

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 scheduled 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.

2 Preparation Tasks

The tasks in this section (i.e., Tasks 1–5) are preparation tasks that should be solved before starting with the computer exercises. Please verify with an assistant that you have solved these tasks correctly before starting with proceeding (since your code implementations will be based on the equations you derive in the preparation tasks).

Make sure that you have read this document thoroughly, as well as the Dymola introduction manual from the course page.

Task 1 – Brake-Force Distribution: *Simultaneous wheel lock-up*

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: *EBD control algorithm*

The brake-force distribution you calculated in the previous task 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 3 – Slip Control: *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 4 – Slip Control: *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 ω_{des} is the desired rotational wheel velocity and k is the controller gain.

- Replace $\dot{\omega}$ with the wheel dynamics from Task 3 and write down the resulting controller using the applied braking torque as output.
- Formulate ω_{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 5 – Slip Control: *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 μ_{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 .

3 Computer Exercise Tasks

Before starting with the computer exercises, download the model file TSFS02_Lab1_Braking.mo from the course homepage. Start Dymola (module `add courses/TSFS02` 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*). Previously saved results can be loaded from *Simulation - Load Result...* in the menu bar.

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.

3.1 Brake-Force Distribution

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

Task 6 – 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). 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 $K_{bf} = 1$. Change it by double-clicking the icon with the K_{bf} label, and then change the value in the parameters section. Save with the *OK* button. Run the simulation from the *Simulation* view. Look at the results by calling functions found under *Commands* in the toolbar. Save the results.
- Adjust the brake balance to rear only (set $K_{bf} = 0$). 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 7 – EBD implementation

Implement an EBD in Dymola, based on the expression you derived in Task 2. Go to the model block called *MyEBD* (TSFS02_Lab1_Braking - Controllers - MyEBD). Switch to *Modelica Text* view using the 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 8 – EBD evaluation

In this task you will evaluate your EBD controller with three different experiments. The first is the *RampBraking* from Task 6. 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.

- 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 value *EBD.ON* to 1; double-click on the icon named *EBD.ON*, and change the value. Run the experiment, and execute the plot and visualize commands.

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

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

- 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 *EBD_ON* is set to 0.)
- ii) Run the experiment with your EBD controller activated. (Switch *EBD_ON* to 1.)

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 9 – Benefits of EBD

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

3.2 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 10 – Slip control implementation

Implement your controller in the model block called *MySC* (TSFS02_Lab1_Braking - Controllers - MySC). 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 11 – 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 *SC_ON* is 0 and run the experiment. Note that the wheels should lock up.
 - ii) Run the experiment with your SC active (set *SC_ON* to 1).

Use the existing plot and visualize commands 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 (*SC_ON* set to 0).
 - ii) Run the experiment with slip control activated (*SC_ON* set to 1).

Use the existing plot and visualize commands 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 12 – Benefits of slip control

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

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, ω 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	1242	kg
h	CoG height	0.45	m
L	Wheelbase	2.65	m
l_1	CoG to front axle	1.23	m
R_w	Wheel radius	0.3264	m
J_w	Moment of inertia of each wheel	2.7	kgm ²
μ_x	Friction coefficient	1	
A_{cp}	Piston area for the brake calipers	$7.9 \cdot 10^{-3}$	m ²
$p_{b,max}$	Max hydraulic brake line pressure	$1.5 \cdot 10^6$	Pa
R_{disc}	Effective radius of brake discs	0.25	m
μ_{bp}	Friction coefficient of brake pads	1	

Table 2 Vehicle sensors for the EDB and slip controllers.

Variable	Description	Unit
a_x	Longitudinal acceleration	m/s ²
a_y	Lateral acceleration	m/s ²
v_x	Longitudinal velocity	m/s
Ω_z	Yaw rate	rad/s
ω_1	Wheel velocity; front left	rad/s
ω_2	Wheel velocity; front right	rad/s
ω_3	Wheel velocity; rear left	rad/s
ω_4	Wheel velocity; rear right	rad/s
δ_{sw}	Hand wheel steering angle	rad
F_{bp}	Brake pedal position	-

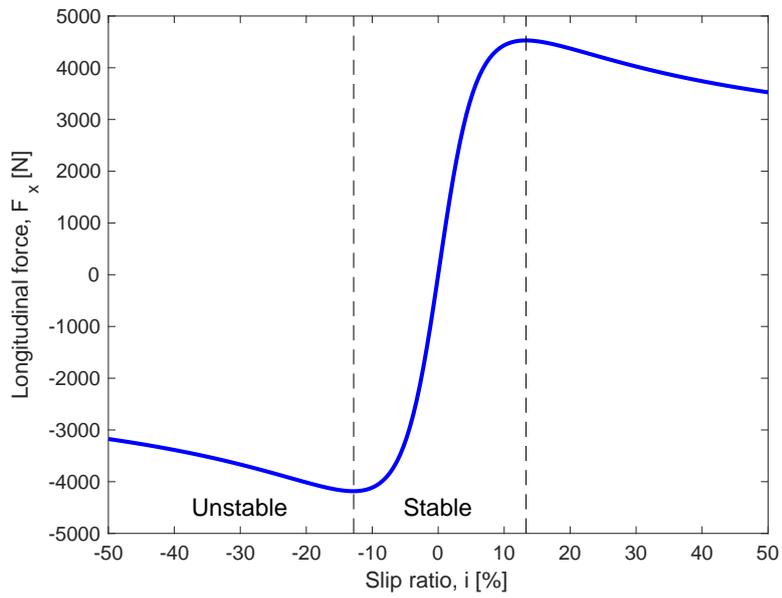


Figure 1 Longitudinal tire force.

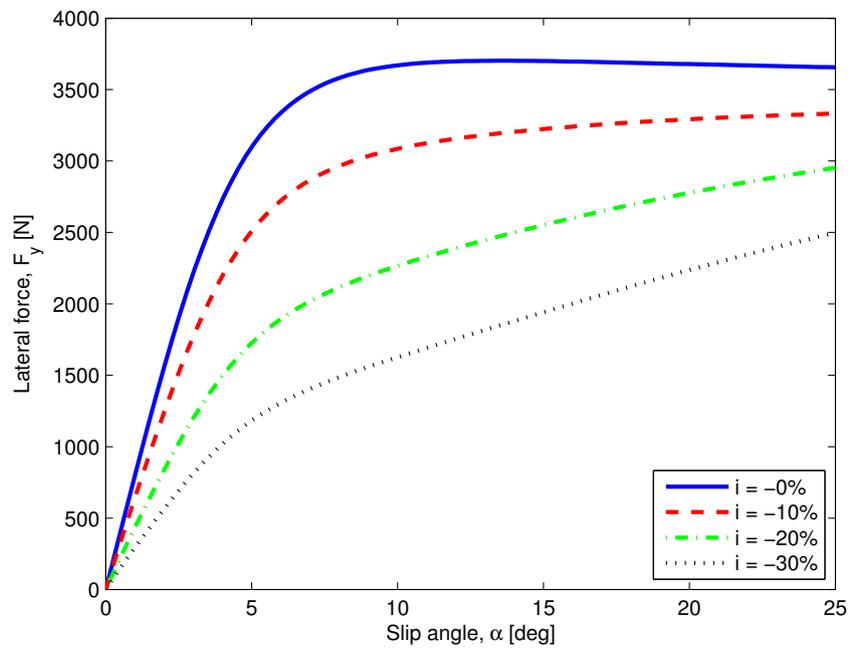


Figure 2 Lateral tire force.