

# TSFS02 — Vehicle Dynamics and Control

## Computer Exercise 1: Brake-Force Distribution and Slip Control

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# 1 Introduction

The purpose of this exercise is to learn about the impact of brake-force distribution and anti-lock brakes, and how they affect the vehicle's longitudinal and lateral dynamics. To get a feel for this you will elaborate with the brake-force distribution, implement your own Electronic Brake-force Distribution (EBD) controller, and implement a slip controller, which is an alternative to the Anti-lock Braking System (ABS). You will show how these systems can be beneficial in terms of safety by running different simulation experiments and compare the results. The software tool you will be using for these simulations is Dymola, for which a short introduction manual is available on the course homepage (written purposely for the TSFS02 exercises).

## 1.1 Examination

To pass this exercise you should have fulfilled the following:

- Solved the preparation tasks.
- Solved all the computer exercise tasks.
- Answered all questions, with motivated and thoughtful answers.

The examination is done by presenting your results and answers to a course assistant at the schedule exercise session. To speed up the examination process, it might be a good idea to present the tasks as you complete them, instead of saving them all to the end.

## 1.2 Preparations

Prior to the exercise session, you should have solved the preparation tasks marked as (P), i.e., Task 1, Task 3, and Tasks 6–8. You should also have read this document thoroughly, and it is recommended to have taken a look at the Dymola introduction manual from the course page.

# 2 Exercise Tasks

Before starting with the computer exercises, download the model file `TSFS02_Lab1_Braking.mo` from the course homepage. Start Dymola (`module add misc/dymola/2017` followed by `dymola` in a terminal window) and open the model file.

You can expect the simulations to take up to a couple of minutes to run each time. Therefore, remember to save the results from all simulations so that you do not have to re-simulate when presenting for an assistant (do this by right-click and *Export Result As...* in the *Variable Browser*).

In the appendix you will find data for some vehicle parameters, tire force behavior, and available sensors, that can be useful when solving the tasks.

## 2.1 Brake-Force Distribution

Electronic brake-force distribution distributes the braking force between the wheels according to the overall weight distribution of the vehicle.

### Task 1 (P) – Calculate brake-force distribution

Calculate the brake-force distribution so that both front and rear wheels lock up at the same time. Use the parameters in Table 1 in the appendix. For simplicity, neglect air and rolling resistance, and assume the road inclination is zero.

Hint: The front wheels will lock when the requested brake force exceeds the maximum tire-road force,  $F_{b,f}^{\max} = W_f \mu_x$ .

### Task 2 – Brake-force distribution: Wheel lock-up

In this task you are going to compare different levels of brake-force distributions using Dymola. Open the experiment named *RampBraking* (TSFS02\_Lab1\_Braking - Experiments - RampBraking - Ramp-Braking). In this experiment the brake-force is applied by slowly increasing it from zero, while driving in a straight line.

- Adjust the brake balance to front only, by setting the parameter  $Kbf = 1$ . Change it by double-clicking the icon in the upper left corner (or right-click and then choose *Parameters*), and then change the value of  $k$  in the parameters section. Save with the *OK* button. Run the simulation from the *Simulation* view. Look at the results by calling the *plot* and *visualize* functions in *RampBraking*. Save the results.
- Adjust the brake balance to rear only (set  $Kbf = 0$ ). Run the simulation, look at the results, and save.
- Set the brake balance to the value you calculated in Task 1. Run the simulation, study the results, and save.

Find the peak deceleration reached during braking and fill it in below.

Front wheels only ( $K_{b,f} = 1$ ): \_\_\_\_\_

Rear wheels only ( $K_{b,f} = 0$ ): \_\_\_\_\_

Calculated brake-force distribution ( $K_{b,f}$  from Task 1): \_\_\_\_\_

### Task 3 (P) – EBD control algorithm

The brake-force distribution you calculated in Task 1 is designed for maximum braking, and for a surface with the specified friction coefficient. This can be circumvented with an Electronic Brake-force Distribution (EBD) that varies the front-to-rear brake-force distribution according to the deceleration. Derive an expression for the brake-force distribution, so that all wheels lock at the same time, if the friction coefficient is unknown. You are free to use the available measurement signals shown in Table 2 in the appendix.

