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Development and Implementation of Drive Away Release Function for a Vehicle

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Abstract

As autonomy increases in today's vehicles, the demands increase on both safety and comfort functions. Vehicle Hold, which holds the vehicle stationary without requiring the driver to press the brake pedal, is an example of such as function. This thesis aims to develop a concept for a Drive Away Release from this hold state, following several requirements regarding such as rollback, comfort, manual and autonomous drive mode, driving direction, road inclinations, with or without a trailer, and following the safety standard ISO 26262.

In order to develop the concept function, a study of the state-of-the-art was made, followed by modeling the dynamics and control. The control algorithm was validated and tested first by running co-simulations between MATLAB/SIMULINK and CarMaker. It was then implemented in a test vehicle. The test vehicle did not have all systems which are usually provided, demanding estimations to be made, such as the road inclination and vehicle mass.

For manual drive mode, the driver controls the propulsion torque, and the control algorithm is based on releasing the brakes depending on estimations of the gravitational and propulsion torques. For autonomous drive mode, the vehicle is supposed to follow an acceleration reference. The control algorithm for autonomous drive mode is then extended with two feedforward compensators, one from reference and one from the gravitational torque, which is regarded as a disturbance, and with a feedback PI controller. To ensure that rollback do not occur at drive away release, a rollback prevention safety feature was also developed.

The results of both the simulations and the test drives show that the concept function provides comfortable drive-off for most inclinations, drive modes and directions, without causing an undesired rollback.

Acknowledgments

At long last, the time at the university nears its end, and we would like to begin by thanking Volvo Cars Corporation for providing the opportunity to do our master thesis here. A special thanks goes to Joakim Aidemark, Nina Fredriksson and all of the people working in Autonomous Motion & State Estimation for their help, guidance and the warm welcome on the first day.

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Contents

Notation

Abbreviations

Abbreviation	Meaning
ACC	Adaptive Cruise Control
AMT	Automatic Manual Transmission
ASIL	Automotive Safety Integrity Level
DAR	Drive Away Release
F	Forward drive
E/E Systems	Electrical and/or Electronic systems
ECU	Electronic Control Unit
EPB	Electric Parking Brake
EV	Electric Vehicle
HARA	Hazard Analysis and Risk Assessment
HAZOP	Hazard and Operability Analysis
HSA	Hill Start Assist
ICE	Internal Combustion Engine
IMU	Internal Measurement Unit
ISO	International Organization of Standards
LQR	Linear-Quadratic Regulator
PWM	Pulse-Width Modulation
QM	Quality Manager
R	Reverse drive
SAE	Society of Automotive Engineers
VCC	Volvo Cars Corporation

Notations

Notation	Meaning
α	Road inclination
α_c	Road inclination for the vehicle
α_v	Road inclination for the trailer
a	Acceleration
a_c	Vehicle acceleration
a_{ref}	Reference acceleration
a_v	Trailer acceleration
C	Constant term to integrate if roll back occurs
F_b	Brake force
F_g	Gravitational force
$F_{g,v}$	Gravitational force acting on the trailer
F_t	Propulsion force working between road and wheels
F_v	Force acting between vehicle and trailer
g	Gravitational acceleration
K_1	Brake torque request change limit factor
K_2	Brake torque request change limit factor
K_3	Brake torque request change limit factor
K_4	Brake torque request change limit factor
K_{low}	Lower change rate limit for brake torque request
k_1	Safety factor for gravitational torque
k_2	Safety factor for torque to keep vehicle stationary
M_b	Acting brake torque
$M_{b,app}$	Applied brake torque
$\hat{M}_{b,app}$	Estimated applied brake torque
$M_{b,req}$	Requested brake torque
M_g	Estimation of actual gravitational torque
$\hat{M}_g$	The DAR function's estimation of the gravitational torque
M_{stat}	Minimum torque to keep vehicle stationary
M_t	Acting propulsion torque
$\hat{M}_t$	Estimated propulsion torque
$M_{t,req}$	Requested propulsion torque
m_c	Vehicle mass
m_v	Trailer mass
R	Vehicle wheel radius
t_0	Time when rollback is detected
t_1	Time when vehicle starts to slow down during rollback
t_2	Time when the vehicle has stopped or started to move forward
v	Vehicle speed relative to the ground

1 Introduction

1.1 Background

In the global vehicle industry there is a campaign towards vehicle autonomy. During this campaign, the number of active vehicle motion control functions has increased. These functions are invented and developed for both safety and comfort reasons. One of these functions is *Vehicle Hold*, which is applied when the vehicle has reached standstill after braking. When the Hold function is active, the system keeps the vehicle stationary with the hydraulic service brakes, thus removing the need for the driver to press down the brake pedal. This is done by applying appropriate braking torque for a given inclination.

To be able to leave the Vehicle Hold function and start driving, a function called *Drive Away Release* (DAR) is used. In order to activate the DAR function, the driver has to either press the accelerator pedal, or the resume button. The latter is only for autonomous drive. When the driver initiates a driving request, the brakes start to release. This function creates comfort for the driver when starting in an inclination without having to worry about rolling backwards, which could result in an accident.

The DAR function used by Volvo Cars Corporation (VCC) is currently developed and delivered by different suppliers. It is therefore of interest to investigate the possibility to develop an in-house solution, both for economical and technical reasons. The current DAR functions are not accessible for VCC to view and structurally modify.

1.2 Purpose

The main purpose of this thesis is to develop and implement a novel and generic concept of a DAR function in a vehicle for

- Both manual (driver) and autonomous drive mode
- At different inclinations
- With and without a trailer

1.3 Requirements

There are several requirements that should be fulfilled by the DAR function, relating to both safety and comfort.

- The DAR function shall follow the ISO 26262 standard
- Smooth release without rollback at uphill (For the purpose of this thesis a rollback up to 10 cm is allowed when a trailer is hitched)
- Smooth release on downhill (and prevent too much acceleration)
- Smooth release on horizontal road
- Be able to release in *autonomous mode*
- Be able to release in *manual mode*
- Function for both *Drive* and *Reverse*

1.4 Method

In order to develop a functioning DAR according to the requirements, the thesis work will be divided into several parts. The first part is to research the state-of-art for Drive Away Release functionalities, as well as other needed research regarding vehicle dynamics and control strategies. In order to find relevant articles, search databases provided by Linköping University's library and VCC are used. Course literature from Linköping University may also be used. The thesis will also include studying the *ISO 26262 Road Vehicles - Functional Safety* standard.

After the research, the next step is to model the system and design a control structure for the DAR function. In order to give a theoretical validation of the function performance, the DAR function will be created in MATLAB/SIMULINK and co-simulated with the CarMaker simulation environment provided by VCC.

When the simulations has presented a valid control strategy for the desired DAR function according to requirements, the next step is to implement the function into a test vehicle. This will be done by CAN communication between dSPACE AutoBox and a computer, where the model is built in MATLAB/SIMULINK and tuned from dSPACE ControlDesk in real time. The test drives will include different scenarios, which the DAR function should be able to handle, and the results will then be compared to the simulations.

1.5 Limitations

During the thesis work there are some apparent limitations, which are presented in the list below.

- *Test Vehicle* - The thesis develops a concept DAR function, which will then be implemented into an older test vehicle. The test vehicle does not have the same signals as a new vehicle. This requires some estimations and extra functions, e.g. the autonomous drive mode, for the test vehicle to be made. Specific limitations because of this are described in Chapter 7.1.

- *Estimations* - In order to implement the desired DAR function into the test vehicle, it is required to estimate certain parameters which normally is implemented into the vehicles. Such estimations include mass and the road inclination.

- *ISO 26262* - The thesis work will apply a safety functionality in accordance to the ISO 26262, however making an accurate risk assessment require both a lot of time and experience. This means that the risk assessment made in this work is not complete, and will be made by VCC if the concept will reach the next level after the thesis work is done.

- *Volvo Documents* - Some data, information and requirements have been provided from company documents. Some of this data and information cannot be shared to the public. In order to handle this, information that has to be used will be rewritten in such a way that it cannot be seen as Volvo specific. For the purpose of the master's thesis, the results will be compared with the publicly available research.

2

System Description

In this chapter the system description is presented. First a basic system overview is given of the torque-based structure. It is followed by a description of the different drive modes the vehicle may use. Finally, a description of the DAR function itself is overviewed.

2.1 System Overview

In the early stages of the automotive history, the driver was in control of the propulsion system of the vehicle, i.e. the driver controlled the mechanical system, including the throttle, clutch, gear and more. Later on, the vehicle propulsion systems started to evolve. More functions were added in order to increase

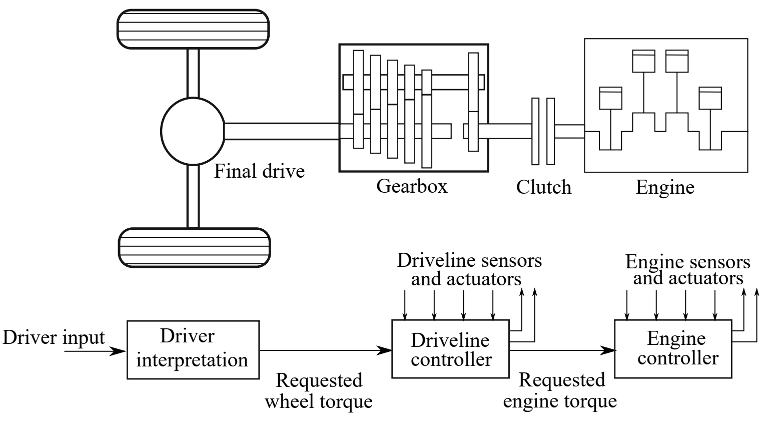


Figure 2.1: *Torque based control structure after [1].*

the performance, and as the number of functions increases, so does the complexity of the control system. This is because one function could influence several actuators, which in turn result in a cross-coupling effect and a demand for new control structures. There are many different control designs for the powertrain, however, the most popular one is the *torque-based structure*, and is termed *Torque-Based Powertrain Control*. The basic idea for this control structure can be seen in Figure 2.1, where the controller has been divided into several subsystems. The first subsystem is the *Driver interpretation*, which takes the driver's information by different inputs, such as the accelerator and brake pedals. The inputs are converted into requested torque at the wheels. The torque request is then sent to the next subsystem, the *Driveline controller*. The driveline controller can limit, or modify, the torque in order to protect the gearbox or prevent unwanted oscillations in the driveline. The last subsystem is the *Engine controller*, which has the task to fulfill the demanded torque from the driveline controller. [1]

2.2 Driving Mode

Before describing the functionality of the DAR function, two different driving modes, the DAR function can operate in, need to be clarified, *Manual* or *Autonomous*. During the manual drive mode the driver is in charge and controls the vehicle. By pressing the accelerator pedal, a request of the propulsion torque is made. Note that the manual drive mode does not indicate a manual transmission. The autonomous drive mode occurs when the vehicle is in an autonomous state. There are different applications which are set within the autonomous functionality, where one of the more popular ones is the *Adaptive Cruise Control* (ACC). The driver can leave the autonomous mode by either turning the autonomous function off or by pressing the brake pedal, meaning that the driver actions will override the autonomous functions.

2.3 Drive Away Release

From the torque-based control structure, the DAR function will be implemented into the driver interpretation block. Initially, in order to activate the DAR function, the vehicle must be in Hold, i.e. the service brakes prevent the vehicle from moving. In order to start driving the vehicle, the driver initiates a drive request. The drive request needs to have a driving direction, i.e. forward or reverse gear, and a drive mode, i.e. autonomous or manual. The driver can activate the DAR function by either pressing the accelerator pedal for manual or by pressing the resume button for the autonomous drive mode.

The two different drive modes supply different reference and control signals for the system. During the manual drive mode, the driver requests the propulsion torque and the DAR function controls the brake torque request, whereas for the autonomous drive mode, the reference is an acceleration request, leading to the DAR function controlling both the propulsion and brake torque requests. Depending on which drive mode the vehicle is in, the signal will enter its corresponding control function. The objective of the control function is to release the brakes in the desired fashion, i.e. without rollback or a high jerk. An overview of the DAR function's input and output signals can be seen in Figure 2.2. The input signals are divided into two groups, the signals which the driver has direct control over, such as driving mode, driving direction, propulsion torque request (manual mode). The other group of input signals are measured or estimated quantities, such as vehicle mass, road inclination, estimated propulsion and brake torques.

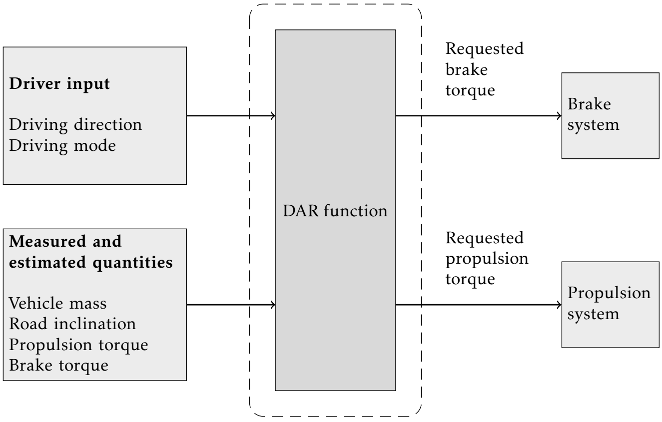


Figure 2.2: *DAR function overview.*

3

Related Research

In this chapter the related research is presented. The chapter contains both theory and state-of-the-art methods of hill starting and control. It covers the basics of the longitudinal vehicle dynamics, measures of comfort and control systems. The chapter ends with a summary of the ISO 26262 standard.

3.1 Vehicle Dynamics

The vehicle dynamics of the thesis report include a general presentation of the longitudinal propulsion when driving in a slope, followed by theory regarding hill start.

3.1.1 Longitudinal Propulsion

When a vehicle moves in the longitudinal direction, there are several forces acting on the vehicle. The dynamics of the vehicle can be determined with the help of the second law of Newton, see e.g. [1]. The acting forces are displayed in Figure 3.1. Which gives the following force equilibrium in the longitudinal direction

$$m_c a = F_t + F_b - F_a - F_r - F_g, \tag{3.1}$$

where F_t is the propulsion force between the road and the wheel. F_b is the brake force which includes the usual brake system, i.e. not negative torque from the engine and powertrain losses which might cause deceleration. Other forces, acting in the opposite direction of the movement, are the resistance forces which occurs during driving. The first one is F_a, the air drag resistance,

$$F_a = \frac{1}{2} c_w A_a \rho_a \left(v - v_{amb}\right)^2, \tag{3.2}$$

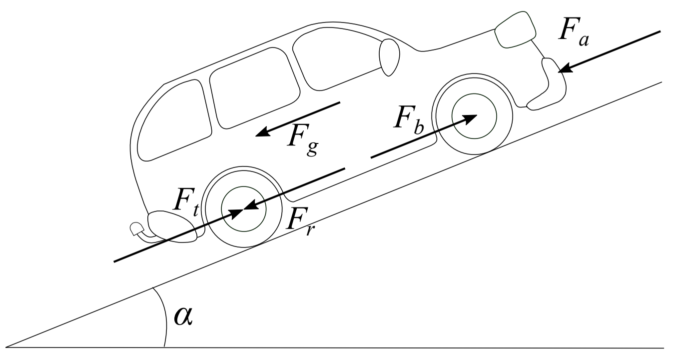


Figure 3.1: *Displaying the different forces acting on the vehicle.*

where c_w is the air drag coefficient, A_a is the cross-section area of the vehicle and ρ_a is the air density. Within the parenthesis are v, the vehicle speed relative to the ground, and v_{amb}, the speed of the ambient wind relative to the ground. The rolling resistance F_r can be described as

$$F_r = f_r mg \cos\alpha, \tag{3.3}$$

where f_r is the rolling resistance coefficient, g is the gravitational acceleration, m is the mass of the vehicle and α is the road inclination. The gravitational force F_g can be described as

$$F_g = mg \sin\alpha. \tag{3.4}$$

3.1.2 Hill Start

Starting in a hill with a so-called *Hill-Start Assist* (HSA) is covered in, e.g. [2–4]. Equation (3.1) shows the forces of a moving vehicle, when the vehicle is stationary F_b in this equation represents the minimum brake force required to keep the vehicle stationary. When a vehicle is at standstill in a hill, the brake force has been applied such that it exceeds the gravitational force [3]. The force equilibrium shown in Equation (3.1), shows resistance forces, F_a and F_r, as well. However, starting in a hill is considered to be a quasi-static vehicular movement, meaning it changes at a slow rate [4]. This leads to the resistance forces and the acceleration force of $m_c a$ often being neglected during a hill start, although, the authors in [2] take the rolling resistances into account. When initiating a hill start the torques during the start are the propulsion torque M_t, the brake torque M_b, and the torque provided from the gravitational force [3]. Before the vehicle starts to move, the braking torque decreases as the propulsion torque increases, see Equation (3.5).

$$M_b = M_t - mgR \sin\alpha, \tag{3.5}$$

where R is the wheel radius. When the propulsion torque increases enough to hold the vehicle of its own, i.e. $M_t = mgR\sin\alpha$, the resulting braking torque equals zero, $M_b = 0$. If M_t keeps increasing, such that $M_t > mgR\sin\alpha$, M_b

starts acting in the opposite direction and therefore preventing the vehicle from moving forward [3]. If the brakes are fully released while the vehicle is moving, the jerk of the vehicle increases at that moment [4]. According to Hu et al. [2], experiments with electric vehicles shows that the vehicles does not start rolling if the grade ramp is less than 2°.

3.2 Comfort

One way to determine the ride quality is to use jerk as a performance index [5], which is the time derivative of acceleration. There are different ways on how to relate comfort to jerk. For instance, one can observe the peak of jerk, i.e. looking at its highest peaks, or determine the root mean square during a sequence. The frequency of the jerk also influences how comfortable the ride is. Huang and Wang [5] made a study of the physiological experience of jerk, where they took these different viewpoints into account. The study was based on going from standstill to driving different drive cycles with different gear shifting, in different scenarios, looking at both durational and transient jerk. During the test runs, passengers pressed one of three graded buttons every time they felt the jerk in an uncomfortable fashion. The results during the drive-off shows that a jerk between 2 – 2.5 m/s^3 could occur without indicating a discomfort from the passengers. Hubbard and Youcef-Toumi [6] states that the limit for passenger comfort is at 0.3 g/s, or approximately 2.94 m/s^3, and in the study by Hu et al. [2] the achieved jerk was 2.5 m/s^3, which the authors claimed to be a very good ride comfort.

Peng et al. [7] made a study looking into different control systems for HSA with an electronic parking brake system. These studies were implemented to look at three different controllers at different road inclinations as well as with different brake release delays. In their results, the values of jerk are presented for the different controllers. The smallest achieved jerk is at 1.03 m/s^3, at an 8 % grade, and the largest 2.06 m/s^3, at an 18 % grade. is as the highest.

3.3 Control Strategy

In this section the state-of-the-art of control of the hill start is presented, as well as control theory which will be used in the thesis solution.

3.3.1 State-of-the-Art: Hill Start Control

Researching the topic of hill-start provides different ways of controlling the hill-start function. The variation can depend on the kind of transmission, brake type and also what is to be controlled, for example the clutch or the valves to hydraulic brakes or something else. Most of the sources handling the hill-start, focus on an up-hill start.

In order for a vehicle to be at standstill in a slope, the braking force needs to exceed the gravitational force [3]. When the drive-off is initiated the brakes start to release, and the time when the brakes have fully release should correspond to when the propulsion force is large enough to hold the vehicle by itself, i.e. $F_t = F_g$. If the brakes release earlier than this, the vehicle starts to roll downhill, and if there is a delay, the jerk increases and the brakes wear. This is a common consideration covered in e.g. [3, 4, 7–9]. To find the optimal torque split between the braking torque and the drive torque of the wheels, and the complete release of the brakes, are some of the big challenges in developing the control [8]. Often this can be improved by releasing the brakes depending on an accurate estimation of the road inclination and vehicle mass [3]. However, it is a common practice when applying the electric parking brake (EPB) to set the brake force to its maximum value, which creates safety from risking undesired movement when the vehicle is supposed to be still, and not relying on measures of mass and road inclination. The consequence of this is that the more the applied brake force exceeds the required force to keep the vehicle stationary, the longer the release time of the brakes. By using a bang-bang controller to control the pressure of the brakes for the hill-start functionality of the EPB for the commercial vehicle, the authors in [7] show that it is possible to gradually release the EPB, with the help of a PWM signal, according to the driving torque.

