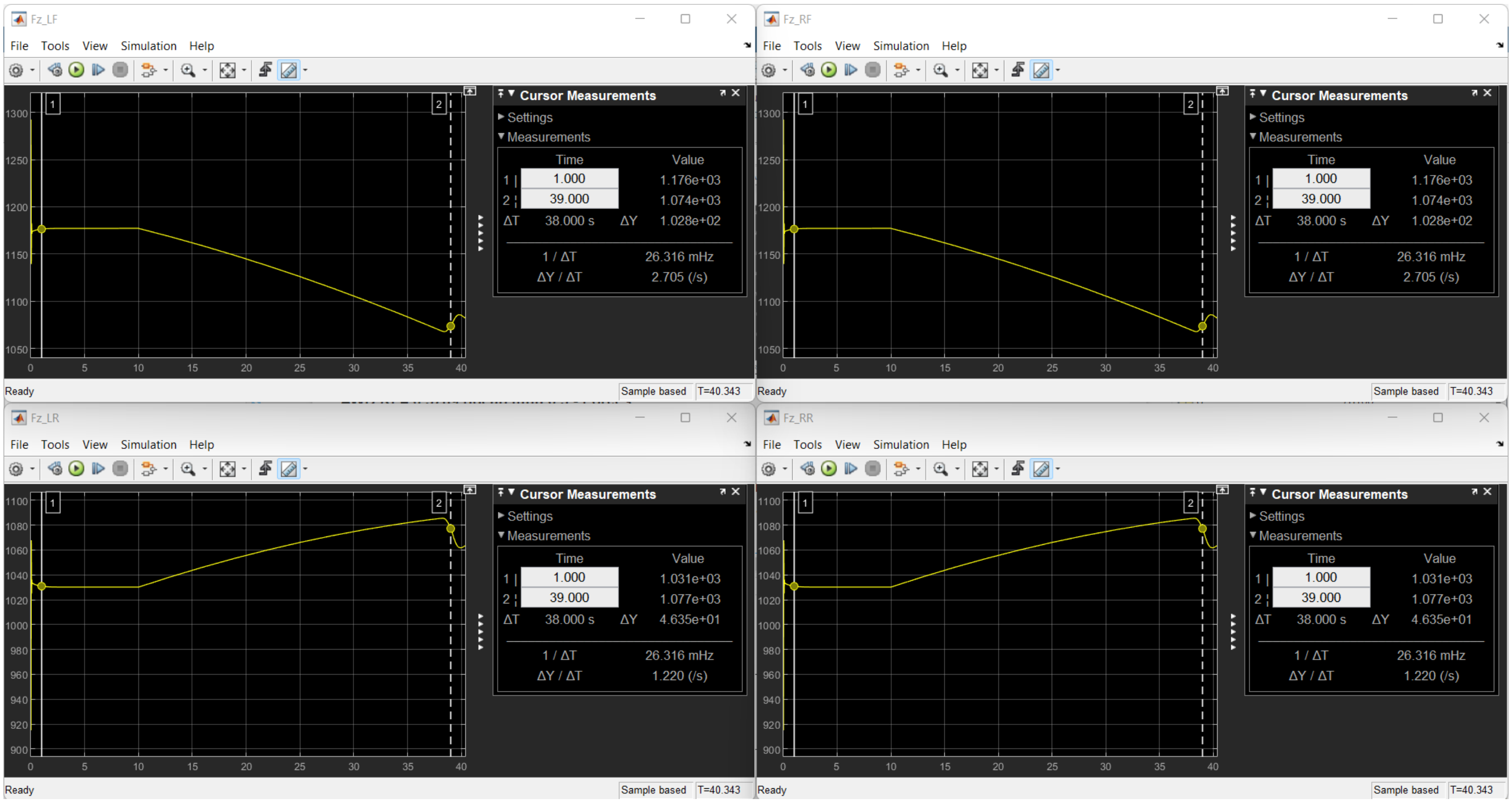


Initially it seems that the front axle start to have certain values of slip, but then as soon thee rear start to have some grip loosage, it rapidly goes to total slippage. This effects can be expliained.