### Task 4 – EBD implementation

Implement an EBD in Dymola, based on the expression you derived in Task 3. Go to the model block called *EBD* (TSFS02\_Lab1\_Braking - Vehicle - Brakes - BrakeComponents - FunctionBlocks - EBD). Switch to *Modelica Text* view, either from the menu bar (*Window - View - Modelica Text*) or from the shortcut button in the toolbar.

In the beginning of the model the available sensor variables are defined. These are considered as inputs to the model, while output is the front brake-force distribution  $K_{bf}$ . Specify the additional parameters and variables you need (the gravity constant  $g$  is already defined as parameter, and  $K_{bf}$  is defined as a variable). Write the equations necessary to calculate  $K_{bf}$  below equation.

## Task 5 – EBD evaluation

In this task you will evaluate your EBD controller with three different experiments. The first is the *RampBraking* from Task 2. The second is similar to *RampBraking*, but for a lower friction coefficient (scaled down to  $\mu \approx 0.3$ ). The third experiment is a “braking while cornering” test, where a closed-loop driver model tries to stay in lane while the brakes are applied abruptly mid-turn.

- a) **Straight-line braking:** Go back to the experiment *RampBraking* and change back to *Diagram* view (from the menu bar *Window - View - Modelica Text*, or the shortcut in the tool bar). Activate EBD by changing the boolean value *EBDOn* to *true*; double-click (or right-click → *Parameters*) on the icon named *EBDOn*, and change the value of  $k$ . Run the experiment, and execute the plot and visualize functions.

Do the front and rear wheels lock up roughly at the same time?

How does the brake-force distribution change with increased braking effort?

- b) **Low-friction braking:** Now switch over to the experiment called *RampBrakingLowFriction*.
- i) Run the experiment with the fixed brake-force distribution from Task 1. (Fill in your  $K_{b,f}$  from Task 1, and make sure *EBDOn* is set to *false*.)
- ii) Run the experiment with your EBD controller activated. (Switch *EBDOn* to *true*.)

How does the wheel lock-up differ between the fixed brake-force distribution and your EBD?

- c) **Braking while cornering:** Open the *BrakingWhileCornering* experiment. Remember to run the *buildRoad* command before running the experiment for the first time (right-click on *buildRoad* and select *Call Function...* followed by *OK*).
- i) Set the brake-force distribution to a “front-heavy setup” (e.g.,  $K_{b,f} = 0.9$ ), and run the simulation.
- ii) Set the brake-force distribution to “rear-heavy” (e.g.,  $K_{b,f} = 0.1$ ), and run the simulation.
- iii) Run a simulation with your EBD active.

Make sure you have results for all three cases in the *Variable Browser* (in the *Simulation* view), and bring the *Animation* window to the front. You can now animate them together by right-clicking on the previous results (in the *Variable Browser*) and choose *Animate Together* (run the visualization function again, or click on the car body to make the “camera” follow the vehicle).

How does the vehicle handle for the different brake-force distributions?

Why is the lateral dynamics affected in this way? (Hint: See Figure 2.)

## Task 6 – Benefits of EBD

Name two benefits with EBD, compared to a fixed brake-force distribution, that you have learned from the above tasks:

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## 2.2 Slip Control

Slip control is an alternative to ABS systems. ABS systems operate by reducing the braking pressure when the slip ratio approaches the unstable region, where if the braking force is kept constant the wheel will eventually lock (See Figure 1). In contrast, slip control systems control the slip ratio towards a desired value.

### Task 6 (P) – Wheel dynamics

Consider the dynamics of a wheel, the rotational acceleration  $\dot{\omega}$  is a function of the tire–road force  $F_b$  and by the applied braking torque  $T$ . Write down the corresponding equation of motion.

### Task 7 (P) – Slip control algorithm

In this task you are supposed to write down the basic control sequences of your slip controller, which you will use as a basis for the implementation. Synthesize your controller using the first order dynamics

$$\dot{\omega} - \dot{\omega}_{des} = k(\omega - \omega_{des}) \quad (1)$$

where  $\omega_{des}$  is the desired rotational wheel velocity and  $k$  is the controller gain.

- Replace  $\dot{\omega}$  with the wheel dynamics from Task 6 and write down the resulting controller using the applied braking torque as output.
- Formulate  $\omega_{des}$  as a function of the desired slip ratio  $i_{des}$ . (The slip ratio is defined in (2).)
- Calculate  $\dot{\omega}_{des}$ .
- Define a slip reference value  $i_{des}$  for your controller. (Hint: You can use Figure 1 for this.)
- Formulate a way to estimate the feedforward braking force  $F_b$ . Use either a fixed value or the sensors. Note that  $F_b$  in this case is the braking force for a single wheel, not all four.
- Which measurement signals do you need? Compare with Table 2 to ensure that your needed measurement signals are available.