For vehicles with an internal combustion engine (ICE), it is common to control the torque converter or the clutch in order to achieve a smooth start [2]. For instance, [10] presents an optimal controller of a dry clutch for an automatic manual transmission (AMT) vehicle, when developing a hill-start function. The control is based on the state space equations of the driveline dynamics and a LQR controller and requires an accurate angle estimation of the road inclination. According to the authors of [9], how smooth the drive-off is dependent on how good the clutch control is. The article suggests that the performance of a hill-start is determined on the coordination between the clutch control, the brakes and the throttle, where the release speed depends on the gravitational torque, and how the torque is transferred to the clutch engagement. For larger gravitational forces, the moment when the brakes start to release should be close to when the clutch torque is able to overcome the gravitational resistance forces. In order to create a smooth drive-off, without sliding and increasing the comfort of the ride, the authors of [8] presents a disturbance observer, with a H_∞ control and a feedforward-feedback compensation when creating the HSA systems. The vehicle mass, the road inclination and the engine torque are considered as disturbances. H_∞ is used in order to reduce the effect of the disturbance. Another example of using a control of the clutch engagement during the hill-start and brake release is presented by Zhang and Li [11]. The control is based on a method using the accelerometer, and where the control system is divided into two different parts. The first part contains a control algorithm with the purpose to keep the engine speed constant during the start-up process. This is achieved by using a cascade double loop control. The other part is setting the reference of the engine speed. The algorithm is based on a fuzzy control, where the reference signal is chosen from a selection of classes depending on slope gradients. [11]

A study of an electric vehicle (EV), where the motor is connected to the driveshaft which has a fixed gear ratio reducer [2], presents a different control compared to starting controls used for the ICE vehicles. Because of the absence of the clutch in the EV, the control requires to make the motor torque to adapt to the vehicle condition. The basic structure and principle of a HSA in an EV is that the vehicle can maintain and release the brake force with help of an electronic control unit (ECU) in order to control an ON/OFF switch. The switch is connected to the hydraulic circuit by controlling valves connected to the brake cylinders and the wheels, thus controlling the hydraulic pressure of the brakes. In order to achieve a smooth and safe start, the system needs to act according to the driver's intention and the integrated control of the hill-start includes the motor control, the resistance calculations and the control of the hill-start valve. The motor control is mainly based on how the drive torque is corresponding to the accelerator pedal's position. [2]

3.3.2 Control Theory

The control theory includes short description of feedforward from both disturbance and from a reference

Feedforward from Disturbance

There are often disturbances which affects the output y of a system [12]. If these disturbances are measurable, they can be used together with the reference signal r in order to calculate the desirable control signal. This is done by creating a feedforward F_f from the disturbance v to the control signal u, although it is important to realise that other disturbances may still be active. By using the feedforward, there is a possibility to eliminate the influence of the disturbance completely. However, even if calculations provide exact results, the reality always have a small difference, leading to the disturbance not being completely eliminated. This will cause an error which will be noticed in the output signal, which means that a feedforward is sensitive to variations of parameters in the system and it also required good knowledge about the process. The benefits of using the feedforward is that it gives the opportunity to compensate for the disturbance before its effects have shown themselves on the output signal, in difference from a feedback loop which is based on the measurements of the output signal. The layout of a feedforward from disturbance is shown in Figure 3.2. [12]

As shown in the figure, the transfer functions from the reference signal and the disturbance to the output signal can be described as

$$Y = \frac{G_2 G_1 F}{1 + G_2 G_1 F} R + \frac{1}{1 + G_2 G_1 F} G_2 (H + G_1 F_{fd}) V \tag{3.6}$$

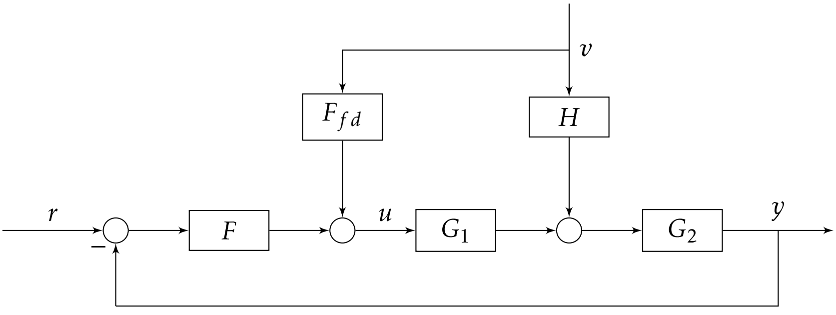


Figure 3.2: *Feedforward from a disturbance and feedback loop [12].*

Feedforward from Reference

Another kind of feedforward control, is to create a feedforward from the reference signal [13], see Figure 3.3. G_m is the reference model to ensure the desired response from the reference signal r. In order to create a smooth reference tracking the reference model can be designed as

$$G_m = \frac{1}{sT+1}, \tag{3.7}$$

where T is the desired time constant. F_f is the desired controller of the feedforward of the reference signal. To create an ideal feedforward loop, the controller should be set to

$$F_{fr} = \frac{G_m}{G}, \tag{3.8}$$

which gives the desired reference tracking regardless of the feedback control. However, there are always some errors in the model development in reality, which means that the reference tracking is not perfect. The effects of the error does, however, decrease due to a feedback loop. [13]

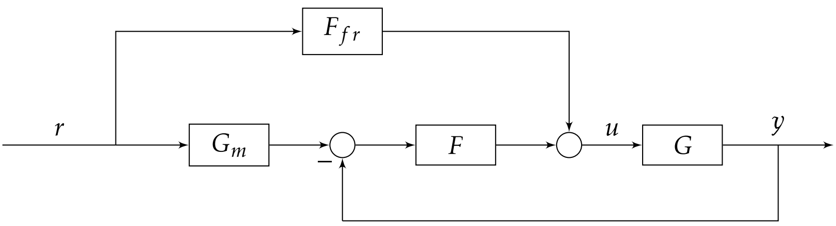


Figure 3.3: *Feedforward of reference signal and a feedback loop [13].*

3.4 ISO 26262

ISO 26262: Road vehicles - Functional Safety is the international standard for the functional safety for electrical and/or electronic systems, i.e. E/E systems, which are installed in series production road vehicles. ISO 26262 has the objective to standardise how to handle possible hazards that may occur due to malfunctioning behaviour of, or interacting with, the E/E systems [14]. Note that when the risk assessment according to ISO 26262 is done in this thesis, the guidelines of SAE International [15] are followed. The description that follows is therefore only a basic explanation of what different steps mean, rather than a thorough description. The result of the risk assessment can be found in Appendix A, and as mentioned in Chapter 1.5, VCC will make a more thorough risk assessment if there is a desire to move forward with the presented concept of this thesis.

3.4.1 Automotive Safety Integrity Level

When making a risk analysis in accordance to ISO 26262, the idea is determine the *Automotive Safety Integrity Level* (ASIL), for the E/E systems. The ASIL is classified in four different groups, A, B, C and D. Where D demands the highest integrity of the function, and A the lowest. In order to make the ASIL classification, the first step is to make a *Hazard Analysis and Risk Assessment* (HARA), which is done during the concept face of the function's development. HARA identifies possible hazards of system malfunction, and the ASIL is then determined by evaluating these hazards from three different perspectives: *Severity*, *Exposure* and *Controllability*. [15]

3.4.2 Hazard Analysis and Risk Assessment

When designing a new system, it is important to define both its intended functionality as well as the safety goals of the system, in order to set the functional safety requirements. Therefore it is of great importance to determine different hazards of the intended system, which can be done with several different analysis techniques. SAE International [15] presents a technique called *Hazard And Operability Analysis*, (HAZOP). The idea of HAZOP is to set *guidewords* for each function of the system. By comparing each function with the guidewords, different vehicle malfunctions can be identified as a results. The setup for guidewords are presented in the list below, and for the DAR function see Appendix A. [15]

1. Loss of function - The function is not provided when it is supposed to
2. Function providing incorrectly when intended - The function is provided, but not as intended i.e. too much, too little or in a wrong direction
3. Unintended activation of function - The function is provided without an intended request
4. Output stuck at a value - The function is not updated to current states or requests

After finding the malfunctioning behaviours, the outcome in terms of vehicle hazards may be determined. The hazards can then be assessed in different steps according to severity, exposure and controllability. [15]

S - Severity

Severity is defined by the potential harm due to a hazardous event. It is categorized into four different classes from S0 to S3, see Table 3.1.

Table 3.1: *Classification of severity.*

Severity Class	Description
S0	No injuries (No ASIL is assigned for this class)
S1	The injuries are light and moderate
S2	The injuries are severe and life-threatening with probable survival
S3	The injuries are life-threatening where survival is uncertain, i.e. fatal

How severe an outcome is due to a collision depends on several factors, which means it is not always possible to determine the severity in advance. Such factors includes collision type, relative speed, the vehicle crash compatibility and more. In order to assign a severity class, hypothetical scenarios have to be created. These are often based on, for example, information of expert analysis, technical reports, simulations, and historical crash data. [15]

E - Exposure

Exposure is classified depending on how probable a vehicle operational situation is, i.e. how often or how long the function is in use. There are five classes of exposure going from E0 to E4, see Table 3.2. The probability of exposure can be determined in different ways, such as frequency, how often the function is used, and duration, percentage of operating time the function is used, of exposure. Note that exposure is not the probability of occurrence since its based on system basis and not compared to a specific user basis. When assessing the probability of exposure, one needs to base the probability on realistic situation from normal driving conditions to more adverse ones. It is important to know that the exposure level may vary due to external factors such as traffic rules and environmental conditions, influence the considered situation. Depending on which way to determine the probability of exposure is used, the classification may end up with different results. [15]

Table 3.2: Classification of Exposure.

Exposure Class	Description
E0	Incredible (No ASIL is assigned for this class)
E1	Very low probability
E2	Low probability
E3	Medium Probability
E4	High Probability

C - Controllability

The last classification to be made is controllability. Controllability is determined by how likely it is for the driver, or other traffic participants, to prevent an injury. This is classified into four different classes scaling from C0 to C3, see Table 3.3. [15]

Table 3.3: Classification of controllability.

Controllability Class	Description
C0	Controllable in general (No ASIL is assigned to this class)
C1	Simply Controllable
C2	Normally Controllable
C3	Uncontrollable or difficult to control

3.4.3 Determine ASIL

After having classified the three different perspectives, ASIL may be determined for the hazardous events which has been identified. The result of the risk assessment is found by combining the results of these perspectives, where combinations of higher classes result in a higher ASIL. As stated before the ASIL classification is determined from A - D, however the ASIL can also be classified as Quality Management (QM) which implies that there is no need for extra safety measures, but rather that normal development process is sufficient according to ISO 26262. The combinations in order to define ASIL are shown in Table 3.4. [15]

Table 3.4: *Determination of ASIL, [15].*

		C1	C2	C3
S1	E1	QM	QM	QM
	E2	QM	QM	QM
	E3	QM	QM	A
	E4	QM	A	B
S2	E1	QM	QM	QM
	E2	QM	QM	A
	E3	QM	A	B
	E4	A	B	C
S3	E1	QM	QM	A
	E2	QM	A	B
	E3	A	B	C
	E4	B	C	D

4

Modeling and Control

In this chapter, models for torque calculations and balances are described, as well as the implemented controls and estimations.

4.1 Modeling

This section starts with a clarification of torques used in the modeling and the system, followed by modeling of the dynamics with only the vehicle, the trailer is then added and how the extra body influences the dynamics equations.

4.1.1 Torque Clarifications

In this report, several different propulsion and brake torques are used. Before presenting the models and control for the DAR function, the differences between these torques need to be clarified. The torques used represent the total torque of all wheels. There are three different propulsion torques: requested propulsion torque $M_{t,req}$, actual propulsion torque M_t and estimated propulsion torque $\hat{M}_t$. $M_{t,req}$ is the torque demanded from the DAR function, it is then up to the powertrain to deliver the requested torque. The actual propulsion torque M_t is the torque acting on the wheels and the estimated $\hat{M}_t$ is an estimate of the actual propulsion torque. The last two torques are quite similar, but the difference is that during the simulations M_t can be used, whereas test vehicle provides an estimation.

There are four different kinds of brake torques: requested brake torque $M_{b,req}$, applied brake torque $M_{b,app}$, estimated applied brake torque $\hat{M}_{b,app}$ and the actual brake torque M_b. The actual brake torque M_b is the brake torque acting on the wheels from the brake discs. The requested brake torque $M_{b,req}$ is a brake torque request from the DAR function which corresponds to how much force should be applied between the brake pads and the discs, which is the maximum torque the brakes should apply. This leads to the applied brake torque $M_{b,app}$, which is the maximum brake torque the brakes can apply. $\hat{M}_{b,app}$ is an estimate of the applied brake torque. As for M_t and $\hat{M}_t$, the applied and estimated brake torques are similar, and represent the simulations and test vehicle, respectively.

There are also two different kinds of gravitational torque. M_b relies on an input from the gravitational torque, as seen in Equation (3.5), as such, the function will need an input of the estimated gravitational torque, denoted $\hat{M}_g$, which will be used within the DAR function and does not include a trailer. In Chapters 6 and 7, the results show gravitational torque which is an estimation of what the actual gravitational torque would be, denoted M_g, i.e. this is calculated with a set road inclination and mass including trailer.

4.1.2 Vehicle without Trailer

As stated in Chapter 3.1.2, the rolling resistance and drag force can be neglected, this means that the Equation (3.1) can be written as

$$m_c a_c = F_t + F_b - F_g. \tag{4.1}$$

F_g is modeled according to Equation (3.4). The propulsion force F_t and brake force F_b acting on the vehicle can then be written as

$$F_t = \frac{M_t}{R}, \tag{4.2}$$

$$F_b = \frac{M_b}{R}, \tag{4.3}$$

where M_t is the total propulsion torque acting on the wheels from the driveline and M_b is the total braking torque acting on the wheels from the brakes. Equation (4.1) can now be written as

$$m_c a_c = \frac{M_t}{m_c R} + \frac{M_b}{m_c R} - m_c g \sin \alpha_c. \tag{4.4}$$

The control signals for this system are the propulsion torque and the brake torque. The system of the vehicle provides an estimate of the propulsion torque at the wheel, however, the estimated brake torque is an estimation of the applied brake torque, $\hat{M}_{b,app}$, i.e. it is not the brake torque present from the torque balance in Equation (3.5), but the maximum torque that the brakes are able to apply at that moment. This gives that the brake force, F_b, can be defined as

$$F_b = \begin{cases} F_t - F_g & \text{if } v = 0, \\ \dfrac{M_{b,app}}{R} \cdot \text{sign}(v) & \text{else,} \end{cases} \tag{4.5}$$

where $M_{b,app}$ is the applied brake torque and v denotes the vehicle velocity in the travel direction.

4.1.3 Vehicle with Trailer

Hitching a trailer to the vehicle will add a force from the trailer, which either pushes or pulls the vehicle depending on travel direction and position relative to the vehicle. When adding the trailer to the vehicle, Equation (4.1) can be written as

$$m_c a_c = F_t + F_b - F_g - F_v, \tag{4.6}$$

where F_v is the force acting between the vehicle and trailer. By neglecting the rolling resistance and aerodynamic drag acting on the trailer, the equation describing the dynamics for the trailer can be written as

$$m_v a_v = F_t - F_{g,v}, \tag{4.7}$$

where m_v is the mass for the trailer, a_v is the acceleration for the trailer and $F_{g,v}$ is the gravitational force acting on the trailer (see Figure 4.1). The gravitational force can then be modeled similar to Equation (3.4), which yields

$$F_{g,v} = m_v g \sin \alpha_v, \tag{4.8}$$

where α_v is the road inclination for the trailer. From Equations (4.4), (4.7) and (4.8) the dynamics of both the vehicle and the trailer can be described as

$$a_c = \frac{M_t}{m_c R} + \frac{M_b}{m_c R} - g \sin \alpha_c - \frac{m_v}{m_c} \left(a_v + g \sin \alpha_v \right). \tag{4.9}$$

However, for this equation to be valid, the slopes for both the vehicle and the trailer need to be the same, i.e. $\alpha_c = \alpha_v = \alpha$. The trailer itself is connected with a rigid link and therefore the vehicle and the trailer should also have the same acceleration, i.e. $a_c = a_v = a$. This gives the common acceleration

$$a = \frac{M_t + M_b}{(m_c + m_v)R} - g \sin \alpha. \tag{4.10}$$

Note that there are two different masses in this equation, one for the vehicle and one for the trailer, and thus the total mass for the vehicle and trailer is uncertain.

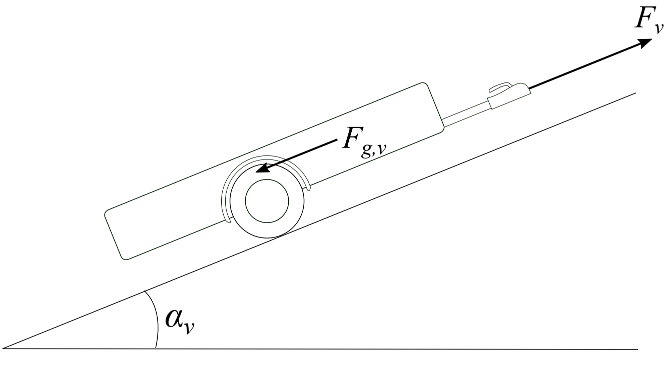


Figure 4.1: *Forces acting on the trailer in the uphill direction.*

4.2 Control Strategy

As mentioned in Chapter 3.3.1, there are several different ways to control the drive-off function when starting in a hill, where the aim is to release the brakes at the same moment as the propulsion torque overcomes the gravitational torque and therefore holding the vehicle. Most of the articles about a HSA function includes EPB rather than the service brakes, but the basic idea is the same. As the system description in Chapter 2 states, the input and output control is based on brake propulsion torque request, leading to a more applicable control regardless of the driveline or engine type. These input signals are provided by other systems, how the signals are measured or estimated is unknown.

4.2.1 Uphill Brake Control

When an uphill drive-off is initiated, there is a risk of rollback if the brakes releases to early. As stated in Chapter 3, there are also risks of increased wear and reduced comfort if the brakes are released to slow. In order to handle this, the brake torque is reduced as the propulsion torque increases. An estimated propulsion torque is a provided signal to the system and the requested brake torque can then be described as

$$M_{b,req} = \hat{m}_c g R \sin\hat{\alpha} - \hat{M}_t, \tag{4.11}$$

where ($\hat{\cdot}$) denotes estimated values for the vehicle mass, road inclination and propulsion torque. Uncertainties in the estimations may cause rollback, for instance mass estimation error could lead to a large impact of the estimated gravitational torque. In order to prevent rollback due to errors in estimations, a safety factor for the gravitational torque is introduced. The brake torque request is therefore defined as

$$M_{b,req} = k_1 \hat{m}_c g R \sin\hat{\alpha} - \hat{M}_t, \tag{4.12}$$

where k_1 is the safety factor and $k_1 > 1$. This control law can be tuned to fulfill the requirement of no rollback when starting without a trailer.

When hitching a trailer to the vehicle, an additional force is acting on the vehicle (see Equation (4.6)). This force can be regarded as a disturbance to the system. In order to keep the vehicle stationary, the force balance

$$F_t + F_b = F_g + F_v, \tag{4.13}$$

needs to be met. Before activating the DAR function, the vehicle is in Hold where $M_{b,req}$ is larger than the gravitational and trailer forces together. When the DAR function is activated, the control law in Equation (4.12) is activated, which lowers the requested brake torque. If the sum of propulsion and brake torques becomes lower than the gravitational and trailer torques, the vehicle starts to roll downhill. This is an undesired behavior and how the rollback is detected is presented in Chapter 4.2.5. When rollback occurs, it is paramount to stop the vehicle, which is done by increasing $M_{b,req}$. However, how much it should be increased is unknown. If the brake torque is increased too much it may result in increased wear of the brakes, or a damaged driveline due to a large propulsion torque which is able to make the vehicle move forward. On the other hand, increasing too little may result in a rollback which violates the rollback requirement of the thesis.