Between the two axles, the front one is the one that have more difficulty in developing more traction forces. As soon as the rear starts also starts to slip, the vehicle cannot bear anymore the slope and start to lose velcocity (real life = stops and moves beackwards with wheel spinning).

To sum up, if the rear lose grip, the vehicle has reached its climbing performance.

AWD Kt = 0.5789 (ideal) mhu 0.3 - Forces:



The forces signals confirm the conclusions done on the slip. In fact, initially all wheels develop the same force, but as soon the rear decreases its traction forces, the vehicle start to slow down. Note how as the rear decreases, the front forces increases. It seems that if the rear becomes critical, the front tries to ttraction but evidently is not enough.

- **What is it the optimal torque split?**

Optimal KT = 0.9355.

Kt directly depends on the grip coefficent. In the ideal condition, in fact, it has more sense to deliver more torque to the rear which has more capability to traction thanks to the load transfer. Not by chance, with mhu = 1, Kt_opt is 0.5789, which means that the rear has the double traction of the front. The total torque provided by the engine then divides like 60% at the rear, 30% at front (more or less).

NOTE: KT = 0.50 DOES NOT MEAN THAT THE SPLIT IS 50/50! IF IT IS EQUAL TO 1 THEN IT IS 50/50, OTHERWISE 0.57 MEANS THAT KR IS ALMOST DOUBLE OF KF

With a critical situaton like a mhu = 0.3 (snow on the road), the Kt becomes equal to 0.9533. This suggest that in this extreme situation it is necessary to have both wheel developing the same traction, the rear even if helped by the load transfer is not capable to develop enough traction to climb the hill. Not by chance, in USA there are competitions of "jeepness" (youtube videos pretty popular of climbing competitions with low grip) where all cars involved have a Kt close to 1.

Doing a simualtion with the new Kt_opt foundedn in fact the slope slightly icreases:

The maximum slope reached is: 29.6518% equal to 16.516 deg

Therefore the vehicle should be able to tune its Kt value depending on the road grip. Unfortunatly, this is not feasible by the technology at our disposal nowadays.

TASK 2. Test the vehicle performance with different inter-axle differentials: open, locked and limited slip differentials

The previous discussion was more over the best driving wheel configuartion for climbability. Once the AWD was set as the best one, the discusison moved to which should be the best value of Kt and how the grip influences it.

The aim of this part is now to compare two different solution for the inter-axle differential a locked one and a limited split differential, trying to understand which one presents the best performance and why.

Due to the lack of knowledge over differentials and their working method, here a theoretical part over definitons and working principle is presented (not your fault, simply they didn't explained to you and assumed that you already know it)

Definitions:

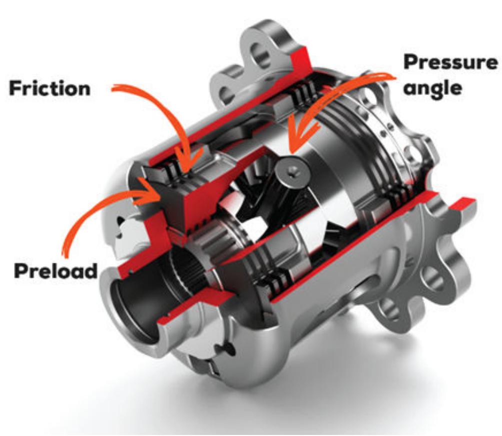
TBR = torque bias ratio or the ratio of the highest torque to the lowest torque between the two axle shafts.

Open = divides the torque perfectly in half between the two driveshafts since there is no friction between the gears.

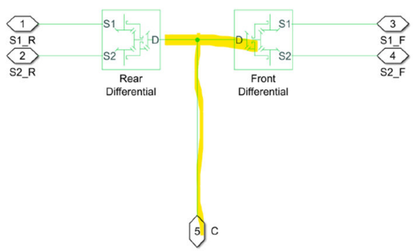
***Real* open** = an open whose TBR is close to 1 but not exactly unity (like 1.3).