Hint: You do not necessarily need to consider the effects from load transfer in your slip control, instead you may activate your EBD control.

### Task 8 (P) – Hydraulic brakes

In the Dymola model, the slip control is controlling a brake-force modulator, in which we have a brake-pressure pump that can raise the brake pressure individually for each wheel. For example, the brake line pressure for wheel 1 can be formulated as  $p_{b,1} = p_{b,max}u_{b,1}$ , where  $p_{b,max}$  is the maximum brake line pressure the brake-pressure pump and brake-force modulator can produce. The pressure will act over the two brake-caliper pistons with areas of  $A_{cp}$ , pressing the brake pads against the brake disc. The friction coefficient for the brake pads against the brake disc is  $\mu_{bp}$ . Thus, the total braking force from the brake caliper  $F_{caliper}$  can be expressed as

$$F_{caliper} = u_b p_{b,max} 2A_{cp} \mu_{bp}$$

which is acting on the brake disc at a radius of  $R_{disc}$  from the wheel center. Formulate an expression for the braking pressure signal  $u_b$  as a function of the braking torque  $T$ .

### Task 8 – Slip control implementation

Implement your controller in the model block called *SC* (TSFS02\_Lab1\_Braking - Vehicle - Brakes - BrakeComponents - FunctionBlocks - SC). Open up the model and switch to *Modelica Text* view. As for the *EBD* model, all sensor variables are defined at the top of the model as inputs (same set of sensors as before). The output variables are  $ub1$ ,  $ub2$ ,  $ub3$ , and  $ub4$ , being the normalized brake-pressure signals.

## Task 9 – Slip control evaluation

You will now evaluate your controller. Depending on your slip control implementation, you may wish to have the EBD controller enabled during simulations.

- a) **Straight-line full braking:** Open the *FullBraking* model.
- i) Make sure *SCOn* is *false* and run the experiment. Note that the wheels should lock up.
  - ii) Run the experiment with your SC active (set *SCOn* to *true*).

Use the existing plot and visualize functions after each simulation to study the results and show that your slip controller act as intended.

Estimate the braking distance (from when the brakes are applied):

Locked wheels: \_\_\_\_\_

With SC active: \_\_\_\_\_

- b) **Braking while cornering (full braking):** Open up *FullBrakingWhileCornering*.

- i) Run the experiment with slip control deactivated (*SCOn* set to *false*).
- ii) Run the experiment with slip control activated (*SCOn* set to *true*).

Use the existing plot and visualize functions after each simulation to study the results. Also, animate the two experiments together to visualize the differences.

How is the steering ability affected when the brakes are applied, with and without slip control?

## Task 10 – Benefits of slip control

Name the benefits of controlling the slip ratio that you have learned from these exercises:

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## A Vehicle and Tire Data

Table 1 specifies a few vehicle parameters, and in Table 2 the different measurement signals, available for the EBD and slip controller implementations, are listed.

Figure 1 show how the longitudinal tire force depends on the slip ratio  $i$ , with the slip ratio defined as

$$i = \frac{R_w \omega - v_x}{v_x} \quad (2)$$

where  $R_w$  is the wheel radius,  $\omega$  the wheel rotational velocity, and  $v_x$  the longitudinal velocity. Note that this slip definition returns a negative slip,  $i < 0$ , for braking. In Figure 2 the lateral force is shown, as a function of slip angle, for different slip ratios (i.e. for different levels of braking effort).

*Table 1 Vehicle parameters.*

Parameter	Description	Value	Unit
$m$	Total vehicle mass	1660	kg
$h$	CoG height	0.5	m
$L$	Wheelbase	2.7	m
$l_1$	CoG to front axle	1.2	m
$R_w$	Wheel radius	0.32	m
$J_w$	Moment of inertia of each wheel	1	kgm <sup>2</sup>
$\mu_x$	Friction coefficient	1	
$A_{cp}$	Piston area for the brake calipers	$9.6 \cdot 10^{-4}$	m <sup>2</sup>
$p_{b,max}$	Max hydraulic brake line pressure	$2.3 \cdot 10^7$	Pa
$R_{disc}$	Effective radius of brake discs	0.15	m
$\mu_{bp}$	Friction coefficient of brake pads	0.3	