In order to find the required brake torque to stop the vehicle, let M_{stat} denote the minimum torque required to keep the vehicle stationary, i.e. the smallest sum of the actual propulsion and brake torques where the vehicle is still stationary. An estimate of the propulsion torque is directly provided by other systems. However, as mentioned in Chapter 4.1.1, the actual brake torque is not. By using Equation (4.5) and replacing the brake torque with the estimated brake torque, the brake force when the vehicle is moving can be estimated as

$$\hat{F}_b = \frac{\hat{M}_{b,app}}{R} \cdot \text{sign}(v). \tag{4.14}$$

The moment rollback occurs provides information about the added trailer force F_v. Let t be the time when the vehicle starts to move and $t-1$ the time when the vehicle is still stationary. This means that $M_{b,app}(t-1)$ is close to the brake torque required to keep the vehicle stationary, note that $M_{b,app}$ is not holding the vehicle of its own, but as Equation (4.10) states, it depends on the propulsion torque as well. The required torque to hold the vehicle can therefore be estimated as

$$\hat{M}_{stat} = \hat{M}_t(t-1) + \hat{M}_{b,app}(t-1). \tag{4.15}$$

However, at the time t, the vehicle is rolling downhill and needs to be stopped. According to Equation (4.10) this requires a positive acceleration, which means that given a constant propulsion torque, this is achieved by requesting a brake torque which exceeds $\hat{M}_{stat}$. Due to errors in estimations of $\hat{M}_t(t-1)$ and $\hat{M}_b(t-1)$, $\hat{M}_{stat}$ might be estimated to low, and therefore needs a safety factor. For safety reasons it is important that the vehicle is able to stop by only reapplying the brakes, i.e. without propulsion torque. When the system detects rollback, it activates the rollback prevention

$$M_{b,req} = k_2\hat{M}_{stat} - \hat{M}_t + C\left(\int_{t_0}^{t_1} 1\ dt + \int_{t_1}^{t_2} 1\ dt\right), \tag{4.16}$$

where $k_2 > 1$ and is the safety factor. The rollback prevention consists of two different integrators in order to give an extra boost to $M_{b,req}$. The time t_0 is the time the system detects rollback, and at t_0 there is an instant brake torque request to $\hat{M}_{stat}$, and the first integrator is activated. The first integrator is active until the vehicle starts to slow down, i.e. positive acceleration, which occurs at the time t_1. At this time, the second integrator activates and requests additional brake torque to ensure that the vehicle stops. When the vehicle has stopped, or the started to move in the desired direction, at time t_2, the second integrator is set to zero.

Uphill Brake Torque Request Limitations

In order to ensure that the brake torque does not release too soon, or applies brake torque after the vehicle starts to move forward, some limitations are set on the brake torque request. To begin with, $M_{b,req}$ cannot be negative, if this is the case it will be set to zero.

The brakes should not be able to release too quickly, and therefore the rate of change in $M_{b,req}$ needs to be limited. This is done by implementing a rate limiter which restricts how fast the brake torque request changes

$$K_{low} \leq \dot{M}_{b,req}, \tag{4.17}$$

where K_{low} is the lower limit of the ramp out when releasing the brakes. For safety reasons, the brakes should be able to reapply without any restrictions, therefore no upper limit is set. The lower limit K_{low} however, should depend on factors as the road inclination and the driver's intention. If the driver intends to drive uphill, the ramp out cannot be too slow, as this would lead to the brakes still being applied when the propulsion torque is large enough to make the vehicle move, causing the brakes to act against the forward movement, decreasing the acceleration, wear the brakes, and when the brakes finally releases, increase the jerk. The lower limit of uphill driving can therefore be set as

$$K_{low} = -K_1, \tag{4.18}$$

where K_1 is a constant which represents the ramp out for uphill driving.

When the vehicle starts to move uphill, $M_{b,req}$ is set to zero, this is determined when the velocity exceeds a velocity limit v_{lim}, which is set to ensure the vehicle is not standing still and therefore risk a premature release of the brakes. Note that $M_{b,req}$ may become zero before this (see Equation (4.12)).

4.2.2 Downhill Brake Control

When the desired direction is downhill, there is no risk of rolling backwards, hence the gravitational and propulsion torque is acting in the same direction. During manual drive mode, the driver has control over the propulsion torque, which means that when the DAR function is activated, the braking torque should be set to zero,

$$M_{b,req} = 0. \tag{4.19}$$

Downhill Brake Torque Request Limitations

As $M_{b,req}$ is zero, the drive-off is determined by the ramp out, i.e. by setting K_{low} in Equation (4.17). According to Equation (4.10) the acceleration depends on the acting propulsion and braking torques, but also the gravitational torque, which depends on the road inclination. A higher inclination leads to a larger gravitational torque which may result in a higher acceleration if there is a quick release of the brakes. A high acceleration puts a higher demand on the driver's reaction time. Another consequence may be an increased jerk, which reduces comfort. It is therefore desired to have a slow ramp out for higher inclinations and vice versa for lower inclinations. The suggested ramp out can be described as

$$K_{low} = -K_2 + K_3 \,|\, \sin\alpha \,|, \tag{4.20}$$

where K_2 is a constant which represents the ramp out on horizontal road, and K_3 is a constant gain in the term $K_3|\sin\alpha|$, which adapts the ramp out depending on the road inclination. However, the vehicle is initially in Hold, which means $M_{b,app}$ is larger than M_g. When leaving Hold and the DAR function is activated, Equation (4.20) leads to different ramp out between these two states depending on the road inclination, and as such the time it takes for $M_{b,app}$ to reach M_g. The ramp out suggested in Equation (4.20) is therefore extended to

$$K_{low} = \begin{cases} -K_2 + K_3 \,|\, \sin\alpha \,| & \text{if } M_{b,req} < \hat{M}_g \text{ or } 0 < v, \\ -K_4 & \text{else,} \end{cases} \tag{4.21}$$

where K_4 is a constant and v is the velocity of the vehicle. The aim of this strategy is to ramp down the brake torque fast to the torque needed to keep the vehicle stationary and then ramp out the braking torque slower to ensure a smooth drive-off. As the DAR function estimates a value for the gravitational torque $\hat{M}_g$, the vehicle could start moving as the actual gravitational torque M_g is larger when a trailer is hitched to the vehicle. If this happens, the first condition in Equation (4.21) would be satisfied and a slower ramp out would requested.

4.2.3 DAR Flow Chart

Figure 4.2 shows a flow chart of how the brakes should release within the DAR function. The DAR function is activated from Hold, and the initial step is to determine if the intended driving is uphill or downhill, this includes both forward and reverse drive. If the direction is downhill, the DAR function for downhill is activated, i.e. $M_{b,req} = 0$. If the driving direction is uphill, the first step determines if the vehicle is moving uphill or not. If it does not, the system checks if the vehicle is moving downhill. If there is a downhill movement, the rollback prevention is entered, and if the vehicle is at standstill, the brakes shall gradually release. When the vehicle starts to move uphill, $M_{b,req} = 0$ in order to fully release the brakes.

4.2.4 Torque Conversion for Autonomous Drive Mode

In autonomous drive mode, the autonomous function sends an acceleration request, which needs to be converted into a propulsion torque request $M_{t,req}$. This is done by implementing a feedforward control of both the reference signal and the disturbance. The overview of the torque conversion control is displayed in Figure 4.3. The signal u represents $M_{t,req}$. In this case the road inclination α is handled as a disturbance. F_{fd} estimates the gravitational torque of the vehicle. F_{fr} creates a torque based on the reference acceleration, vehicle mass and the wheel radius. F is a PI-controller in the feedback loop based on the vehicle's

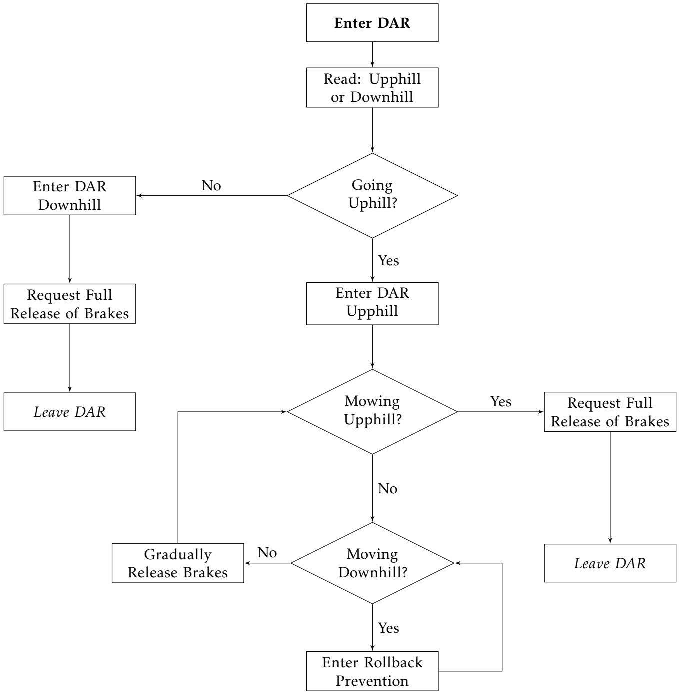


Figure 4.2: *Flow chart of the DAR function.*

acceleration a_c. The transfer function H represents how the road inclination α is converted to gravitational force. G_1 transfer the propulsion torque to force and finally G_2 converts a force input to acceleration of the vehicle.

In order to meet the requirement of a smooth start, a feedforward from the reference signal is implemented. The reference model G_m is selected according to Equation (3.7), which gives the opportunity to tune the reference model to achieve a smooth start. From Equation (4.10) the transfer functions of G_1 and G_2

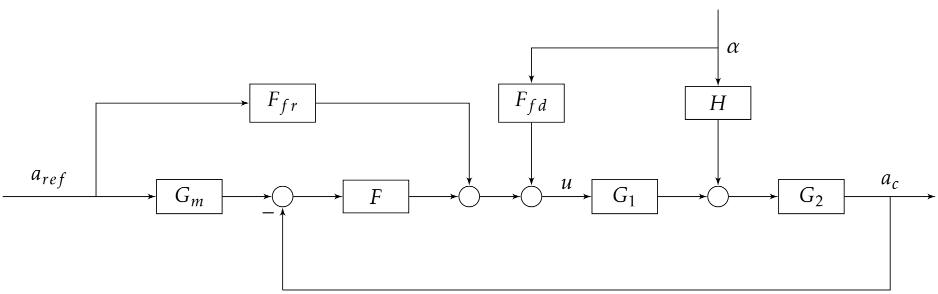


Figure 4.3: *Feedforward control for torque conversion.*

can be described as

$$G_1 = \frac{1}{R}, \tag{4.22}$$

$$G_2 = \frac{1}{m_c + m_v}. \tag{4.23}$$

The feedforward function, can be selected as according to Equation (3.8). However, when a trailer is hitched to the vehicle, the trailer mass is unknown. The feedforward function will therefore only consist of the vehicle mass,

$$F_{fr} = \frac{m_c R}{sT + 1}. \tag{4.24}$$

So far the gravitational force has not been taken into account. This is done by regarding the gravitational torque as a disturbance, and as such the feedforward F_{fd} can be used. Equation (3.6) gives that the influence of the disturbance will become zero if F_{fd} is defined as

$$F_{fd} = -\frac{H}{G_1}. \tag{4.25}$$

The disturbance function H can be seen as the gravitational contribution to the vehicle acceleration, thus describing F_{fd} as

$$F_{fd} = m_c g R \sin\alpha. \tag{4.26}$$

The torque conversion for autonomous drive creates $M_{t,req}$. The system should not be able to request a negative propulsion torque, thus setting the demand

$$M_{t,req} = \max(0, u). \tag{4.27}$$

Since the autonomous drive is based on the acceleration, the brake control needs to take this into account, and it may vary depending on uphill and downhill driving. Whilst driving uphill the brake torque changes its direction if M_t exceeds M_g, and the same brake torque control, as presented in Chapter 4.2.1, is suggested.

When driving downhill instead, the same brake request control is not always valid since M_g might fulfill, or exceed, the acceleration request on its own. The control system in Figure 4.3 would lead to a negative propulsion torque request, however, this is not possible according to Equation (4.27), setting $M_{t,req} = 0$. Whilst driving downhill, M_b is always acting opposite M_t and M_g. Considering the control signal u becoming negative implies that brake torque should be added in order to prevent the vehicle from accelerating too much. The requested brake torque for going downhill in autonomous mode can therefore be defined as

$$M_{b,req} = -\min(0, u). \tag{4.28}$$

When implementing the autonomous drive in the test vehicle, a pre-existing autonomous drive mode will not be used, but rather a request of the propulsion torque as described above. It is important to implement some safety measures to avoid malfunctioning behaviour, e.g. requesting propulsion torque when the driver is in manual drive mode. These safety measures are implemented by setting several conditions which need to be fulfilled in order for the function to be active. If all the conditions are not met, there should be no request of the propulsion torque.

4.2.5 Rollback Detection

In Chapter 4.2.1 the drive-off in uphill and the situation of rollback was presented, and its requirements are considered in Chapter 1.3. The solution to handle rollback is presented in Equation (4.16). This rollback prevention is a safety feature and should only function if there is a rollback, and as such a rollback detection needs to be implemented.

The rollback is detected with the help of the position and velocity. If both of these are going in a downhill direction, the vehicle enters the rollback prevention. Comparing a simulation with CarMaker and signal data from the test vehicle, the simulation can get instant information about rolling backwards, whereas in the test vehicle the signals has delays and resolutions, which means the test vehicle may roll downhill before the movement is detected. In order to handle this in the simulation environment, the rollback detection will not activate the prevention until the vehicle has rolled back a certain distance. However, it should be noted that the results of rollback presented in Chapter 6 are not affected by this function, but show the actual position of the vehicle.

4.3 Estimations

A key part of the brake release is to balance it with the gravitational torque. Therefore it is important to have a good estimations of the parameters related to the gravitational torque, i.e. the road inclination and the mass. For the test vehicle used, these estimations are usually provided by other systems, but are not accessible, meaning these estimations has to be made within the thesis work.

4.3.1 Estimate Road Inclination

In CarMaker the the road inclination is a given input signal, however for the test vehicle the road inclination estimation does not exist. In the test vehicle, there is a provided signal from an accelerometer. According to [4], the road inclination can be estimated as

$$a_{out} = a + g \sin \alpha, \tag{4.29}$$

where a_{out} is the longitudinal acceleration given by the accelerometer or internal measurement unit (IMU). Before the DAR function is activated there is no longitudinal motion, which means the vehicle acceleration a is zero. The road inclination can be estimated from Equation (4.29) as

$$\hat{\alpha} = \arcsin \frac{a_{out}}{g}. \tag{4.30}$$

4.3.2 Estimate Vehicle Mass

To develop a mass estimation is a complex task and still an open research topic [3]. There are two main categories in which the estimations can be classified [4], Sensor-based and Model-based. The first one includes several sensors, where a larger number of sensors and their positions may increase the accuracy, although it is a costly method. The model-based estimation focuses on vehicle dynamics and vehicle start information instead, however this may require estimations of several other parameters as well, which greatly influence the accuracy of the mass estimation. An other problem is that such an estimation cannot be performed when during standstill [4]. In real application, these estimations often have an error of up to 10 % [3].

In the simulations and CarMaker, the actual mass can be used, but this is not the case for the test vehicle. Due to the complexity of creating a decent mass estimation, the mass estimation will be set as a constant value, which can be changed online and thus easy to modify. This value is set as the vehicle's curb weight including the driver and add on the passenger's weight during the test drive. This means that fuel and equipment weight etc. are not taken into account. The trailer mass is not included in this, as this estimation is used for the DAR function's estimation of the gravitational torque $\hat{M}_g$.

4.3.3 Estimate Jerk

As stated in Chapter 3.2, jerk is the time derivative of the acceleration. In order to estimate the jerk, a specific acceleration signal is differentiated and filtered according methods provided by VCC, and can therefore not be described further.

4.3.4 Torque clarifications overview

In Chapter 4.1.1 different torques where defined and clarified. Figure 4.4 shows an overview the different torques and where they are present in the DAR function. Note that only an estimation of the gravitational torque $\hat{M}_g$ is available to the DAR function and is shown in Figure 4.4. The actual gravitational torque M_g is shown in the resulting plots in Chapters 6 and 7 for reference purpose only.

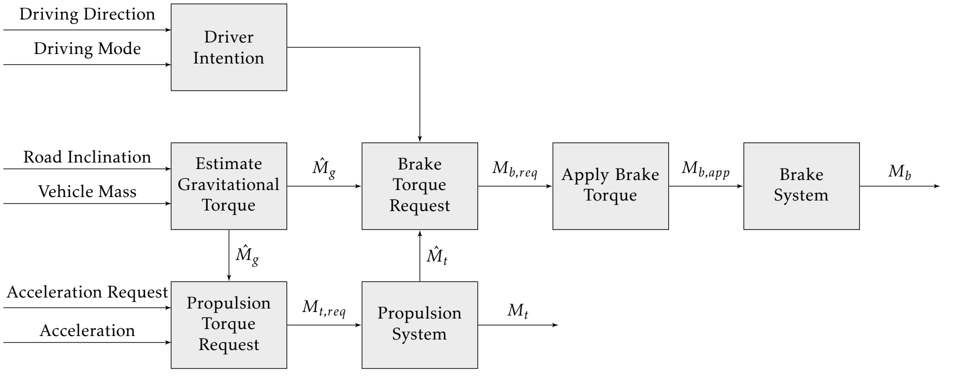


Figure 4.4: *Overview of the signal and blocks of the DAR function.*

5 Test Scenarios

In this chapter the intended test cases are described for both the simulated and implemented systems, and there are several different cases which could be tested. The number of tests depend on the slope direction, drive mode, driving direction as well as whether there is a trailer or not, i.e. the conditions which may change between tests are

- The direction of the road inclination: uphill, downhill or horizontal road
- The drive mode for the vehicle: manual or autonomous
- The desired direction: forward or reverse
- If a trailer is hitched to the vehicle or not

This gives 24 possible test scenarios, as the minimum number of cases, if every combination is to be tested. Changes in the driver behaviour, such as aggressiveness, or different reference accelerations in autonomous mode, are other factors which could be tested, however, this would greatly increase the number of tests and it is therefore neglected. The DAR function needs to function at different road inclinations as well, and not only its direction, as such five different cases are created depending on the inclination and direction. The intended tests for each case is presented in Table 5.1.

5.1 Test Cases

Below follows different test cases. These are based on the vehicle position, where the front of the vehicle determines if the case is uphill or downhill.

Case I: Uphill Start - Large Inclination

Case I represents the vehicle facing upwards at a relatively large inclination, which will produce the largest gravitational force. The release should be smooth and within the rollback demands.

Case II: Uphill Start - Small Inclination

Case II represents the vehicle facing upwards, at a road inclination smaller compared to Case I. The release should be smooth and within the rollback demands.

Case III: Horizontal Road Start

Case III is set on a horizontal road. This means that there are no risks of rolling backwards, and a quick release of the brakes is desired.

Case IV: Downhill - Small Inclination

In Case IV the vehicle is facing downhill at the same road inclination as Case II. The release should be smooth without causing a slow drive-off. Reverse driving should be within rollback demands.

Case V: Downhill - Large Inclination

In Case V the vehicle is facing downhill at the same road inclination as Case I. This case gives the largest gravitational force, the creating a higher acceleration if free-rolling. The release should be smooth without causing a slow drive-off, nor too quick resulting in a high acceleration. Reverse driving should be within rollback demands.

5.2 Test Chart

In Table 5.1, the different combinations of test cases to be made are shown for respective drive mode (Man/Auto), driving direction (F/R) and trailer status, i.e. with or without trailer. As seen in the table, there are several combinations which are not tested and the reason for this is that logic behind the control is already tested in other cases.

People are mainly driving in a forward direction, therefore it is important to test all five cases in forward gear for both the autonomous and manual drive mode. When driving forward in Cases I and II no rollback is allowed unless a trailer is hitched to the vehicle. The trailer is handled as an unknown disturbance, where the extra mass increases the gravitational torque. As Case III will have almost no influence of the gravitational torque, the drive-off is sufficient to test without a trailer. In the other cases the trailer may produce a rollback, Cases I and II, or a large acceleration, Cases IV and V.

Table 5.1: Chart over which tests that will be made.