LSD = Limited Slip Differential. The name literally evinces its structure. This is a differential that includes friction plates on both sides of the axle shafts. These two clutches generate friction, which is the basis of the operating principle of the entire differential. By doing the balance of torques and powers, we see that if one axle suffers more friction, the other does not necessarily have the same level of friction. Therefore, the axle shaft with less friction will receive more torque, consequently the axle shaft that will have less torque will go faster.

LSD adopted both between wheelbases between wheelbases, but it is more appropriate when used in the 'wheelbase because it allows good distribution of speed and torque. "Limited-slip differentials (LSD) are considered a compromise between a standard differential and a locking differential because they operate more smoothly, and they do direct some extra torque to the wheel with the most traction compared to a standard differential, but are not capable of 100% lockup".

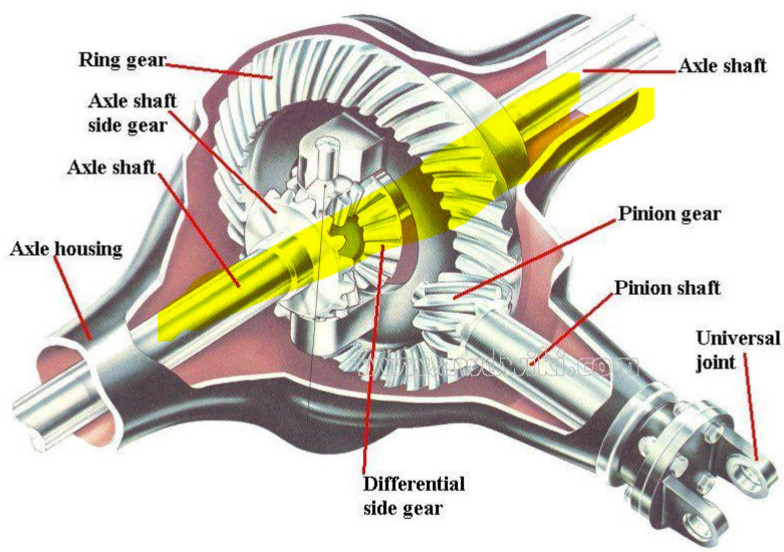


Blocked = Differential that can transmit the same input torque in equal value for the two axle shafts. It is ideal for a climb because it can transmit all torque to only one axle. The ratio is not fixed and depends on conditions.



NOTE: Along the yellow line speed and torque are constant!

(Mechanically, it is as if the two sides in the figure below are locked type welded).



The ability to change torque although the differential is fixed is due to power balance. In fact, should the two wheels have different speeds (e.g. front axle with higher speed uphill because they slip more) since the given power remains that, necessarily the torque decreases. By decreasing the torque at the front the torque at the rear increases, why? Because the given power that is and implies a fixed input torque that is necessarily the sum of front and rear: in other words if you take away front it will go behind!

Then also think of it as a change in friction, that is, if the front offers less torque resistance, this additional torque given by the increased efficiency will transfer to the rear; therefore, there is a balance between the two.

Model preparation:

New variables to declare for the new model. Everything is already included into the new matlab file.

```
% AWD_LSD=Simulink.Variant('DRIVE==4');       % FWD (select DRIVE=2)
% AWD_LOCKED=Simulink.Variant('DRIVE==5');    % AWD (select DRIVE=1)
%
% i_max_AWD_PGS = 1; i_max_AWD_id = 1;
%
% NOTE: Here a model gifted was used since the one deveopled by me didn't
% provided the expected results
```

```
Init_EL2_Part1_2wd_vs_4wd_max_slope_DOC;
```