*Table 2 Vehicle sensors for the EDB and slip controllers.*

Variable	Description	Unit
$a_x$	Longitudinal acceleration	m/s <sup>2</sup>
$a_y$	Lateral acceleration	m/s <sup>2</sup>
$v_x$	Longitudinal velocity	m/s
$\Omega_z$	Yaw rate	rad/s
$\omega_1$	Wheel velocity; front left	rad/s
$\omega_2$	Wheel velocity; front right	rad/s
$\omega_3$	Wheel velocity; rear left	rad/s
$\omega_4$	Wheel velocity; rear right	rad/s
$\delta_{sw}$	Hand wheel steering angle	rad
$F_{bp}$	Brake pedal force	N

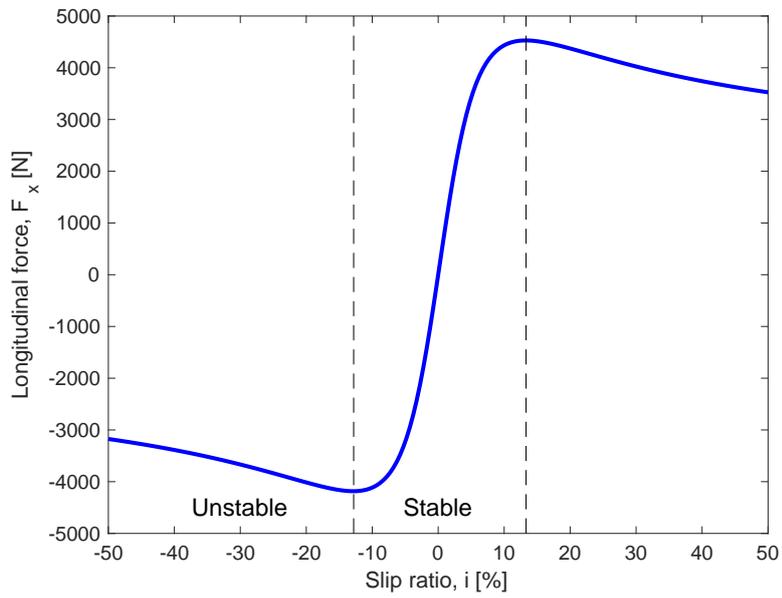


Figure 1 Longitudinal tire force.

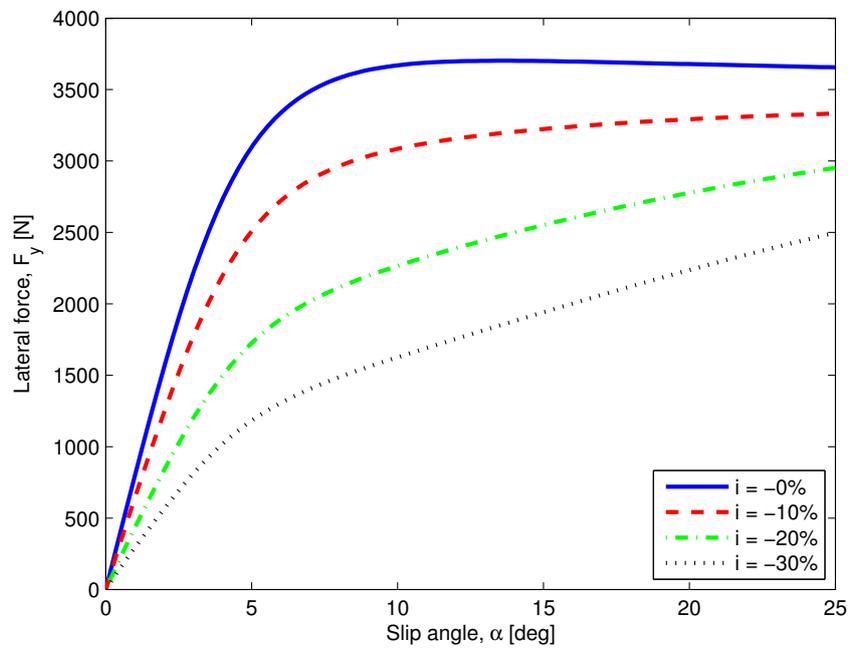


Figure 2 Lateral tire force.