	Case I	*Case II*	*Case III*	*Case IV*	*Case V*
Without Trailer					
F_{Man}	✓	✓	✓	✓	✓
R_{Man}				✓	✓
F_{Auto}	✓	✓	✓	✓	✓
R_{Auto}				✓	✓
With Trailer					
F_{Man}	✓	✓		✓	✓
R_{Man}					
F_{Auto}	✓	✓		✓	✓
R_{Auto}					

Driving in reverse gear uses the same control as forward gear which means that most of the cases do no have to be tested. As seen in Table 5.1, only Cases IV and V are tested. For reverse driving these tests are the same I and II in forward gear. The purpose of these tests is to ensure that there is no rolling downhill when reverse driving. If the DAR function works as intended while driving in reverse uphill without a trailer, and meets the demands forward uphill with a trailer, it should function reversing uphill with a trailer.

5.3 Rollback Prevention Test

When driving with a trailer a small rollback is allowed, and a rollback will likely occur as the release of the brakes is based on an estimation of the gravitational torque. This estimation will be inaccurate as it only takes the vehicle's mass into account and not the trailer's (see Chapter 4.2.1). Most of the time, the driver will produce a propulsion torque when the DAR function is active, making it possible to hold the vehicle at a standstill with less brake torque (see Equation (4.13)). Due to safety reasons, the rollback prevention should be able to stop the vehicle without a propulsion torque. Therefore, the rollback prevention's functionality should be tested without a propulsion torque acting on the vehicle.

5.4 Measurements

The purpose of the tests is to determine how well the concept DAR function meets the requirements, however, it is good to see how the propulsion torque and brake torque balance looks during the drive-off scenario. The measurements of the test will therefore include the data listed on the next page.

- Simulation and test vehicle for both drive modes
  - *Position*
    The position of the vehicle will show how much the vehicle rolls backwards to verify that the roll-back requirements are fulfilled.
  - *Jerk*
    The jerk is a measure to look how comfortable the drive-off is, giving an indication of the smoothness of the drive-off.
  - *Requested Brake Torque*
    Shows what brake torque is requested from the DAR function to ensure that it works as intended.
  - *Applied/Estimated Brake Torque*
    Applied brake torque is used for simulations and estimated for the test vehicle. The maximum brake torque produced by the brakes, i.e. based on the pressure the brakes are pressed against the wheels.
  - *Actual/Estimated Propulsion Torque*
    Actual propulsion torque is used for simulations and estimated for the test vehicle. For manual mode it shows how the driver controls the propulsion torque and for autonomous it shows how the torque responds to the requested propulsion torque.
- Simulations and test vehicle for autonomous drive mode
  - *Acceleration*
    Both vehicle and reference acceleration to determine how well the control function fulfills the request.
  - *Requested Propulsion Torque*
    Shows how the requested propulsion torque behaves during the drive-off. This is done to ensure that the propulsion torque request works as intended.
- Only simulations for both drive modes
  - *Actual Brake Torque*
    The brake torque acting on the wheels to analyze how well the brake control works.

6

Simulation Results

In this chapter, an introduction to the co-simulation between MATLAB/SIMULINK and CarMaker is presented, followed by simulation and analysis of first the roll-back prevention, and then drive-off scenarios according to Table 5.1.

6.1 SIMULINK and CarMaker

CarMaker provides a virtual vehicle, driver and environment, and the opportunity to run co-simulations with MATLAB/SIMULINK. CarMaker sends signals, such as drive cycles and vehicle data, to SIMULINK, which is equipped with several subsystems representing the dynamics of the vehicle. Signals travel through these subsystems and the output is then transmitted back to CarMaker. By intercepting these signals, controllers can be implemented and validated into the virtual vehicle.

The vehicles can be created with different components, such as the powertrain, brakes, tires, chassis, etc. The virtual driver can control the same actuators as a real driver, i.e. steering wheel, accelerator, brake and clutch pedals as well as gear shifting. It is possible to create different environments and drive cycles, in this thesis, a virtual driver perform a drive-off in a road with an inclination. CarMaker also provides a direct access to all variables, meaning that all values can be read.

The vehicle used in CarMaker has been tuned to match the test vehicle, mainly the masses and dimensions for the vehicle body. The powertrain used is a default provided within CarMaker, however, the power it can provide has been tuned to the same as the test vehicle. This will result in that the signals in CarMaker and the test vehicle will differ, for instance the requested propulsion and brake torques, and therefore some dynamics in-between has to be implemented. In the case of the brake torque, this is done by adding a time delay and a first order filter. The propulsion torque is more complicated, as it is not possible to create a propulsion torque request at the wheels. As such, the requested propulsion torque needs to be set somewhere on the driveline, which has some unknown dynamics, and does not represent the driveline in the test vehicle, which may cause differences in behaviour. The propulsion torque in the simulation is requested at the output of the gears, and then converted to propulsion torque at the wheels. A first order system has been implemented to attempt to capture the dynamics, this was created by comparing differences when requesting the propulsion torque at different places in the driveline.

6.2 Rollback Prevention

The first simulations test the safety of the rollback prevention, with the purpose to ensure that it can stop the vehicle by only re-applying brake torque, i.e. without depending on propulsion torque. These simulations were done with two different trailer masses, 500 kg and 1000 kg, and at two different inclinations, 10 % and 30 %, in order to test at different scenarios. Figure 6.1 shows the results of the simulations. The DAR function is activated at 1 s, and the requested brake torque $\hat{M}_{b,req}$ starts to drop to its estimated gravitational torque $\hat{M}_g$. After about 1.5 s the rollback starts. When the system detects the rollback, $\hat{M}_{stat}$ is estimated as described in Equation (4.15), and $M_{b,req}$ increases according to Equation (4.16), which can be seen as $M_{b,req}$ makes a step up to the value of about M_g, the dashed lines in the plot. $M_{b,req}$ then increases linearly until the vehicle stops, which is the function of the integrators in Equation (4.16). When the vehicle has stopped, the second integrator is set to zero, and the excessive brake torque is reduced to the required value to hold the vehicle. This value is represented by the sum of $\hat{M}_{stat}$ and the first integrator (see Equation (4.16)). The results of these simulations agree with the statement in Chapter 4.2.1, that there is a need of a greater brake torque to stop a vehicle in motion than required to hold it, which is achieved by the integrators. Since the vehicle stops moving and the requested brake torque reaches a higher estimated brake torque to hold the vehicle than the gravitational torque, it is possible to say that the function works as intended.

Figure 6.1 shows the the longest rollback distance of 7 cm occurs with a heavier trailer at a larger road inclination, which is reasonable as this leads to a larger gravitational torque from the trailer and therefore a larger error within the system. The rollback prevention starts with a delay, compared to when the position plot shows a rollback. The reason for this is that the control is implemented to have a margin for the rollback detection, and is tuned after restrictions which occur in the signals of the test vehicle. The purpose of this test was to ensure that the rollback prevention safety feature is able to stop the vehicle by only reapplying the brakes, as described in Chapter 5.3, however, there will be a propulsion torque during most drive-offs, which also counters the rollback.

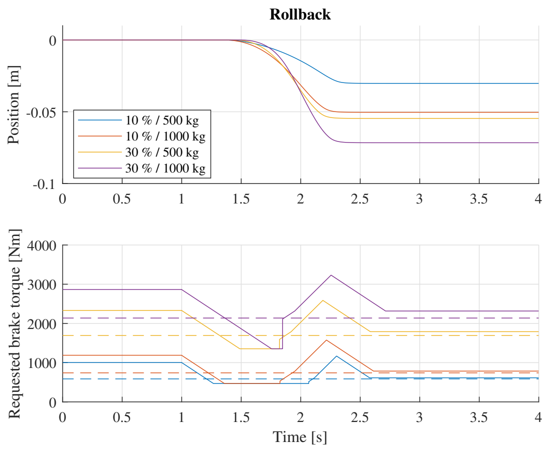


Figure 6.1: *Position and requested brake torque change when the DAR function is activated. Dashed line represents the gravitational torque M_g.*

6.3 Simulation Results

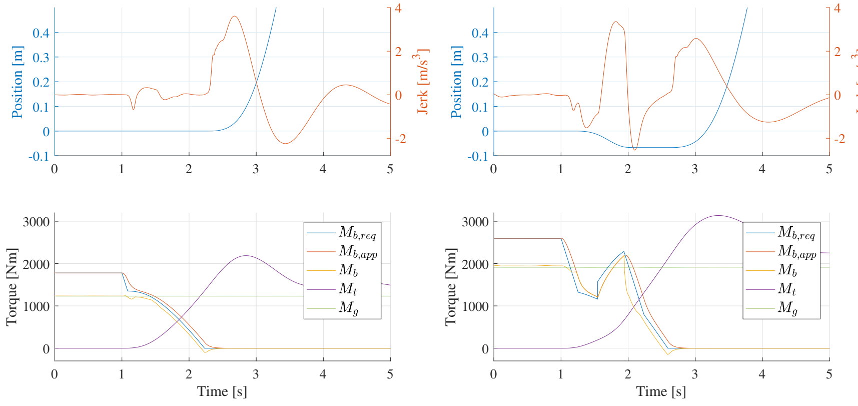
The results of the simulations include the test cases shown in Table 5.1. In this chapter, the results of Case I and Case V in forward drive-off for both drive modes are shown as these cases include the largest gravitational torque. The rest of the simulations results can be found in Appendix B. In all simulations the DAR function is activated at 1 s, and the trailer mass is set to 800 kg.

6.3.1 Manual Drive Mode

This section shows the results of Case I and V for the manual drive mode. For both cases the driving direction is forward. The rest of the manual drive results are presented in Appendix B.1.

Case I

Figure 6.2 shows the simulated results for Case I when driving forward in manual drive mode. When the DAR function is activated, $M_{b,req}$ starts to drop to $k_1 \hat{M}_g$ (see Equation (4.12)), note that $\hat{M}_g$ does not include the trailer mass, whereas the plot shows M_g, which represents the actual gravitational torque. The actual brake torque M_b decreases by a small amount when the applied brake torque $M_{b,app}$ starts to decrease, this occurs without an increase of propulsion torque M_t. There is a small delay between $M_{b,req}$ and $M_{b,app}$. Figure 6.2a represents the vehicle without the trailer, and when $M_t = M_g$, $M_{b,req}$ is zero. At this time the jerk increases up to 2.5 m/s^3. When the vehicle starts to move forward, M_b starts acting in the opposite direction. The jerk peaks at about 3.6 m/s^3. No rollback occurs.



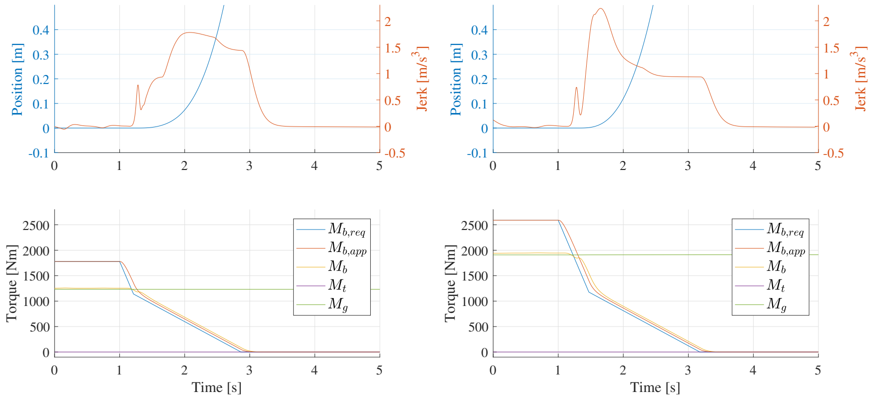
***(a)** Without trailer.* ***(b)** With trailer.*

***Figure 6.2:** Test Case I, driving forward in manual drive mode, uphill with an inclination of 30 %.*

Figure 6.2b shows the case with an added trailer, which causes a larger M_g, note that a larger M_g increases $M_{b,req}$ in Hold. As the $M_{b,req}$ drops, the vehicle starts to roll backwards at 1.2 s. After 1.5 s the rollback prevention activates, causing an instant increase of $M_{b,req}$, which then keeps increasing gradually until the vehicle stops. During the rollback and stopping there is a jerk peaking at about 3.4 m/s^3. When M_t has reached M_g, $M_{b,req}$ starts to decline again in order to release the brakes. At this point M_b turns negative, thus preventing forward movement instead. The brakes fully release after 2.7 s and the total rollback is 7 cm. During the actual drive-off the jerk peaks at about 3 m/s^3.

Case V

The results of Case V in forward manual drive mode are shown in Figure 6.3. The ramp out of $M_{b,req}$, shows two different steps. At first there is a quick ramp out, which reduces $M_{b,req}$ from the Hold function to $\hat{M}_g$ (see Chapter 4.2.2). Once $\hat{M}_g$ is reached, the ramp out is slower until $M_{b,req} = 0$. Driving forward downhill does not require the driver to produce any propulsion torque, leaving $M_t = 0$ during the drive-off. Figure 6.3a shows the vehicle without the trailer, where brakes have fully released after 2.9 s. The maximum jerk is at 1.8 m/s^3. Adding the trailer causes a longer time before the brakes have released (see Figure 6.3b), which occurs due to a larger value of $M_{b,req}$ from Hold, which gives a larger difference to $M_{b,req} = 0$. The jerk peaks at about 2.1 m/s^3.



(a) *Without trailer.* ***(b)*** *With trailer.*

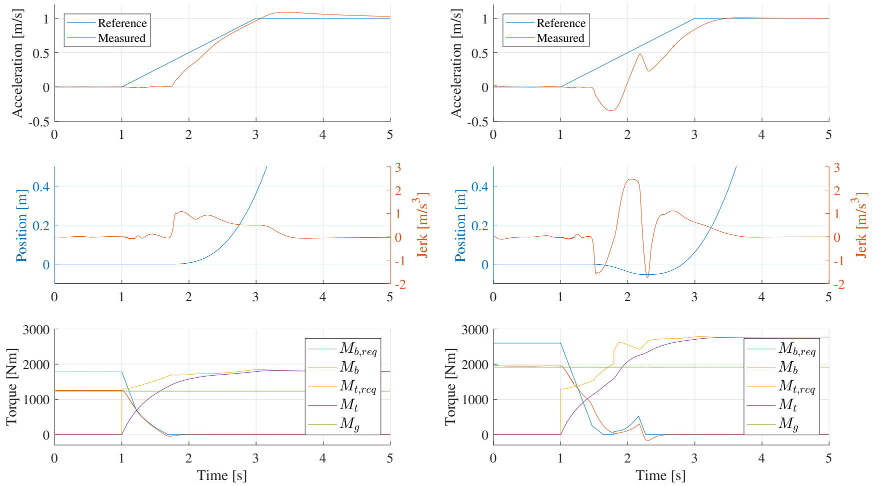
Figure 6.3: *Test Case V, driving forward in manual drive mode, downhill with an inclination of 30 %.*

6.3.2 Autonomous Drive Mode

In this section the results of Case I and V are presented for the forward autonomous drive mode. For the rest of the autonomous drive results see Appendix B.2. Compared to the manual drive some changes has been made in the plots. An acceleration plot has been added. In the torque plot $M_{t,req}$ has been added as the autonomous drive requests a propulsion torque, and $M_{b,app}$ has been removed to reduce number of plotted torques as this torque is based to $M_{b,req}$, and M_b is more relevant to study. For all autonomous simulations, the acceleration request going from 0 to 1 m/s^2, with a ramp of 0.5 m/s^3.

Case I

Figure 6.4 shows Case I in autonomous mode, driving forward. When the DAR function is activated, the autonomous drive mode initiates an acceleration request and $M_{b,req}$ starts to drop from the stationary torque in Hold towards $k_1\hat{M}_g$. $M_{t,req}$, instantly increases to $\hat{M}_g$. Figure 6.4a shows the simulation without the trailer. Just before the brakes are released at 1.8 s, M_t is large enough to move the vehicle forward, causing M_b to act in the opposite direction. When the brakes have fully released the jerk peaks at about 1.1 m/s^3. During the drive-off, $M_{t,req}$ increases with a few distinctive, almost linear, changes in the request curve, however, M_t increases smoothly. There is no rollback without the trailer, and there is a small overshoot in the acceleration when the reference reaches its stationary value.



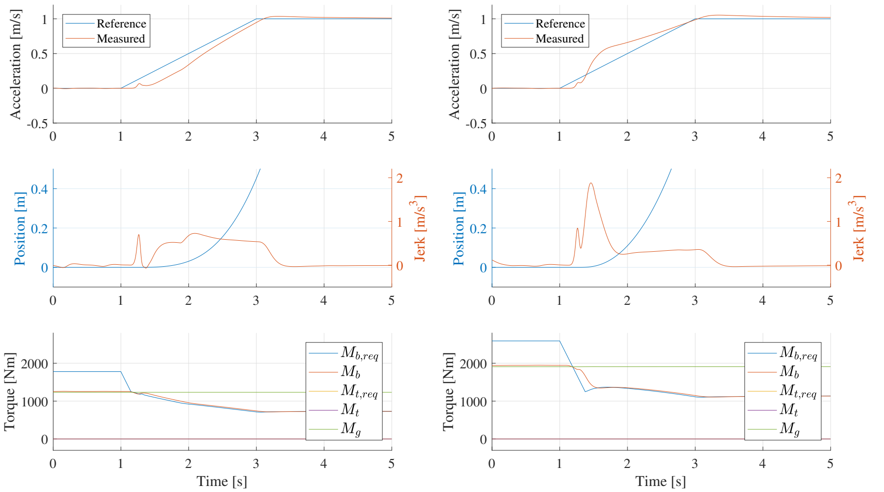
***(a)** Without trailer.* ***(b)** With trailer.*

***Figure 6.4:** Test Case I, driving forward in autonomous drive mode, uphill with an inclination of 30 %.*

Figure 6.4b shows the case with the trailer. At 1.5 s the vehicle starts to roll downhill and the rollback prevention activates at 1.8 s, causing $M_{b,req}$ to instantly increase, followed by gradually increasing until the vehicle stops moving backwards. Comparing to the manual case, Figure 6.2b, the brake torque is not increased as much, as the propulsion torque is larger. During the rollback and stopping, the jerk peaks at about 2.2 m/s^3, whereas the maximum jerk of the drive-off forward is roughly 1 m/s^3. The total rollback is 6 cm.

Case V

Figure 6.5 shows the autonomous forward downhill drive-off in an inclination of 30 %. When the DAR function is activated an acceleration request is sent. $M_{b,req}$ initially decreases quickly, but slows down in order to follow the acceleration request. Figure 6.5a shows the drive-off without the trailer. When the change of ramp out occurs, the jerk peaks with 0.7 m/s^3, which is roughly the same as the maximum jerk which occurs at 2 s. When adding the trailer, Figure 6.5b, the jerk peak is larger and in two steps, which also can be seen in the acceleration curve. The acceleration is a bit to high during the increase of the reference signal. The maximum jerk with the trailer is 1.9 m/s^3. In both these cases $M_{b,req}$ then gradually decrease, and M_b with it, without the brakes never fully releasing. $M_{t,req}$ and M_t remain zero.



(a) *Without trailer.* ***(b)*** *With trailer.*

Figure 6.5: *Test Case V, driving forward in autonomous drive mode, downhill with an inclination of 30 %.*

6.4 Simulation Analysis

In this section an analysis is made of the manual drive mode and the autonomous drive mode.

6.4.1 Manual Drive Mode

In the manual drive mode, the DAR function only requests brake torque, whereas the driver requests the propulsion torque. The results of the simulations show that the brakes manage to release without rollback when there is no trailer. However, when the trailer is hitched, rollback may occur, as seen in Figure 6.2b, this simulation also represents the largest rollback including the results in Appendix B.1. Case I and Case V provides the largest M_g due to steepest road inclination. This rollback was at 7 cm, which is within the requirements of the thesis.

Both cases in Figure 6.2 show that the brake torque M_b also decreases when the applied brake torque $M_{b,app}$ starts to decrease even if the propulsion torque M_t has not increased. The effect of this is more noticeable in Figure 6.2a, where M_b gets a momentary drop shortly after the DAR function is initiated. This is a strange behaviour, since from Equation (4.5) it can be concluded that M_b should be proportional to M_t. This might occur due to differences in the model of the brake torque compared to the one within CarMaker. The control strategy used still fulfills the requirements and is therefore still regarded as valid.

During the uphill drive-off, the jerk may be considered high, especially comparing to the limit of passenger comfort of about 2.94 m/s^3 [6]. However, as this is the manual drive mode, the driver influences the jerk. The high jerk occurs because M_t has already exceeded M_g and the brakes started to act in the opposite direction (see Equation (3.5)). An aggressive driver produces more propulsion torque, thus increasing the jerk. Looking at the same case with trailer instead there are two peaks of the jerk (see Figure 6.2b). The second one occurs similar to the case without the trailer, the first peak is the result of the rollback and not the actual drive-off. Between the two peaks there is a drop in jerk to more than -2 m/s^3. This drop occurs when the rollback prevention activates and starts to reapply the brakes in order to stop the vehicle.