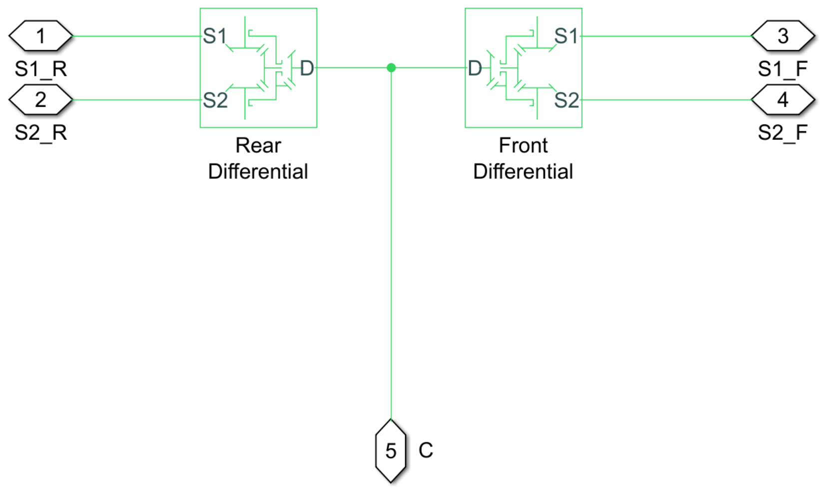
```
%-----------------------------AWD LSD----------------------------%
%                                                                %
%                                                                %
%----------------------------------------------------------------%
EXPERIMENTAL MAX SLOPE
The maximum slope reached is: 88.4892% equal to 41.5054 deg
%                                                                %
%----------------------------------------------------------------%
```

Analysis to perform:

Run the simulations with = 1 (high friction)

- **what is the maximum slope with a locked central differential?**

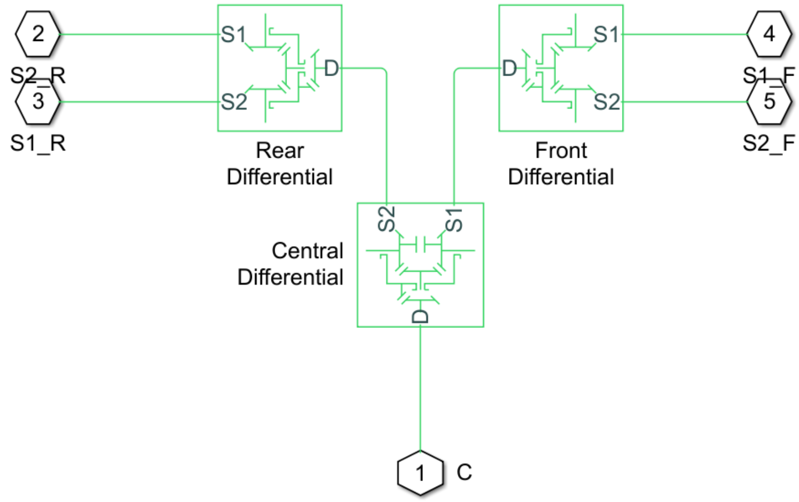
Note: the sensotìr and the free end are adopted for the torque split evualtion requested in the next bullet points.



The maximum slope reached is: 99.3204% equal to 44.8046 deg

In the previous section it was observed how having similar torque value among front and rear axle is the best solution in terms of climbability, having a mhu = 1. Here the same conclusion can be get. The peculiar characteristics of blocked differential is taht they permit to provide the same torque and speed to the two semi-axles but more important for this scenraio, the TBR has no limitation. This effect will be better explained when comparing the Kt evolution along the simualtion, therefore the reader is invited to go to the next second section for further explanations