Making a downhill drive-off shows a quick drop of $M_{b,req}$ down to $\hat{M}_g$ within the DAR function. This drop occurs as the Hold function requests a larger brake torque in order to keep the vehicle at a stand still, to counteract some disturbances. In the first second of the simulations, M_b is about the same as M_g, however, in a real vehicle this is not the case. If the drop of $M_{b,req}$ was instant, the brakes may release too quick, causing the vehicle to start moving earlier, and then when the ramp out goes slower, the jerk may increase. The brakes release slower for the downhill drive-off so the acceleration will not be to quick. This means that the acceleration of the vehicle is entirely based on the gravitation and the brakes, if the acceleration might be considered to large, the driver would be able to press the brake pedal and brake. However, if the driver would press the brake pedal it would result in that the driver takes control of the requested brake torque, thus deactivating the DAR function. For this reason the driver is disconnected from the manual downhill driving simulation.

6.4.2 Autonomous Drive Mode

In the autonomous drive mode there is no driver, instead an acceleration request is sent, which is converted to a propulsion torque request (see Chapter 4.2.4). This requires both the propulsion torque and brake torque to behave according to the acceleration request. For both torques, the actual torque follows its requested counterpart smoothly. The rollback distance is at 6 cm, which is not exceeded if results in Appendix B.2 are included. This occurs as both the propulsion torque increases and the brake torque decreases quite fast, leading to the sum of these torques to have a larger difference to the actual gravitational torque. However, as the propulsion torque increases fast, there is less need to produce extra braking torque. This leads to a smaller brake torque active when the propulsion torque exceeds the gravitational torque, and thus reducing the jerk.

As the brake torque depends on the propulsion torque, and both in turn affect the acceleration, in the autonomous mode, the equilibrium of Equation (3.5) is more accurate, which causes smaller amount of the brake torque to act against the desired moving direction when the propulsion torque has passed the gravitational torque when going uphill. During the downhill drive-off, the brakes are never fully released as there is a desire to follow the acceleration reference (see Figure 6.5). This leads to $M_{t,req}$ and M_t remaining zero as the gravitational torque is enough to produce acceleration.

As the autonomous drive mode depends on an acceleration reference and how well the vehicle follows this reference, the acceleration may vary during the drive-off. The results show quite a decent reference tracking, although an overshoot may be produced. However, since the acceleration request has a rate of 0.5 m/s^2, it takes 2 s before it reaches the request of 1.0 m/s^2. At this time the vehicle has already started moving, and M_t is quite large and peaks at this time. The peak of M_t and the acceleration overshoot does not seem to lead to a high jerk. The results of the autonomous drive does not show much difference in peak value depending on the inclination, including the results in Appendix B.2. However, at a steep inclination there is a difference depending on whether there is a trailer or not. The jerk peaks at about 2 m/s^3 with the trailer and about half as much without it. According to Chapter 3.2, the autonomous drive has a comfortable drive-off.

7

Test Results

In this chapter the model has been implemented into the test vehicle. It is divided into a section describing the implementation, followed by tests of the rollback prevention, and finally results and analysis of test drives.

7.1 Implementation in the Test Vehicle

When implementing the system into the test vehicle, there are some changes compared to the simulation model. The test vehicle is limited in available signals, and different signals have different time intervals in which they are sent, causing a delay between signals. Besides the torque signals, some other signals are used to determine different states, for instance the rollback detection is based on more than one signal, meaning the function will only be as quick as the signal with the longest interval between signals sent.

In order to detect which direction the vehicle is moving, two signals are used. The first one defines if the vehicle is stationary, this is based on the wheel movement, which provides a fast update whether the vehicle is stationary or moving. The other signal provides information if the vehicle is moving backwards, however it does not differentiate between if the vehicle is stationary or is moving forward. This signal does not update as fast as the first one, which means they do not have the same restrictions. When detecting rollback in forward drive, only the second signal is required, however, both needs to be used when reversing uphill.

The rollback distance is determined by integrating the vehicle speed when rollback has been detected. The vehicle speed requires a minimum speed in order to show a value larger than zero. In turn, the measured acceleration is based on the vehicle speed, which therefore have the same restriction. The consequence of this is that the vehicle may have started to move before the estimated rollback distance and acceleration show that. The vehicle is also equipped with an IMU that could be used to determine the acceleration, however, this signal is also dependent on the pitch of the vehicle which could change during drive-off.

To estimate the road inclination, the signal from IMU is used in Equation (4.30). This is because initially the vehicle is standing still and the pitch is not changing. To determine the jerk, acceleration from the IMU is used, as the IMU is equipped within the vehicle and will provide a more accurate representation how the passengers experiencing the drive-off.

In difference to the simulations, the test vehicle produces a torque when the engine is idling. This includes when the vehicle is in Hold, which can be seen in the results of the test drives (see Chapter 7.3), whereas in the simulation the propulsion torque was zero in Hold. This torque functions in an additive way when driving, which means that the measured propulsion torque will exceed the requested. This has been compensated for when the DAR function is active, however, it cannot be adjusted for Hold.

The control strategy according to Chapter 3.3 is implemented in SIMULINK, with the signals of the necessary torques etc., as described in the chapter, and signals to detect rollback as mentioned above. By compiling the model, the dSPACE program ControlDesk can be used to control the model, and thus reading and sending signals to the AutoBox. All signals and blocks from the SIMULINK model becomes accessible to monitor and tune in ControlDesk, where the measurements and tuning are done in real time.

7.2 Rollback Prevention

As in the simulation, the rollback prevention has to be tested to ensure that the vehicle can stop without requiring propulsion torque. The results are presented in Figure 7.1. However, compared to the simulations (see Chapter 6.2), the test vehicle has an extra torque present which has the desire to move the vehicle forward. As this is the case, this torque has been subtracted from the gravitational torque in the figure, which means that the dashed lines shows the required brake torque to keep vehicle stationary given the extra torque. In the case of a 10 % inclination, the test was performed in neutral gear and therefore does not have a propulsion torque present. During these tests only one trailer with a mass of 800 kg was used. In order to create another scenario to change the gravitational torque, the function was also tested at an inclination of 20 %.

In all three test cases, the DAR function was activated at 1 s, which can be seen as the requested brake torque $M_{b,req}$ starts to drop towards its estimated gravitational torque $k_1 \hat{M}_g$. When the brake torque is lower than the required torque to keep the vehicle stationary, the vehicle starts to move downhill, which activates the rollback prevention and $M_{b,req}$ immediately increases to $\hat{M}_{stat}$. The integrators starts to increase $M_{b,req}$ to stop the vehicle, in the same way as in the simulations (see Chapter 6.2). Only the test in a 30 % inclination shows a rollback

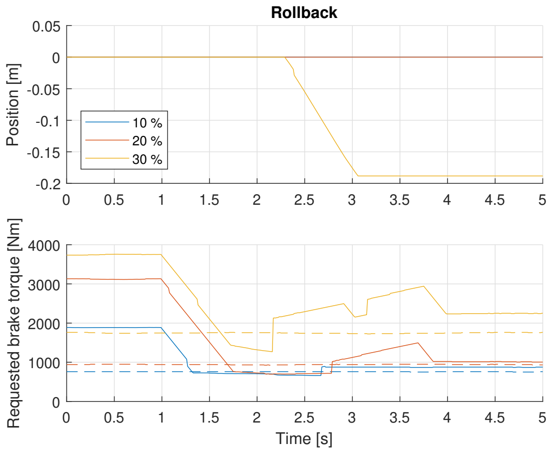


Figure 7.1: *Position and requested brake torque change when the DAR function is activated. Dashed line represents the required torque to hold the vehicle.*

distance, about 19 cm. This starts after rollback prevention has started to reapply the brakes, and therefore indicating that the vehicle speed was to low before this time, and in the case of the other inclinations. After the vehicle has stopped the requested brake torque starts to ramp out to $\hat{M}_{stat}$.

In the case of the 30 % inclination, there is drop of brake torque request at about 3 s, which occurs when the system determines which integrator should be active (see Equation (4.16)), and which is determined based on the acceleration. Because of the difference in signal behaviours, it cannot be accurately determined how far the vehicle has rolled downhill. However, the implemented rollback prevention system does manage to stop the vehicle without producing extra propulsion torque, which would occur during a normal drive-off.

7.3 Results from Test Drive

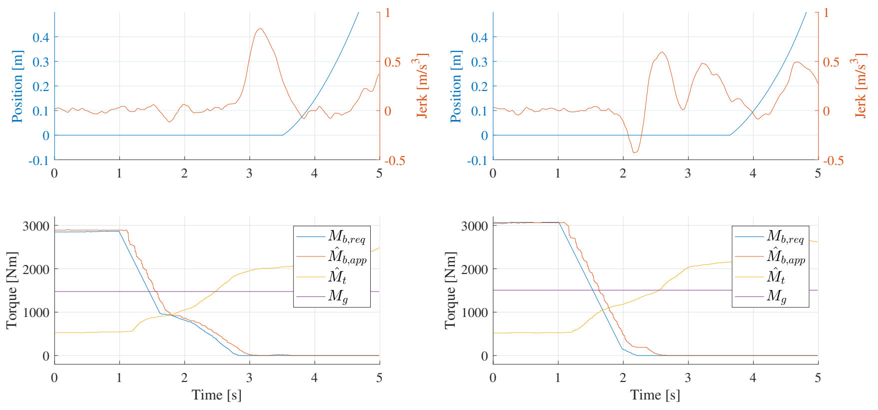
In this section the results of the test drives in forward drive, Case I and Case V, both manual and autonomous drive mode are presented. In Appendix C the rest of the results of the conducted tests from Table 5.1 are presented. A difference from the simulations is that the tests with the trailer is done at an inclination of 20 % instead of 30 %, as the vehicle did not have enough traction to perform the drive-off with the trailer in 30 % inclination. As in the simulations, the drive-off is initiated after 1 s. As mentioned in Chapter 7.1, $M_t > 0$ even when the vehicle is in Hold, this is the case for all test results.

7.3.1 Manual Drive Mode

In this section the results of Case I and V are presented for the manual drive mode. For both cases the driving direction is forward. For the rest of the manual drive results see Appendix C.1.

Case I

Figure 7.2 shows the results of the test drives in Case I in manual drive mode. When the drive-off is initiated, $M_{b,req}$ starts to decrease towards $k_1\hat{M}_g$. In both cases, with and without trailer, $\hat{M}_{b,app}$ follows $M_{b,req}$ with a small delay. Figure 7.2a, shows the case without the trailer. In this case the test is performed at an inclination of 30 %, which results in about the same gravitational torque as for a 20 % inclination with the trailer. $M_{b,req}$ starts to drop linearly until it reaches the same level as the propulsion torque. After this point, $M_{b,req}$ decreases proportionally as $\hat{M}_t$ increases. When the complete brake release occurs $\hat{M}_t$ has exceeded M_g, and at this point the jerk peaks at a value of about 0.8 m/s^3. Figure 7.2b shows the case with the trailer. As mentioned above, the difference is not only the trailer, but also the inclination, and as can be seen in the figure, this results in roughly the same M_g as in Figure 7.2a. As without the trailer, this case has a quite linear decrease of brake torque. When the brakes have fully released, $\hat{M}_t$ is about the same as M_g and the jerk peaks at a slightly smaller value of 0.6 m/s^3. There was no rollback in either of the cases.

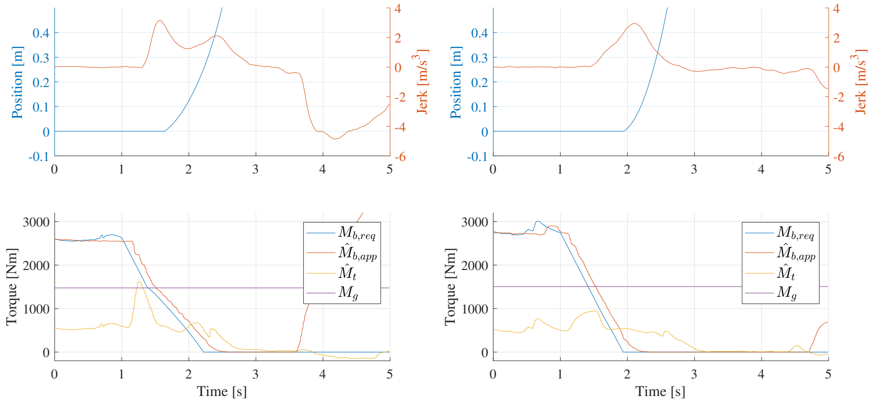


(a) *30 % inclination without trailer.* ***(b)*** *20 % inclination with trailer.*

Figure 7.2: *Test Case I, driving forward in manual drive mode, uphill.*

Case V

Figure 7.3 shows tests in the same inclinations as above, but with a downhill drive-off. The test is initiated by having the driver making a quick press on the accelerator pedal, which activates the DAR function. This leads to a short peak of a $M_{t,req}$ from the driver, and therefore $\hat{M}_t$. Figure 7.3a shows the case without the trailer, and when the $\hat{M}_t$ increase occurs, the jerk peaks at about 3.2 m/s^3. The ramp out of $M_{b,req}$ can be seen following two different inclinations, at first a quicker release towards $\hat{M}_g$, and afterwards it slows down. The position shows the vehicle is moving forward at about 1.8 s, when the brakes are still acting on the wheels, which indicates they are acting against the forward movement, whereas $\hat{M}_t$ is still showing a propulsion torque driving the vehicle forward even though the driver did not press the accelerator pedal after initiating the drive-off. When the brakes has fully released there is a peak in jerk just about 2.0 m/s^3. Figure 7.3b shows Case V with the trailer. Comparing to the case without the trailer, the brakes releases quicker, whereas the position plot shows a slower drive-off, although the brakes releases earlier. When the brakes have fully released the jerk peak at about 2.9 m/s^3. Both figures have a negative peak of jerk at the end, this is however after the drive-off has occurred and the driver has full control of the vehicle.



(a) 30 % inclination without trailer. *(b) 20 % inclination with trailer.*

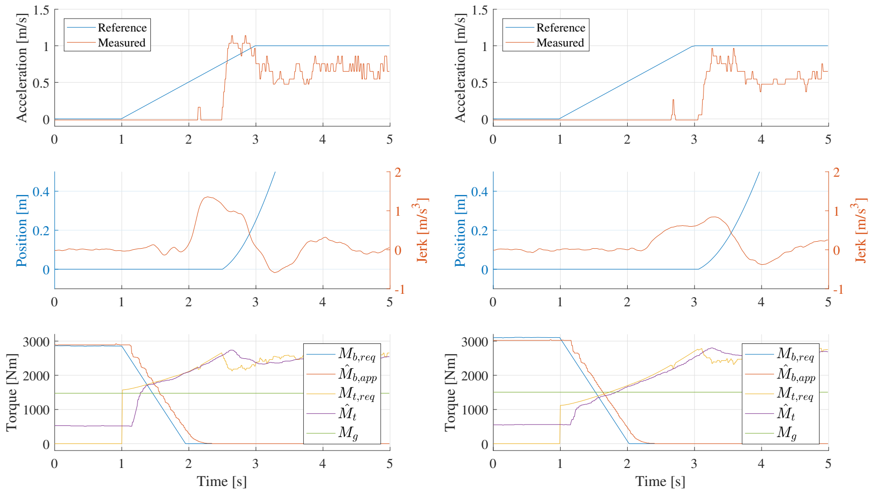
Figure 7.3: *Test Case V, driving forward in manual drive mode, downhill.*

7.3.2 Autonomous Drive Mode

During the tests in autonomous drive mode, the drive-off is performed by sending an acceleration request of 1 m/s^2 at 1 s, according to the model presented in Chapter 4.2.4. As stated in Chapter 7.1, the measured acceleration is based on the speed at the wheels, which requires rotations in order to provide a signal. In this chapter, the results from the tests in forward driving in Case I and V are presented, the rest of the results are provided in Appendix C.2.

Case I

Figure 7.4 shows the forward, autonomous drive-off uphill. When the DAR function is activated, $M_{b,req}$ is decreases and $\hat{M}_{b,app}$ follows with a small delay. At this time there is an immediate increase of $M_{t,req}$ to $\hat{M}_g$, where as $\hat{M}_t$ starts increasing shortly after. The acceleration starts 1.5 - 2 s after the drive-off is initiated, and as this occurs the position shows the movement. When this happens, the acceleration quickly increases towards the reference value, and then is placed slightly lower. Figure 7.4a shows Case I without the trailer, and $\hat{M}_t$ has exceeded M_g as it intersects with $\hat{M}_{b,app}$. When the the acceleration increases, there is a slight overshoot, which reduces $M_{t,req}$. When the brakes have fully released the jerk peaks at about 1.3 m/s^3. Figure 7.4b shows the case with the trailer. The overall behaviour is about the same as without the trailer, although $\hat{M}_t$ does not increase as fast, and therefore intersects with $\hat{M}_{b,app}$ just below M_g. The acceleration never reaches the reference signal, but has an overshoot which gives a reduction in $M_{t,req}$. At this point the jerk peaks at a value of 0.8 m/s^3. There is no rollback in either test.

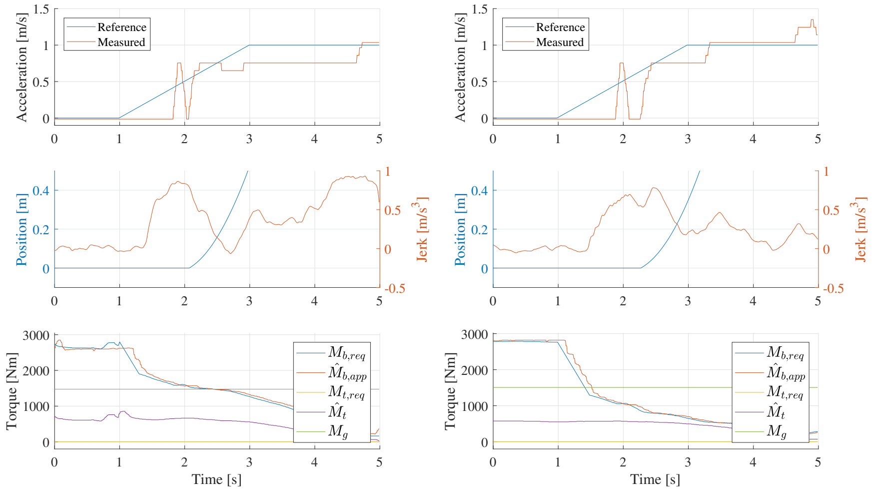


(a) 30 % inclination without trailer. *(b) 20 % inclination with trailer.*

Figure 7.4: *Test Case I, driving forward in autonomous drive mode, uphill.*

Case V

Figure 7.5 shows the autonomous downhill drive-off. In both cases, $M_{t,req}$ is zero, but $\hat{M}_t$ shows an active propulsion torque. As the DAR function activates, $M_{b,req}$ decreases in two steps, first quickly towards $\hat{M}_g$, and then more slowly. The brakes never fully releases in these tests, but keep decreasing over time. The acceleration acts as for uphill, being activate when the vehicle starts to move, at this time the jerk peaks. In the case without the trailer the jerk reaches 0.9 m/s^3, the peak at the end occurs due to the driver braking (see Figure 7.5a). For the case with the trailer the jerk peaks at 0.8 m/s^3 (see Figure 7.5b).



(a) *30 % inclination without trailer.* ***(b)*** *20 % inclination with trailer.*

Figure 7.5: *Test Case V, driving forward in autonomous drive mode, downhill.*

7.4 Analysis of Test Drive

In this section an analysis is made of the manual drive mode and the autonomous drive mode.

7.4.1 Manual Drive Mode

When performing the tests in the manual drive mode, the system only requests brake torque, and the driver is responsible for the request of propulsion torque. The results show no rollback detected, regardless of trailer status, which would have been noticeable on $M_{b,req}$, as it would receive a similar look as the requested brake torque in Figure 7.1 or the results in Chapter 6. The absence of rollback detection may occur due to limitations within the signals, as described in Chapter 7.1, meaning different signals are sent with different time intervals, and enough propulsion torque has been produced to hold the vehicle, or drive it forward, before the rollback could be detected. The reason why the propulsion torque might have increased fast enough is the fact that $\hat{M}_t > 0$ when in Hold, which means $\hat{M}_t$ is closer to M_g when the DAR function is activated compared to if it would have been zero.