- **what is the maximumum slope with an active differential (LSD)?**

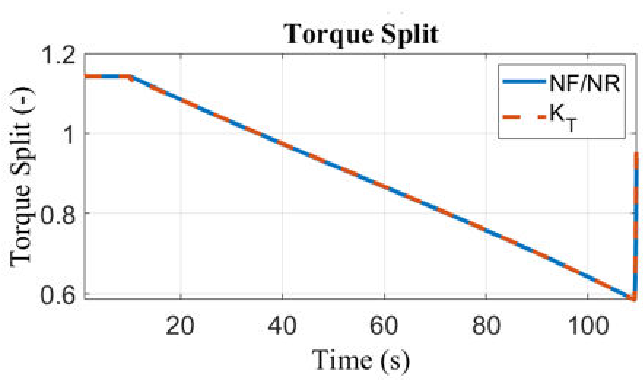


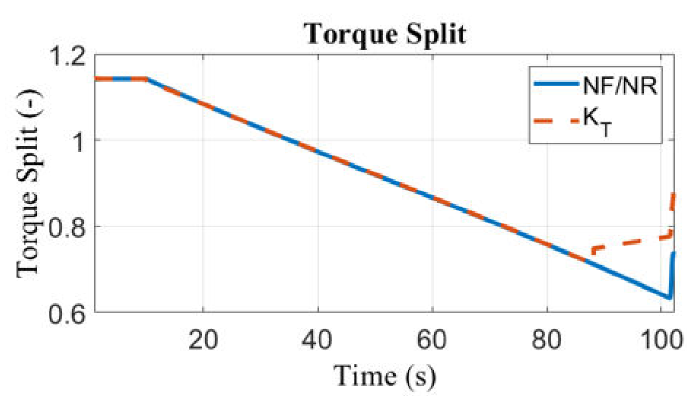
The maximum slope reached is: 88.4892% equal to 41.5054 deg

The LSD differential was adopted as shown. Even if usually it is included to differenciate the torque among each side of the vehicle, in this exercise it was used for splitting it among the two axles instead. But most important thing the peculirity of the LSD is that it can vary the TBR until a certian point, over which the clutch engages and reduces the difference of torque bwtween the two semi-axles. The lower slope reached by the LSD then it can be explianed following this principle: in a certian point, in order to overocme the slope, a certian TBR is required but the LSD cannot proivde it since the clutches starts to slip. Due to this, the LSD vehcile will stop before beacausa cannot proivde the right torque split and the wheels starts to split.

- **Plot and discuss the <u>torque split</u> between the axles: is it constant? what is the value?**

LOCKED (left) - LSD (right)