$M_{b,req}$ depends on $\hat{M}_t$ and $\hat{M}_g$ (see Equation (4.12)). Since $\hat{M}_t > 0$, and thus being closer to M_g, a consequence may be that the brakes have not fully released when M_t exceeds M_g (see Figure 7.2a), which indicates that the brakes start to act in the opposite direction. Since $\hat{M}_{b,app}$ is always positive, it is not shown in the tests. As stated in Chapter 3.3.1 a delay in the brake release increases the jerk, which can be seen in the results as there is a peak of jerk when this occurs. Figure 7.2b does not show this effect though and has a smaller jerk. In both cases when starting uphill, the jerk is less than 1 m/s^3, which is good according to the comfort measure discussed in Chapter 3.2. In manual drive mode the jerk does also depend on how aggressive the driver is.

The fact that $M_t > 0$ also affects the downhill drive-off as it acts in the same direction as M_g, the consequence of this may be an increase in acceleration and jerk. The jerk is a bit high as it is around the limits of comfort according to [6]. $\hat{M}_{b,app}$ follows $M_{b,req}$ well, and ramp release occurs in a desired fashion, much like for uphill drive-off, although comparing Figure 7.2 and Figure 7.3 the overall behaviour of the drive-off is smoother for uphill drive. This could depend on how the drive-off is initiated as the there is a quick peak of propulsion request by the driver to initiate it, and as $M_t > 0$ and acts in the same direction as M_g, which would provide a larger acceleration compared to uphill, where the torques are opposite each other.

7.4.2 Autonomous Drive Mode

As for the manual drive mode, the fact that $\hat{M}_t > 0$, leads to the same problems as stated above. The DAR function is activated when an acceleration request is sent, which produces $M_{t,req}$ and $M_{b,req}$. The results show that the actual acceleration does not provide a signal at this moment as it is based on the vehicle speed. As described in Chapter 4.2.4, to reduce the difference between the acceleration request and the measured acceleration, a PI controller is used. Since the measured acceleration requires the vehicle to move over a certain speed limit, it quickly increases to the reference signal once the acceleration occurs making a not so smooth reference tracking. When the accelerations increases it sometimes achieves a slight overshoot, see e.g. Figure 7.4a. When this occurs, there is a drop of $M_{t,req}$, this is a consequence of the feedforward from disturbance, which depends on the inclination. The inclination is estimated according to Equation (4.30), and a sudden increase in acceleration increases the estimated inclination used by the DAR function and as such will affect $M_{t,req}$.

The steep increase in acceleration, does not seem to cause much discomfort. As the vehicle starts to move, the jerk increases, which it should. However, it is worth noting that the jerk is overall 1 m/s^3, including the results in Appendix C.2, which is comfortable according to Chapter 3.2, which discuss the comfort level. During the drive-off, both $\hat{M}_{b,app}$ and $\hat{M}_t$ follows their requested signals quite smoothly with a small delay.

8

Discussion

The purpose of the thesis is to develop and implement a novel and generic concept of a DAR function in a vehicle for both drive modes, at the different inclination and with or without a trailer. In order to achieve the requirements (see Chapter 1.3), the presented concept described in Chapter 4 aims to have released the brakes fully when the propulsion torque manages to hold the vehicle, which agrees with the state-of-the-art control presented in Chapter 3.3.1. In order to prevent rollback, a late release is preferable, although this is at the cost of comfort.

8.1 Rollback

When designing the DAR function, a rollback prevention was developed, which is an important safety feature. The aim of the rollback prevention is to ensure the vehicle stops if rollback occurs. The maximum allowed rollback is 10 cm, but only when a trailer is hitched to the vehicle. Both simulations and test drives showed that this safety feature managed to stop the vehicle by only reapplying the brakes. However, in the test drive at 30 % inclination, a rollback distance of 19 cm was measured, which exceeds the 10 cm limit. During a normal drive-off there will also be an increasing propulsion torque which would act against the rollback, thus reducing the rollback distance. However, as mentioned in Chapter 7.1, the implemented system does not always detect rollback or manage to measure it. This occurs due to a too small rollback and low speed. Therefore it is not possible to be completely sure of the actual rollback distance and whether the requirement is fulfilled or not, but the rollback prevention is working.

An alternative to measure rollback would be to use external equipment during testing, however, this was not accessible during testing, and would not provide any input to the system. In order to achieve the requirement, it would require signals which detect directional movement and speed quicker than the ones provided in the test vehicle, which is an older vehicle compared to vehicles in production. It stands to reason that the quicker the signals, the quicker the rollback prevention starts reapplying the brakes, the quicker the vehicle stops. The results of the simulations had no problem meeting the requirements, and since the results of the test drives did not show any rollback, meaning that according to the system within the vehicle, the requirements are met and the DAR function works as intended.

The test vehicle used in the thesis is an older one, which leads to more restrictions on available signals, and another restriction is that several functions which are within newer models are not available. For example, a vehicle with ACC implemented could provide a way to conduct an autonomous drive-off. However, since this was not available, the autonomous function was created according to Chapter 4.2.4, which functions well enough to test the concept, but it is likely that this function is not as precise as an existing VCC function. This means that the more functions created to estimate certain states, which are normally provided by other systems, within the thesis may reduce the quality of the actual DAR function. The same goes for estimations, it is reasonable to assume that the more accurate the estimations are the better the DAR function would be. It would be beneficial to implement this concept DAR function into a newer vehicle with more signals and parameters. However, the results of the test drives show that the DAR function performs the drive-off quite well, from both a rollback and a comfort perspective, even if the estimations may be inaccurate.

8.2 Comfort

The limit when jerk causes discomfort is at about 2.94 m/s^3 [6], although most research only states their levels, which are lower, i.e. 2 - 2.5 m/s^3 [2, 5], as comfortable (see Chapter 3.2). Based on this, both the simulations and test drives show that the concept manages to keep a comfortable level during the autonomous mode, as the worst simulation result showed a jerk of 1.9 m/s^3, and the largest jerk during the autonomous test was 1.5 m/s^3. This is not the case for manual drive mode, and there is a difference between the simulations and the test drives. During the manual test drive in a downhill inclination of 30 %, the comfort limit was exceeded without the trailer with a jerk of 3.2 m/s^3. The case with the trailer at 20 % inclination, a jerk of 2.9 m/s^3 was measured, which is just below the comfort level. It is likely that the jerk increases as a consequence of when the driver initiates the drive-off by pressing the accelerator pedal, thus making a propulsion torque request. Chapter 7.1 states that there is an active propulsion torque at all times, and the ramp out for the brake torque as stated in Equation (4.21) does not take this into account, which may result in a higher jerk. The manual test drive showed a jerk under 1 m/s^3 for all of the cases when going forward uphill, which is considered to be comfortable because it is relatively low compared to the discomfort limit. The manual simulations showed the opposite behaviour, with a comfortable jerk driving downhill, and large jerk during uphill. The largest jerk during the manual uphill simulations was 3.6 m/s^3.

8.3 Simulations and Test Drives

When comparing the jerk between the simulations and the test drives, the jerk levels are of roughly the same magnitude for autonomous drive in both cases. However, as stated above, the jerk for manual drive-off differs. This could depend on several things and therefore it may be difficult to pin down the actual reason. The powertrain used in the simulations was provided within CarMaker, which likely differs from the one in the test vehicle. The driver may also influence the manual test cases. In the simulations a virtual driver was used and to imitate this behaviour in the test vehicle can be challenging. The reason why autonomous drive mode shows a comfortable drive-off is that when driving off in autonomous mode, the DAR function does not need to take the driver influence into account which result in a more predictive outcome. Another reason for the difference between the simulations and the test drives is that in the test drive the propulsion torque was active even in Hold.

Comparing the reference tracking in autonomous mode, it can be noted the simulations manages to reach the reference signal in most of the cases, whereas the results from the test drives differs. The reason for this is that the measured acceleration of the vehicle is based on the wheel speed, which does not update until the vehicle is moving at a certain speed. This means that the acceleration cannot be measured until this threshold has been reached. All the test drive plots show a quick increase from zero in the measured acceleration. Since the feedback error is handled with a PI-controller, fast changes in the measured acceleration will effect the control signal. This can be noted as when the measured acceleration changes rapidly, the control signal oscillates, which in turn changes the vehicle acceleration. However, the vehicle still manages to drive-off with the help of the feedforward from disturbance and reference.

Overall the same behaviours are shown in the test results as in the simulation results. Some differences occur due to the provided signals to the system in the test vehicle. Comparing the jerk of the tests and simulations, there is not much difference, although the tests with the trailer in a steeper slope shows a lower jerk. However, in the test drive the inclination is at 20 % rather than 30 % as in simulations which may influence the results, and as such it cannot be certain that the trailer reduces the jerk at steeper slopes. Comparing to the manual drive instead, the jerk is larger at when driving uphill in autonomous drive mode, but smaller during the downhill drive-off. When driving downhill in manual drive mode, $M_{b,req}$ is ramped out disregarding the acceleration, but in autonomous mode the brake release still depends on the acceleration request, compare e.g. Figure 7.3 and Figure 7.5 where the brakes fully release for the manual mode and not autonomous.

Using a simulation environment as CarMaker may be a good tool to use for simulation and look at the functionality of the controls. The settings of the vehicle within the simulations was set as close to the test vehicle as possible, however, there are still several differences such as the driveline. Overall in CarMaker there are a lot of possibilities to change and configure the vehicle, and also how the driver should behave, which is overwhelming and several settings might not be completely accurate for the simulations. This may result in the simulation not being completely valid for the test vehicle.

8.4 Reconnect to the Related Research

A state-of-the-art study was presented in Chapter 3.3.1. Several studies pointed out that the brake wear and jerk increases if braking torque is still applied when the propulsion torque is large enough to keep the vehicle from rolling backwards. This provided the basis for the brake control presented in Chapter 4.2.1, which was based on a trade-off between the applied brake torque and propulsion torque.

Several studies were presented with different solutions for different control signals, sensors and estimations. The studies worked other control signals compared to this thesis, which is based on the *Torque-Based Powertrain Control* and hill start with this kind of control was not found during the related research study. This lead to that most of control structures used in the studied articles were not directly applicable. However, they provided inspirations for how a solution, for example the authors in [8] used a feedforward-feedback structure which gave the idea of the autonomous drive mode control.

9 Conclusions

In this thesis a concept of a DAR function has been developed with aim to perform a drive-off for both *autonomous* and *manual* drive modes, in both *drive* and *reverse*, as well as at different inclinations.

In order to have an autonomous drive mode, a model was designed with a feedback loop, and feedforward from both a reference and disturbance. The autonomous drive mode functioned as intended, and worked well enough to perform autonomous testing. The drive-offs are overall at a comfortable level, which is important to both drivers and passengers. Both the simulations and the test drives show a more comfortable drive-off for the autonomous drive mode compared to manual drive mode. There are larger variations in jerk in the manual drive mode, where the jerk is also influenced by the driver's behaviour.

In order to handle rollback, a rollback prevention safety feature was developed, with the basic concept of reapplying the brakes when the vehicle is detecting a downhill movement. This safety feature was implemented and evaluated on a test vehicle. When testing the rollback prevention without requesting propulsion torque, i.e. only reapplying the brakes, the vehicle managed to stop for various inclination angles. However, the rollback distance on a 30 % road inclination during these tests exceeded the requirement.

Both the simulations and test drive results show that the DAR function was able to perform the uphill drive-off without exceeding rollback requirement: no rollback without a trailer and 10 cm rollback with a trailer. During the test drives, no rollback was detected with the signals that was available in the vehicle. To ensure that the requirements are met, the rollback distance needs to be estimated or measured more accurately.

9.1 Future Work

Implement in a new test vehicle - To keep the thesis relevant for VCC the concept should be tested in a newer test vehicle, with their current signals and systems. It would also be good to see how it would function in another vehicle, as this is only tested in one, and the idea of the propulsion torque control is to have control regardless of the driveline.

Reducing the number of tuning parameters - The concept described in Chapter 4.2 introduce several parameters which could be tuned. It might be a good idea to look into the possibility of reducing the tuning parameters, which always is desired.

More testing - The concept function requires more testing. The tests provided in Table 5.1 give a decent amount of results for the thesis, however, there are plenty more variations this function could be tested. For instance, testing the concept with different trailer loads and drivelines.

Appendix

A

ISO 26262 - Risk Assessment

System safety is an essential part of system design in the automotive industry. Therefore, as part of the master thesis work, a risk assessment was performed in order to understand the process around hazard analysis and what safety aspects that needs to be consider when developing a DAR function. The analysis has not undergone the required verifications and should therefore only be regarded as an initial indication of possible hazards and ASIL levels.

The DAR function is intended to work in both manual and autonomous drive. During the manual drive, the driver has control over the propulsion torque request while the brake torque request is intended to be handled by the DAR function. For autonomous drive the DAR function controls both torque requests. The DAR function has therefore been divided into three different subfunctions

- **Manual drive-off - Brake torque request**
  Controls the brake torque request when a manual drive-off is requested
- **Autonomous drive-off - Brake torque request**
  Controls the brake torque request when an autonomous drive-off is requested
- **Autonomous drive-off - Propulsion torque request**
  Controls the propulsion torque request when an autonomous drive-off is requested

The HAZOP analysis can be found in Table A.1, where each of the subfunctions for the DAR are listed. The HAZOP analysis identifies malfunctions of each subfunction. The mapping of the subfunctions can be found in Table A.2, note that the manual and autonomous drive-off request are listed in the same table due to identical malfunction behaviour and vehicle hazards, and Table A.3. The HARA analysis for the subfunctions can be found in Tables A.4 - A.12.

Table A.1: *HAZOP analysis for Drive Away Release function.*

System function vs. HAZOP Guidewords	**Loss of Function**	**Incorrect Activation (More than requested)**	**Incorrect Activation (Less than requested)**	**Incorrect Activation (Activation in Opposite Direction)**	**Activation (When none was requested)**	**Output Stuck at a Value (Failure of function to update as intended)**
Manual drive-off function (Brake torque request)	Loss of brake release request	Excessive brake request release	Reduced brake request release	-	Unintended brake request release	Locked braking (Brake request output stuck at value)
Autonomous Drive-off function (Brake torque request)	Loss of brake release request	Excessive brake request release	Reduced brake request release	-	Unintended brake request release	Locked braking (Brake request output stuck at value)
Autonomous drive-off function (Propulsion torque request)	Loss of propulsion torque request	Excessive propulsion torque request	Insufficient propulsion torque request	-	Unintended propulsion torque request	Constant propulsion torque request

Table A.2: *Mapping of DAR manual/autonomous drive-off - Brake torque request malfunction behaviours to vehicle hazards.*

Malfunction Behaviour	Vehicle Hazards
Loss of brake release request	Vehicle remains stationary
Excessive brake request release	Unintended vehicle longitudinal motion
Unintended brake request release	
Reduced brake request release	Unintended decrease in acceleration
Locked braking (brake request output stuck at value	Vehicle remains stationary / Unintended decrease in acceleration

Table A.3: *Mapping of DAR autonomous drive-off - Propulsion torque request malfunction behaviours to vehicle hazards.*

Malfunction Behaviour	Vehicle Hazards
Loss of propulsion torque request	Vehicle remains stationary
Unintended propulsion torque request	Vehicle remains stationary / Unintended vehicle longitudinal motion
Constant propulsion torque request	
Excessive propulsion torque request	Unintended increase in acceleration
Insufficient propulsion torque request	Unintended decrease in acceleration

Table A.4: *Manual Drive-off - Brake torque request.*

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Manual drive-off (Brake torque request)	Loss of brake torque release request	Unintended loss of acceleration/ Vehicle remains stationary	No fault in propulsion torque request	The brakes do not release even though there is a driver request to drive-off, malfunction results with the vehicle remaining stationary or slow drive-off	Standing still, or a slow drive-off, in high traffic density may result in collision with vehicle from behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in stand still, which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	-
Manual drive-off (Brake torque request)	Unintended brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides the requested brake torque	The brakes starts to release prematurely without DAR demands are met	Potential collision with a pedestrian	2	Vehicle is stopped in a slope. Pedestrian close to the vehicle when the failure occurs. Low speed	2	Collision speed will be relatively low, as initial speed was very low and pedestrian is regarded to be close to the vehicle	3	Some drivers may be startled at the moment of unintended acceleration and the close proximity of vehicle and pedestrian lowers the reaction time	A	-
Manual drive-off (Brake torque request)	Unintended brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides the requested brake torque	The brakes starts to release prematurely without DAR demands are met	Potential collision with a pedestrian	2	Vehicle is stopped in a slope, with enough free space to roll, i.e. to pick up hazardous speed. Pedestrian is in the hazard area (downhill) when the failure occurs	3	Collision speed more than 40 km/h	2	Driver normally able to react and brake the vehicle	A	-

Table A.5: *Manual Drive-off - Brake torque request (Continued).*

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Manual drive-off (Brake torque request)	Excessive brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides the requested brake torque	The brakes releases completely prematurely causing the vehicle to move	Potential collision with a pedestrian	2	Vehicle is stopped at a slope. Pedestrian close to the vehicle when the failure occurs. Low Speed	2	Collision speed will be relatively low, as initial speed was very low and pedestrian is regarded to be close to the vehicle	2	Driver normally able to react and either accelerate more or brake the vehicle	QM	-
Manual drive-off (Brake torque request)	Excessive brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides the requested brake torque	The brakes releases completely prematurely causing the vehicle to move	Potential collision with a pedestrian	2	Vehicle is stopped in a slope, with enough free space to roll, i.e. to pick up hazardous speed. Pedestrian is in the hazard area (downhill) when the failure occurs	2	Collision speed more than 40 km/h	2	Driver normally able to react and brake the vehicle	QM	-
Manual drive-off (Brake torque request)	Reduced brake request release	Unintended decrease in acceleration	No fault in propulsion torque request	The brakes releases to slow which results in a lower acceleration than intended	A slow drive-off might result in a collision from the vehicle behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in stand still, which results in low speed collisions	1	Driver normally able to react and either accelerate more or brake the vehicle	QM	-

Table A.6: *Manual Drive-off - Brake torque request (Continued).*

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Manual drive-off (Brake torque request)	Late brake request release	Unintended high acceleration	No fault in propulsion torque request	Increase of propulsion torque by driver or autonomous function and then DAR releases brake torque late resulting in a sudden, high acceleration	Potential collision with pedestrian	3	A significant proportion of drive cycles includes areas where pedestrians are present. However, it is evaluated that only a certain proportion of the driving time is spent at these locations and pedestrians are not always in the hazardous area	2	Collision speed will be relatively low, as initial speed was very low and pedestrian is regarded to be close to the vehicle	1	Most of the drivers are able to control the situation	QM	Increases jerk
Manual drive-off (Brake torque request)	Locked braking (Brake request output stuck at value)	Vehicle remains stationary/ Unintended loss in acceleration	No fault in propulsion torque request	The brakes will not release fully when a drive-off is requested	Standing still or a slow drive-off might result in a collision from the vehicle behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in stand still, which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	Driving off with the brakes fully not released will wear them out. Driving with partly applied brakes may also result in brake fade, i.e. buildup of heat in the brake disc resulting in reduced brake performance. This need further analysis and is not covered here.

Table A.7: Manual Drive-off - Brake torque request (Continued).

Function	**Malfunctioning Behavior(s)**	**Vehicle Level Hazard**	**Assumption**	**Hazard Detailed Description**	**Potential accident scenario(s)- considering worst case mishap potential**	**ASIL Assessment**							**Comments or Considerations (if applicable)**
						E	**Rationale**	**S**	**Rationale**	**C**	**Rationale**	**ASIL**	
Manual drive-off (Brake torque request)	Unintended brake torque request	Unintended decrease in acceleration	No wheel locking	Brakes starts to reapply while driving causing the vehicle to slow down	Rear collision if vehicle behind is traveling too closely and unable to stop	4	Driving on country road or highway	3	Rear collision with another vehicle with medium speed	2	Most drivers are able to control the situation if travelling distance is kept	C	-
Manual drive-off (Brake torque request)	Unintended brake torque request	Unintended decrease in acceleration	Locking of wheels, affecting vehicle stability	Brakes are fully reapplied while driving causing the vehicle to slow down	Potential for vehicle to depart lane and collide with other vehicles, pedestrians, or objects	4	Driving on country road or highway	3	Collision with other vehicle or stationary object	3	Situation puts high demand on the driver’s skills	D	-

Table A.8: Autonomous Drive-off - Brake torque request.