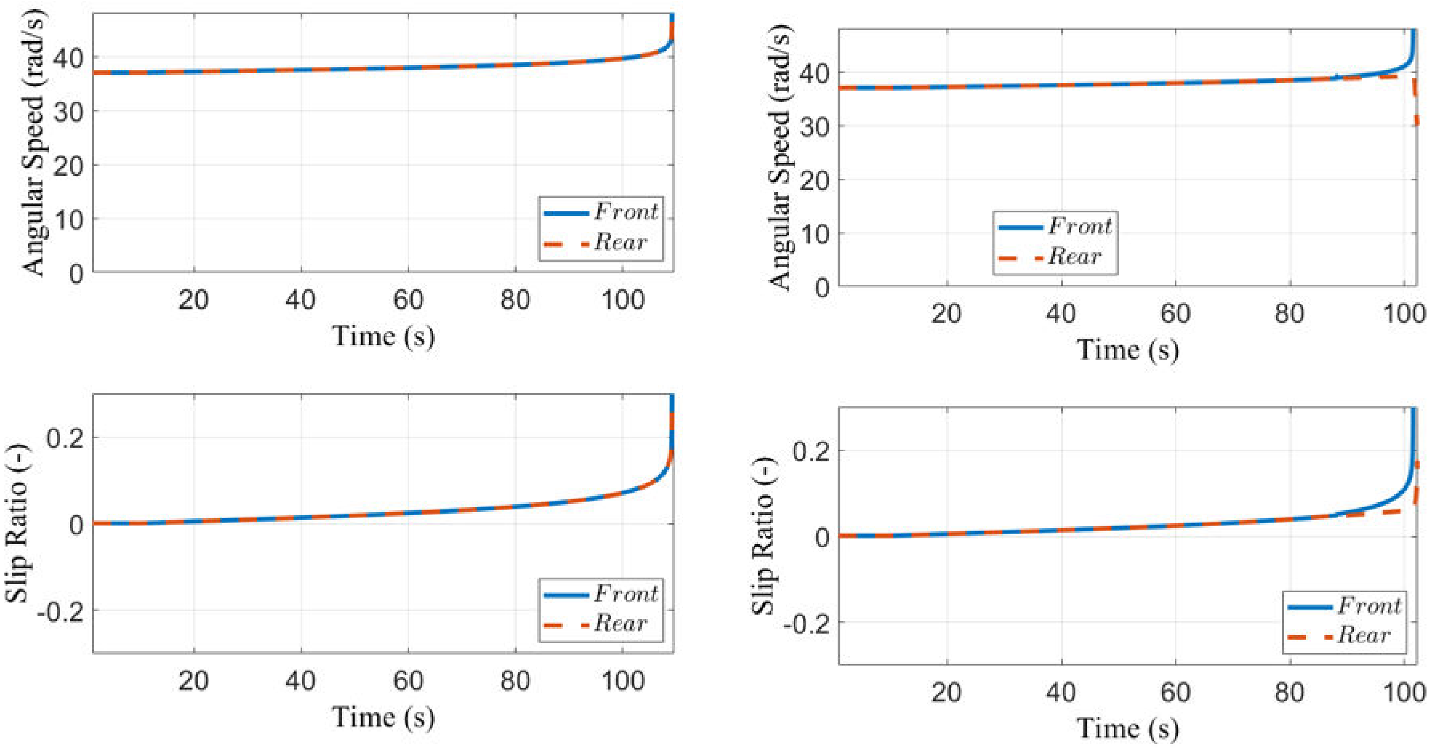


Here is clearly visible the difference in the TBR developmente from the two differentials. The blocked one has no limit, it can divide the torque between thw two axles to whichever ratio, the LSD instead has some limitiation since the clutches inside it will start to slip. This slippage is wll represented by the increase of Kt in the LSD chart. As soon the clutches slips, the torque provided to the rear is not anymore the requested one from the slope. Therefore the vehcile will losse its capability to have the right torque ratio. and since the ratio is not enough for climbing, this lead to the stoppage of the vehicle.

The locked differential instead has the capcity to follow exactly the TBR requested by the slope (caused from the load transfer), resulting then into an excelent climbing capacity.

- **Plot and discuss the <u>angular velocity</u> and <u>slip</u> of front and rear axle: Are they the same for F and R axle?**

LOCKED (left) - LSD (right)



Since the locked differential provide torque

With a locked differential, both axle start to slip. Due to the construction of this differential, the situation is similar between the two axles, since delivering a constant growing ratio of torque to the rear, both of them will have as consequence to have the same behaviour. The limitation of the maximum slope reachale then is due to the vehicle itself since there is no way that it can climb a 45° slope.

Different is the situation for the LSD. Once the slippage of the clutch is reached, the front start to recive more torque. Theoretically the front anxle in this situation should reduce its rotational speed, however the change of torque let the front tyres to lose their grip, starting to slip increasing their speed. This increasage implies a decrease of speed on the rear, always following the concept of differentials. This situation however is not beneficial for climbing, in fact as soon the front increase its speed the car stops and starts to move backward, reaching in this way its climbabilty limit.

Simulate the installation of the Front Left (FL) wheel with a different radius (0.25m): vary tyre data accordingly

- **check torque split, slip and angular velocity of the two axles: what are the differences?**

```
% Radius and inertia are changed accordinlgy in the code thanks to a flag properly set
```

```
EXPERIMENTAL MAX SLOPE
The maximum slope reached is: 97.5772% equal to 44.2974 deg
%                                                               %
%---------------------------------------------------------------%
```

LOCKED

The maximum slope reached is: 99.3585% equal to 44.8156 deg

LSD

The maximum slope reached is: 88.6118% equal to 41.5447 deg

No matter the flat tyre, the locked will alwayse outperform the LSD into climbing performance due to its capacity to not have limited Kt setting. Also note how a flat tyre helps the simulation into reaching sligthly higher inclination. Probably since the modification was done by a simple radius change reducing therefore the inertia of the FL tyre, it seems that this reduction effect is more beneficial than the acutal loss of grip due to a flat tyre (also considered that the effect of a changed conditon in the grip zone was not considered).