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Autonomous drive-off (Brake torque request)	Loss of brake release request	Unintended loss of acceleration/ Vehicle remains stationary	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes do not release even though there is a driver request to drive-off, malfunction results with the vehicle remaining stationary or slow drive-off	Standing still, or a slow drive-off, in high traffic density may result in collision with vehicle from behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in stand still, which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	-
Autonomous drive-off (Brake torque request)	Unintended brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes starts to release prematurely without DAR demands are met	Potential collision with a pedestrian	2	Vehicle is stopped in a slope. Pedestrian close to the vehicle when the failure occurs. Low speed	2	Collision speed will be relatively low, as initial speed was very low and pedestrian is regarded to be close to the vehicle	3	Some drivers may be startled at the moment of unintended acceleration and the close proximity of vehicle and pedestrian lowers the reaction time	A	-
Autonomous drive-off (Brake torque request)	Unintended brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes starts to release prematurely without DAR demands are met	Potential collision with a pedestrian	2	Vehicle is stopped in a slope, with enough free space to roll, i.e. to pick up hazardous speed. Pedestrian is in the hazard area (downhill) when the failure occurs	3	Collision speed more than 40 km/h	2	Driver normally able to react and brake the vehicle	A	-

Table A.9: *Autonomous Drive-off - Brake torque request (Continued).*

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Autonomous drive-off (Brake torque request)	Excessive brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes releases completely prematurely causing the vehicle to move	Potential collision with a pedestrian	2	Vehicle is stopped at a slope. Pedestrian close to the vehicle when the failure occurs. Low Speed	2	Collision speed will be relatively low, as initial speed was very low and pedestrian is regarded to be close to the vehicle	2	Driver normally able to react and brake the vehicle	QM	-
Autonomous drive-off (Brake torque request)	Excessive brake torque request release	Unintended vehicle longitudinal motion	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes releases completely prematurely causing the vehicle to move	Potential collision with a pedestrian	2	Vehicle is stopped in a slope, with enough free space to roll, i.e. to pick up hazardous speed. Pedestrian is in the hazard area (downhill) when the failure occurs	2	Collision speed more than 40 km/h	2	Driver normally able to react and brake the vehicle	QM	-
Autonomous drive-off (Brake torque request)	Reduced brake request release	Unintended loss in acceleration	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes releases to slow which results in a lower acceleration than intended	A slow drive-off might result in a collision with the vehicle behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in stand still, which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	-

Table A.10: *Autonomous Drive-off - Brake torque request (Continued).*

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Autonomous drive-off (Brake torque request)	Locked braking (Brake request output stuck at value)	Vehicle remains stationary/ Unintended loss in acceleration	No fault in propulsion torque request, the brake pedal overrides autonomous function	The brakes will not release fully when a drive-off is requested	Standing still or a slow drive-off might result in a collision with the vehicle behind	4	DAR function will be used on every drive	1	Most of the time the vehicle will start stand still, which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	Driving off with the brakes fully not released will wear them out. Driving with partly applied brakes may also result in brake fade, i.e. buildup of heat in the brake disc resulting in reduced brake performance. This need further analysis and is not covered here.
Autonomous drive-off (Brake torque request)	Unintended brake torque request	Unintended decrease in acceleration	No wheel locking	Brakes starts to reapply while driving causing the vehicle to slow down	Rear collision if vehicle behind is traveling too closely and unable to stop	4	Driving on country road or highway	3	Rear collision with another vehicle with medium speed	2	Most drivers are able to control the situation if travelling distance is kept	C	-
Autonomous drive-off (Brake torque request)	Unintended brake torque request	Unintended decrease in acceleration	Locking of wheels, affecting vehicle stability	Brakes are fully reapplied while driving causing the vehicle to slow down	Potential for vehicle to depart lane and collide with other vehicles, pedestrians, or objects	4	Driving on country road or highway	3	Collision with other vehicle or stationary object	3	Situation puts high demand on the driver's skills	D	-

Table A.11: *Autonomous Drive-off - Propulsion torque request.*

Function	**Malfunctioning Behavior(s)**	**Vehicle Level Hazard**	**Assumption**	**Hazard Detailed Description**	**Potential accident scenario(s)- considering worst case mishap potential**	**ASIL Assessment**							**Comments or Considerations (if applicable)**
						E	**Rationale**	**S**	**Rationale**	**C**	**Rationale**	**ASIL**	
Autonomous drive-off (Propulsion torque request)	Loss off propulsion torque request	Unintended loss of acceleration	No fault in brake torque request, the brake pedal overrides autonomous function	The propulsion torque will be zero leading to that the brakes will not release, the vehicle will remain stationary	Standing still might result in a collision with the vehicle behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in stand still, which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	-
Autonomous drive-off (Propulsion torque request)	Unintended propulsion torque request	Vehicle remains stationary/ Unintended vehicle longitudinal motion	No fault in brake torque request, the brake pedal overrides autonomous function	If the propulsion torque request result in a propulsion torque high enough to release the brakes, the vehicle will start moving, otherwise the vehicle will remain stationary	When the vehicle starts to move unintendedly, it might cause a collision with another vehicle or a pedestrian	3	A significant proportion of drive cycles includes areas where pedestrians are present, however not always in the hazardous area. It is evaluated that only a certain proportion of the driving time is spent at these locations	2	Colliding with a pedestrian can result in life-threatening injuries	3	While using an autonomous drive mode, the driver might not be as alert and therefor have a longer reaction time than usual	B	-
Autonomous drive-off (Propulsion torque request)	Loss of propulsion torque request during DAR	Vehicle remains stationary/ Unintended vehicle longitudinal motion	No fault in brake torque request, the brake pedal overrides autonomous function	If the propulsion torque is low the brakes will not release. If the propulsion torque is high enough the brake starts to release. If the propulsion torque is to low when the brakes released, rollback may occur	When the vehicle starts to move unintendedly, it might cause a collision with another vehicle or a pedestrian	2	Vehicle is stopped at a slope. Pedestrian close to the vehicle when the failure occurs	2	Collision speed will be relatively low, as initial speed was very low and pedestrian is regarded to be close to the vehicle	3	While using an autonomous drive mode, the driver might not be as alert and therefor have a longer reaction time than usual	A	-

Table A.12: *Autonomous Drive-off - Propulsion torque request (continued).*

Function	Malfunctioning Behavior(s)	Vehicle Level Hazard	Assumption	Hazard Detailed Description	Potential accident scenario(s)- considering worst case mishap potential	ASIL Assessment							Comments or Considerations (if applicable)
						E	Rationale	S	Rationale	C	Rationale	ASIL	
Autonomous drive-off (Propulsion torque request)	Excessive propulsion torque request	Unintended increase in acceleration	No fault in brake torque request, the brake pedal overrides autonomous function	The propulsion torque will be higher than intended resulting in a higher acceleration than intended	When the vehicle starts to move unintendedly, it might cause a collision with another vehicle or a pedestrian	3	A significant proportion of drive cycles includes areas where pedestrians are present. However, it is evaluated that only a certain proportion of the driving time is spent at these locations and pedestrians are not always in the hazardous area	2	Colliding with a pedestrian can result in life-threatening injuries	3	While using an autonomous drive mode, the driver might not be as alert and therefor have a longer reaction time than usual	B	-
Autonomous drive-off (Propulsion torque request)	Insufficient propulsion torque request	Vehicle remains stationary/ Unintended decrease in acceleration	No fault in brake torque request, the brake pedal overrides autonomous function	The propulsion torque will not be high enough to initiate the brake release, resulting in that the vehicle remains stationary	Standing still might result in a collision with the vehicle behind	4	DAR function will be used on every drive	1	Most of the time the vehicle behind will start in standstill which results in low speed collisions	1	Most of the drivers are able to control the situation	QM	-

B

Simulation Results from CarMaker

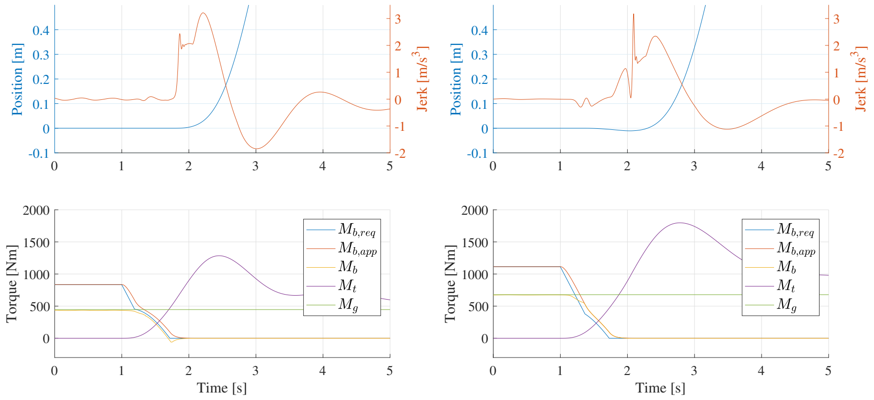
In Table 5.1 the performed test cases of the thesis are presented. In this appendix the results of the simulated tests, not included in the main report (see Chapter 6.3) are presented. The vehicle has the same mass in all simulations, and when testing a vehicle with a trailer, the trailer mass is set to 800 kg. In all simulations the system is initially in Hold and activates the DAR function at 1 s.

B.1 Manual Drive

The tests of the manual drive mode presented in this appendix include forward driving in Case II, Case III, Case IV and reverse driving in Case IV and V.

Case II

Figure B.1 shows the simulated results for test Case II in forward manual drive mode. When DAR function is activated, $M_{b,req}$ starts to ramp out until it reaches $k_1\hat{M}_g$ (see Equation (4.12)). After this point, $M_{b,req}$ gradually decreases as the propulsion torque M_t increases. Figure B.1a represents the vehicle without the trailer. When the brakes are fully released, the jerk peaks at a maximum of 3 m/s^3. The brakes are released after M_t has exceeded M_g, causing M_b to act against the forward motion. There is no rollback in this case. Adding the trailer to the same case results in a small rollback of about 1 cm (see Figure B.1b). The driver is providing enough propulsion torque M_t, which causes the vehicle to stop before the rollback prevention function activates. As this happens, the jerk makes a quick down and up movement and peaks at 3 m/s^3.



(a) *Without trailer.* ***(b)*** *With trailer.*

Figure B.1: *Test Case II, driving forward in manual drive mode, uphill with an inclination of 10 %.*

Case III

Figure B.2 shows the manual forward drive-off of Case III without the trailer. As there is no inclination, M_b and M_g are zero, however the Hold function still applies a requested brake torque $M_{b,req}$, which rapidly decreases to zero. Before $M_{b,req} = 0$, M_b becomes negative as M_t increases, causing the brakes to act against forward motion. When the brakes have released there is a peak in jerk at 2.2 m/s^3 as M_t increases, although this occurs after the actual drive-off sequence.

Case IV

Figure B.3 represents Case IV in forward manual drive mode. During the drive-off downhill $M_t = 0$. The brakes release after about 0.3 s, in the case without the trailer, with a jerk at about 1.8 m/s^3, which occurs as the vehicle starts to move (see Figure B.3a). When the trailer is added the brakes take a bit longer to release as the vehicle is held with a larger $M_{b,req}$ in Hold (see Figure B.3b). The increased time, indicates that the brakes are applied longer and thus reducing the acceleration of the vehicle. The jerk peaks at a value about 2 m/s^3.

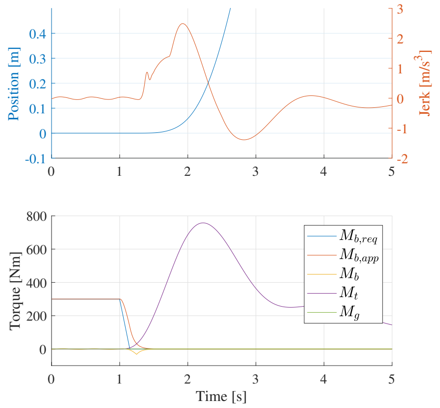
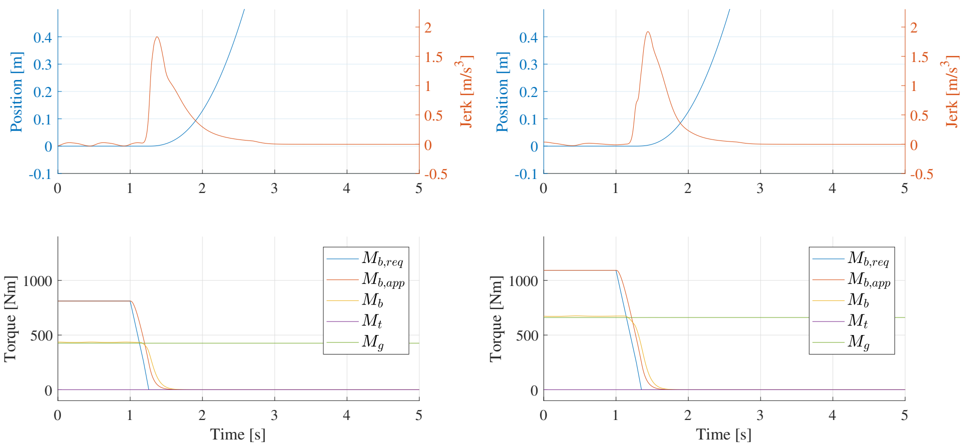


Figure B.2: *Test Case III, driving forward in manual drive mode on a horizontal road, without trailer.*

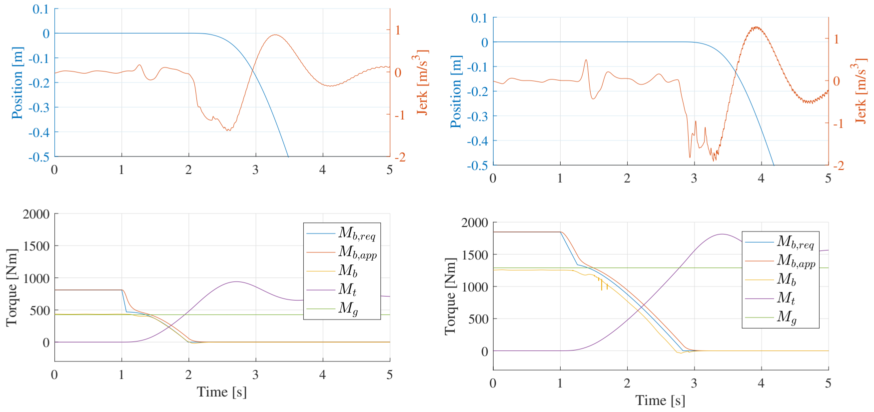


*(**a**) Without trailer.* *(**b**) With trailer.*

Figure B.3: *Test Case IV, driving forward in manual drive mode, downhill with an inclination of 10 %.*

Reverse Driving Case IV and V

Figure B.4 shows the vehicle reverse driving uphill in manual drive mode. As the vehicle is moving backwards, the position and jerk changes direction. Comparing to driving forward in manual in Cases I and II, M_t increases quite slowly and to a lower value while driving in reverse. Figure B.4a represents reverse driving in an inclination of 10 %, which has a maximum absolute jerk of about 1.3 m/s^3, which occurs when M_t peaks. In Case V, inclination of 30 %, the jerk increases compared to Case IV, 1.8 m/s^3, and it takes even longer to start moving the vehicle (see Figure B.4b). M_t is not as fast in reverse as in forward, and comparing to Case IV, the vehicle needs to overcome a larger gravitational torque, i.e. a larger propulsion torque is required.



(a) *10 % inclination without trailer.* ***(b)*** *30 % inclination without trailer.*

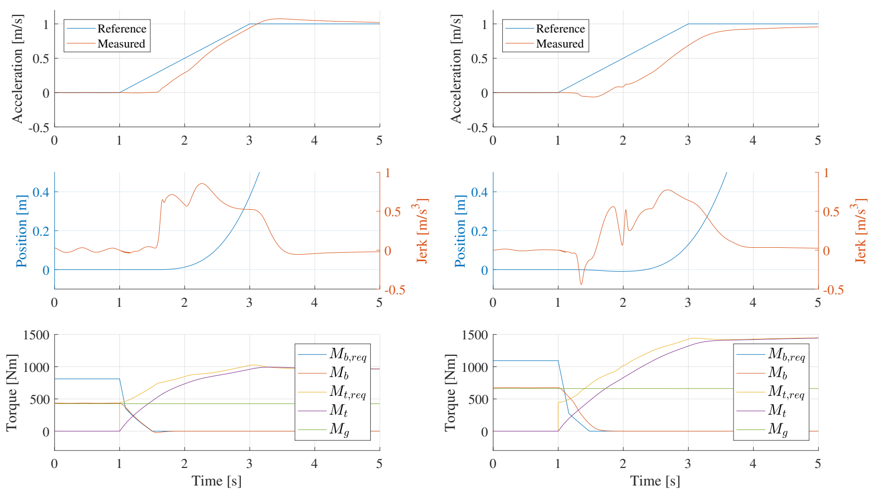
Figure B.4: *Test Case IV and V, driving reverse uphill in manual drive mode.*

B.2 Autonomous Drive

The tests of the autonomous drive mode presented in this appendix include forward driving in Case II, Case III, Case IV and reverse driving in Case IV and V. When the DAR function is activated, the autonomous drive mode initiates an acceleration request going from 0 to 1 m/s^2, with a ramp of 0.5 m/s^3, this is the same for all autonomous simulations.

Case II

The forward autonomous drive-off in Case II is shown in Figure B.5. When the DAR function is activated, $M_{b,req}$ starts to decrease and $M_{t,req}$ is instantly increases to $\hat{M}_g$. Afterwards M_b decreases with $M_{b,req}$ until the brakes have fully released, and M_t increases with $M_{t,req}$ in order to maintain the desired acceleration. Figure B.5a shows the case without trailer. When the vehicle starts to move, M_b is slightly acting against M_t and the forward motion. When the acceleration of the vehicle begins, the jerk increases and reaches a maximum value of 0.8 m/s^3. There is no rollback during this drive-off, however there is a small overshoot in the acceleration. In Figure B.5b the trailer is added. After 1.7 s, the vehicle starts to rollback, however, the rollback is small and the rollback prevention never activates. The rollback occurs when $M_t \approx M_g$, i.e. the limit when M_t can hold the vehicle without brakes, which means that as M_t keeps increasing, it is able to stop the rollback without the need of reapplying the brakes. The jerk reaches its peak value of 0.7 m/s^3.



(a) Without trailer. *(b) With trailer.*

Figure B.5: *Test Case II, driving forward in autonomous drive mode, uphill with an inclination of 10 %.*

Case III

The forward drive-off on a horizontal road with the autonomous drive mode is shown in Figure B.6. In Hold, $M_{b,req}$ has a value, whereas M_b and M_g are zero. When the DAR function is activated $M_{b,req}$ starts decreasing to zero and $M_{t,req}$ increases as the reference acceleration start to ramp up. M_t has a delay, but follows $M_{t,req}$. After the reference acceleration has reached a stationary value there is a small overshoot in the vehicle acceleration. The jerk reaches a maximum value of 0.8 m/s^3.

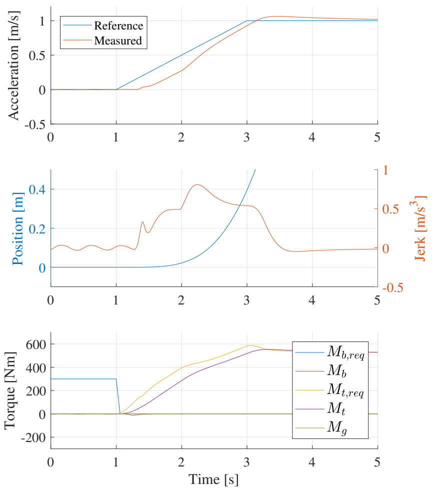
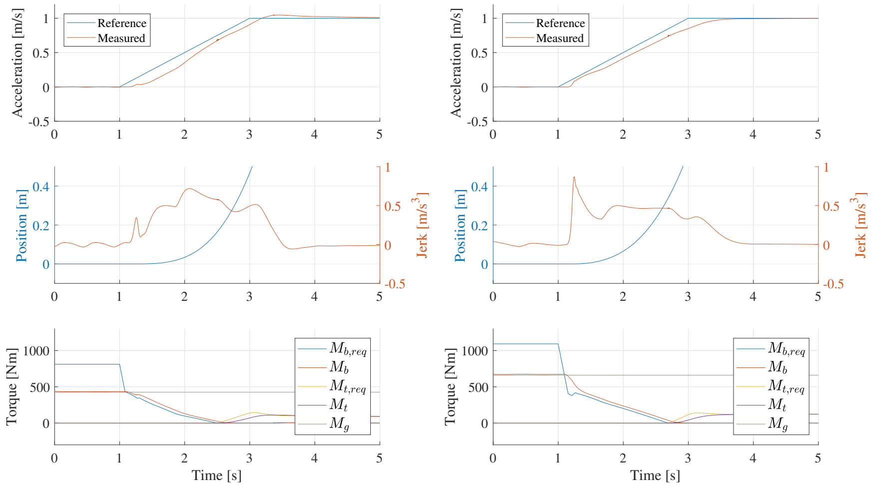


Figure B.6: *Test Case III, driving forward in autonomous drive mode on a horizontal road, without trailer.*

Case IV

The autonomous drive forward in Case IV is shown in Figure B.7. In the beginning of the drive-off there is a quick ramp out of $M_{b,req}$, which then slows down to keep with the acceleration requests. When the change of ramp out occurs, the jerks peaks. For the case of no trailer the peak is 0.4 m/s^3 (see Figure B.7a), and when the trailer is added it has its maximum peak at this point with 0.9 m/s^3 (see Figure B.7b). In both these cases, there is no need to provide a propulsion torque M_t until the brakes has released. The brakes take longer to release, partly due to the difference in initial $M_{b,req}$, and because of the acceleration request. In Figure B.7a, the acceleration has a small overshoot, and the case of no trailer has a maximum jerk of 0.7 m/s^3.

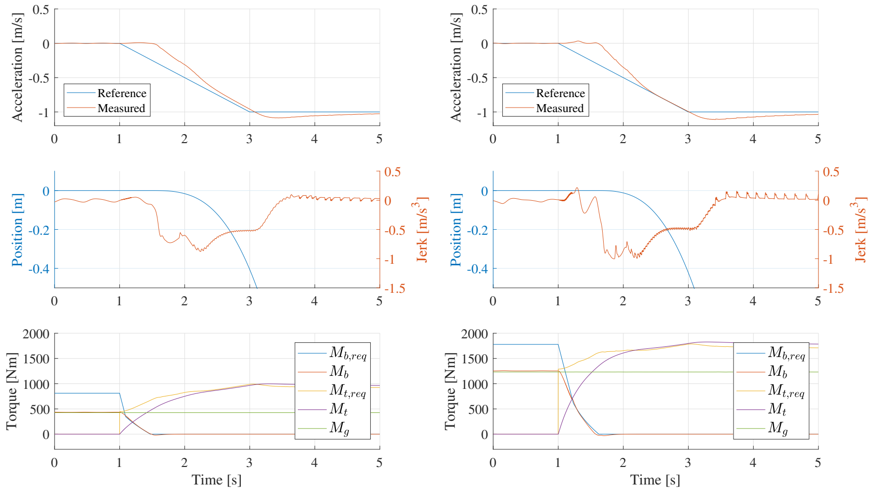


(a) Without trailer. *(b) With trailer.*

Figure B.7: *Test Case IV, driving forward in autonomous drive mode, downhill with an inclination of 10 %.*

Reverse Driving Case IV and V

The results for test Case IV and Case V, when the vehicle is driving reverse in autonomous drive mode, can be seen in Figure B.8. When the DAR function is activated, the acceleration reference starts to ramp down, $M_{t,req}$ has an instant increase, and $M_{b,req}$ decreases fast to $k_1 \hat{M}_g$. $M_{b,req}$ then starts to ramp out proportionally to the propulsion torque M_t. When M_t becomes larger than M_g the vehicle starts to move uphill, there is no roll downhill in either of the two cases. For an inclination of 10 %, i.e. Case IV, the absolute peak value for the jerk is around 0.8 m/s^3 (see Figure B.8a). For 30 % inclination, i.e. Case V, the jerk peaks at an absolute value of 1 m/s^3 (see Figure B.8b). In both cases there is a small overshoot when the reference reaches its stationary value.



(a) *10 % inclination without trailer.* ***(b)*** *30 % inclination without trailer.*

Figure B.8: *Test Case IV and V, driving reverse uphill in autonomous drive mode.*

C

Test Drive Results

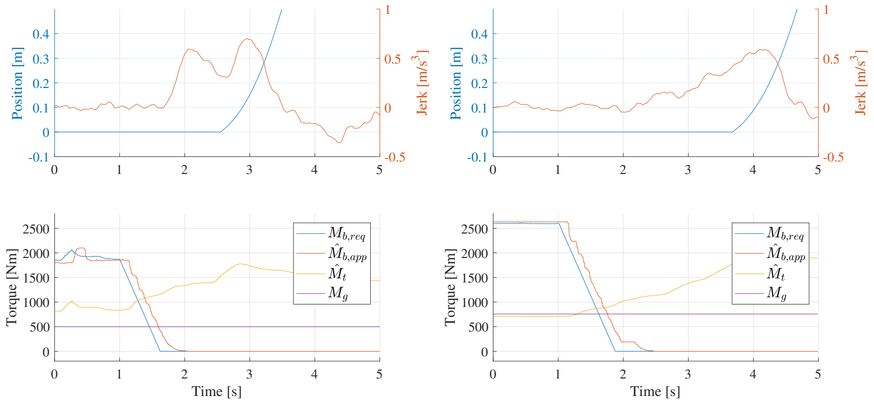
In this appendix, the remaining results from the implementation in the test vehicle are presented. The trailer mass is 800 kg when a trailer is hitched to the vehicle. In all of the figures presented, the DAR function is activated at 1 s.

C.1 Manual Drive

The test of the manual drive mode presented in this appendix includes forward driving in Case II, Case III, Case IV and reverse driving in Case IV and V.

Case II

Figure C.1 shows the results for manual drive mode with and without trailer going uphill at a 10 % inclination. When the DAR function is activated, the requested $M_{b,req}$ and estimated applied brake torque $\hat{M}_{b,app}$ start to decrease immediately. The gravitational M_g and estimated propulsion torque $\hat{M}_t$ are also plotted. When driving without the trailer, $\hat{M}_t$ is larger than M_g, however, when the trailer is hitched to the vehicle, $\hat{M}_t$ and M_g is nearly the same. No rollback was detected in either test. Figure C.1a shows when no trailer is hitched to the vehicle. In this case the jerk has two peaks, first one is about 0.6 m/s^3 and the second is 0.7 m/s^3. When the trailer is hitched to the vehicle the jerk levels peaks about 0.6 m/s^3 (see Figure C.1b).



***(a)** Without trailer.* ***(b)** With trailer.*

***Figure C.1:** Test Case II, driving forward in manual drive mode, uphill with an inclination of 10 %.*

Case III

Figure C.2 shows the manual drive-off for Case III without the trailer. Since the road inclination is zero, M_g is zero. When the DAR function is activated the $M_{b,req}$ and $\hat{M}_{b,app}$ starts to decrease. $\hat{M}_t$ remains between 500 – 1000 Nm during the drive-off. When the brakes release the jerk peaks to about 1.6 m/s^3.

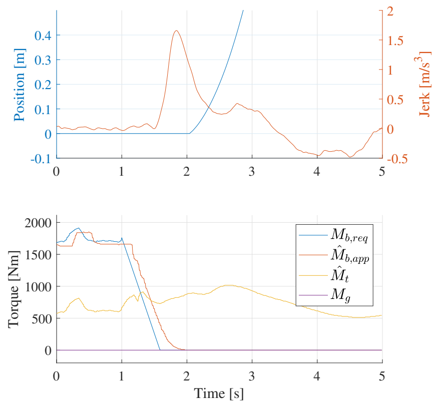
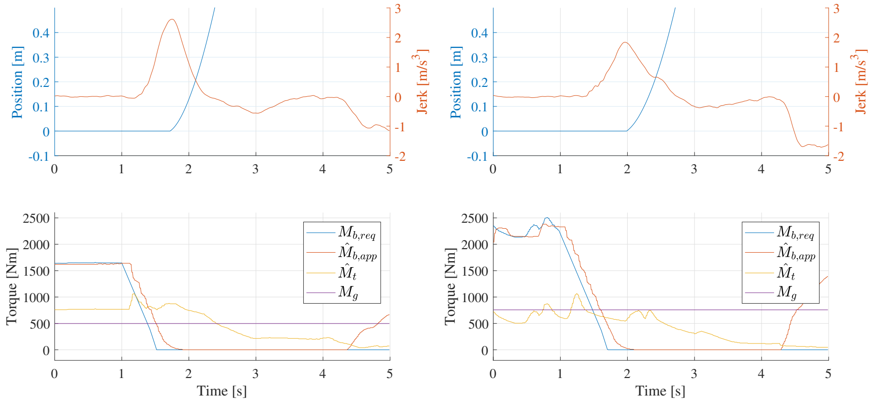


***Figure C.2:** Test Case III, drive-off forward in manual drive mode on a horizontal road without trailer.*

Case IV

Figure C.3 shows manual forward drive-off for Case IV with and without the trailer. The function is activated by the driver, who presses the accelerator pedal. This causes the propulsion torque to increase momentarily. $M_{b,req}$ and $\hat{M}_{b,app}$ start to decrease when the DAR function is activated. In both tests, the jerk peaks when the brakes releases fully. The peak jerk, when driving without the trailer, is about 2.8 m/s^3 (see Figure C.3a) and, when the trailer is hitched to the vehicle, the jerk peaks about 1.9 m/s^3 (see Figure C.3b).

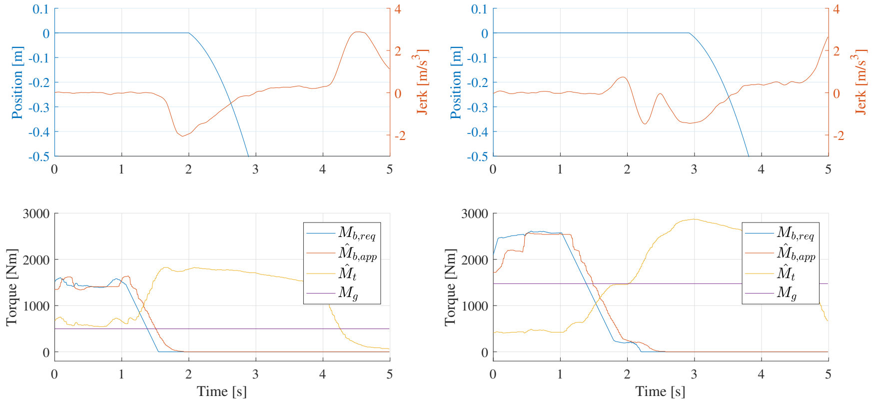


(a) *Without trailer.* ***(b)*** *With trailer.*

Figure C.3: *Test Case IV, driving forward in manual drive mode, downhill with an inclination of 10 %.*

Reverse Driving Case IV and V

Figure C.4 shows going in reverse direction for both Case IV and V in manual drive mode without the trailer. When the DAR function is activated $M_{b,req}$ and $\hat{M}_{b,app}$ start to decrease, $\hat{M}_t$ from the driver starts to increase. For Case IV, in Figure C.4a, the absolute value for the jerk peaks about 2 m/s^3 and this is when the brakes release fully. For Case V, in Figure C.4b, the peak for the absolute value of the jerk is about 1.5 m/s^3. There is no rollback in either of the cases.



***(a)** 10 % inclination.* ***(b)** 30 % inclination.*

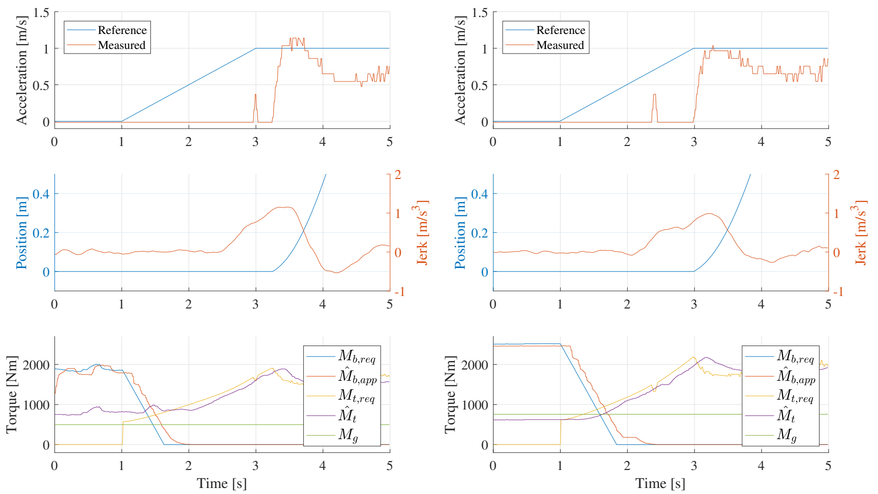
***Figure C.4:** Test Case IV, driving reverse in manual drive mode uphill, without trailer.*

C.2 Autonomous Drive

The tests of the autonomous drive mode presented in this appendix include forward driving in Case II, Case III, Case IV and reverse driving in Case IV and V. When the system activates the DAR function at 1 s, the autonomous drive mode initiates an acceleration request going from 0 to 1 m/s^2, with a ramp of 0.5 m/s^3, this is the same for all autonomous test drives.

Case II

Figure C.5 shows the results of Case II when driving uphill. In Figure C.5a the drive-off without the trailer is shown. When the DAR function is activated, $M_{b,req}$ and $\hat{M}_{b,app}$ start to decrease until they reach zero. The requested propulsion torque $M_{t,req}$ makes a step up to $\hat{M}_g$ and then starts to gradually increase. The estimated propulsion torque $\hat{M}_t$ follows the requested propulsion torque. When comparing the reference and measured accelerations, the figure shows a delay between the two. Afterwards the actual acceleration manages to increase to the requested and then drops slightly below it. The jerk peaks around 1 m/s^3 when the acceleration changes the most. This is also when the vehicle starts to drive-off. The same behaviour can be seen in Figure C.5b, where the trailer is hitched to the vehicle. The jerk peaks around 1 m/s^3. There is no rollback in either test.



***(a)** Without trailer.* ***(b)** With trailer.*

***Figure C.5:** Test Case II, driving forward in autonomous drive mode uphill, with an inclination of 10 %*

Case III

In Figure C.6, Case III is shown for driving forward without the trailer. It can be noted that when the DAR function is activated that $M_{b,req}$ and $\hat{M}_{b,app}$ start to decrease, $M_{t,req}$ starts to increase. The jerk peaks around 1.5 m/s^3 when the brakes fully release. This is also when the vehicle start to drive-off. When looking at the reference and measured acceleration it can be noted that there is a delay in the measured acceleration but that it then manages catch up to the the reference acceleration.

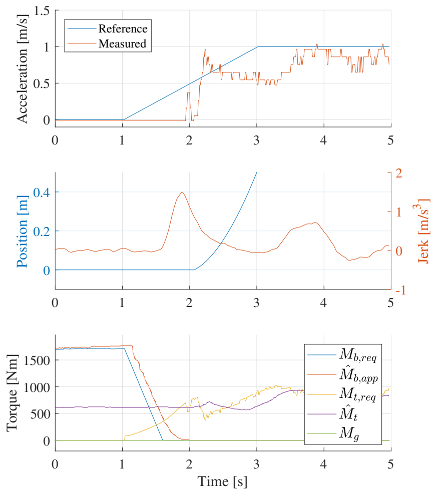
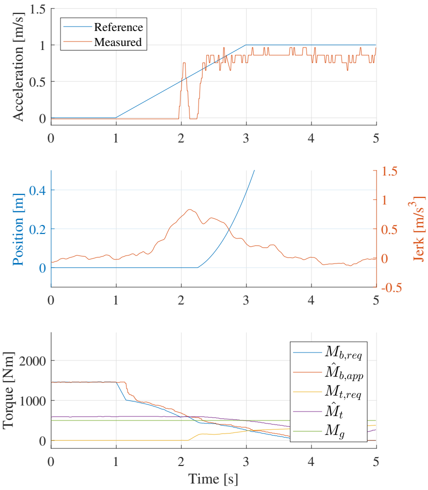


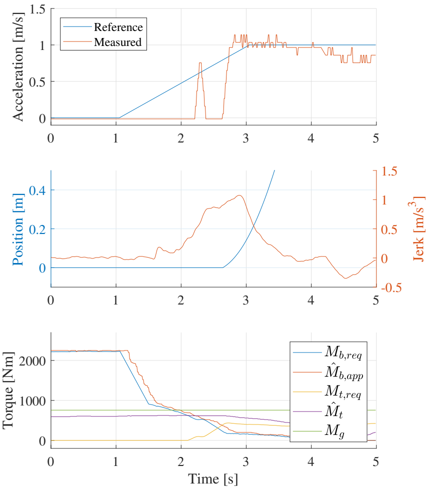
Figure C.6: *Test Case III, driving forward in autonomous drive mode on a horizontal road without trailer.*

Case IV

Figure C.7 shows the autonomous drive-off in forward gear, downhill direction at a slope of 10 % both with and without the trailer. $M_{b,req}$ decreases quickly, and then ramps out more slowly when the DAR function is activated. When the vehicle starts to move, the jerk increases and there is a quick increase of the measured acceleration towards the reference value. When the vehicle starts to move, $M_{t,req}$ is initiated to meet the acceleration request. For the case without the trailer the jerk peaks at 0.8 m/s^3 (see Figure C.7a), and at 1.1 m/s^3 with the trailer (see Figure C.7b).



***(a)** Without trailer.*

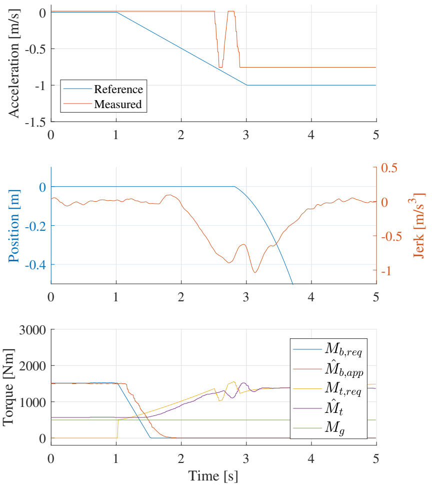


***(b)** With trailer.*

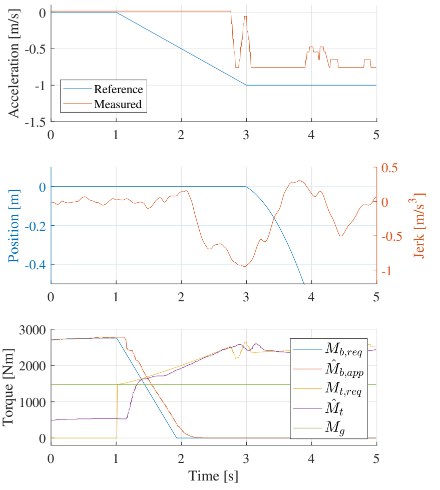
Figure C.7: *Test Case IV, driving forward in autonomous drive mode downhill with an inclination of 10 %.*

Reverse Driving Case IV and V

Figure C.8 shows reverse driving uphill in both 10 % and 30 % without the trailer. In both cases, the initial response when the DAR function is activated, $M_{b,req}$ starts to decrease, and $M_{t,req}$ has a step to the function's estimated gravitational torque, before the DAR function is active. $\hat{M}_t$ then increases slowly compared to the decrease of the brake torque. When the measured acceleration increases towards the reference acceleration, $M_{t,req}$ drops causing the measured acceleration to go back to zero, this results in some oscillations for $M_{t,req}$ followed by oscillations in $\hat{M}_t$. This occurs in both cases at the time when the jerk is as largest. In both cases there is a stationary error between the measured and the reference acceleration. The jerk in Case IV has a negative peak at a value of -1.0 m/s^3 (see Figure C.8a) and Case V at -0.95 m/s^3 (see Figure C.8b).



(a) 10 % inclination.



(b) 30 % inclination.

Figure C.8: *Test Case IV and V, driving reverse uphill in autonomous drive mode, without trailer.*

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